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## lab 1 Session 1: SF

### O. Prelab Q 1:

- a) Given a 5mm diameter field of view at the object, what diameter should the iris at field stop be set to? Under Köhler illumination.

→ Note Given that in Köhler illumination. Field stop (FS) is imaged onto object plane by field lens ( $L_2, f_{field} = 50\text{mm}$ ) and Condenser lens ( $L_3, f_{condenser} = 100\text{mm}$ ). This is the 4-f-ray system

$$\text{Magnification, } M_{\text{im}} = \frac{f_{\text{condenser}}}{f_{\text{field}}} = \frac{100\text{mm}}{50\text{mm}} = 2$$

field stop  $\rightarrow$  object

$$\rightarrow \text{Illuminated diameter: } D_{\text{obj}} = M_{\text{field}} D_{\text{Fieldstop}}$$

$$D_{\text{FS}} = D_{\text{obj}} = \frac{5\text{mm}}{2} = 2.5\text{mm}$$

is the value we must set the iris diameter

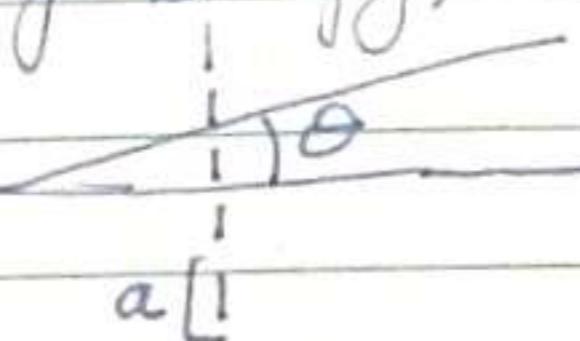
Then fine tune while watching object illumination

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- b) To resolve diffraction orders clearly from 10 lp/mm Ronchi ruling, what pinhole diameter at the aperture stop should be used so that diameter (FWHM) of each diffraction order peak is  $\approx 1/10$  of the spacing between adjacent orders?

→ For a grating of period  $a$ , the diffraction angles satisfy,

$$\sin \Theta_m \approx \Theta_m \approx \frac{m\lambda}{a}$$



→ In the Back focal plane of objective / Fourier plane, transverse position is  $x_m \approx f_g \Theta_m \approx f_g \frac{m\lambda}{a}$

So spacing between adjacent orders is:

$$\Delta x = x_{m+1} - x_m = f_g \frac{\lambda}{a} (m+1) - f_g \frac{\lambda}{a} m$$

$$\Delta x = f_g \frac{\lambda}{a} (m+1-m) = \boxed{f_g \frac{\lambda}{a}}$$

Recall:  $f_g = 150 \text{ mm} = 0.15 \text{ m}$ ,  $\lambda = 525 \text{ nm} = 525 \times 10^{-9} \text{ m}$

$$a = 1 \times 10^{-4} \text{ m}$$

$$\therefore \Delta x = 0.15 \times 525 \times 10^{-9} \text{ m} = 7.875 \times 10^{-9} \text{ m} = 0.7875 \text{ mm}$$

$$\text{So target FWHM: } \omega_{\text{target}} = \frac{1}{10} \Delta x \approx 0.07875 \text{ mm}$$

→ Approximate the diffraction-limited spot size at Fourier plane as the airy disk FWHM for circular pin hole aperture:  $\text{FWHM}_x \approx 1.03 \frac{\lambda f}{D_{\text{pin hole}}}$

$$D_p$$

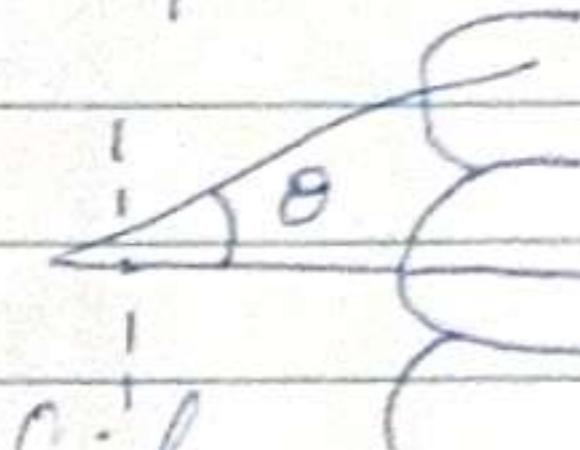
iii

c)

### Spectral Broadening of grating order

For a Ronchi ruling (transmission grating) with period  $d$

$$d \sin \Theta_m (\lambda) = m \lambda$$



If illumination is not monochromatic but has a finite spectral width  $\Delta \lambda$  around central  $\lambda_0$ , then the same diffraction order is produced at slightly different angles for different wavelengths.

For small bandwidth, the angular spread is approximately

$$\Delta \Theta_{\text{spec}} \approx \left| \frac{\partial \Theta_m}{\partial \lambda} \right|_{\lambda_0} \Delta \lambda \quad (1)$$

→ Taking differential:  $d \cos \Theta_m \times \frac{\partial \Theta_m}{\partial \lambda} = m$

$$\therefore \frac{\partial \Theta_m}{\partial \lambda} = \frac{m}{d \cos \Theta_m}$$

So spectral contribution to FWHM is:

$$\Delta \Theta_{\text{spec}, m} \approx \frac{m}{d \cos \Theta_m} \Delta \lambda$$

\* The zero order ( $m=0$ ) does not move with wavelength, so it has no spectral broadening. Its observed FWHM is set by the imaging/illumination angle, dominated by aperture-stop pin hole.

iv

①

For a circular pinhole of diameter  $a$ , the far-field pattern is an Airy disk.  $\Delta\theta_0 \approx 1.03 \cdot \frac{\lambda_0}{a}$

from Airy disk formula for circular aperture FWHM.

If the total FWHM of the  $m$ -th order is dominated by both aperture diffraction:  $\Delta\theta_0$  & spectral broadening  $\Delta\theta_{\text{spec},m}$

The total width is  $\approx \Delta\theta_m = \sqrt{\Delta\theta_0^2 + \Delta\theta_{\text{spec},m}^2}$

$$\Rightarrow \text{To find } m, \Delta\theta_m = 2\Delta\theta_0$$

$$\Rightarrow \sqrt{\Delta\theta_0^2 + \Delta\theta_{\text{spec},m}^2} = 2\Delta\theta_0 \Rightarrow \Delta\theta_{\text{spec},m}^2 = 3\Delta\theta_0^2 \Rightarrow \Delta\theta_{\text{spec},m} = \sqrt{3}\Delta\theta_0$$

$$\text{Plugging } \Delta\theta_{\text{spec},m}: \frac{m}{d\cos_m} \Delta\lambda = \sqrt{3} 1.03 \cdot \frac{\lambda_0}{a}$$

Assuming small  $\theta_m$ ,  $\cos\theta_m \approx 1$

$$m \approx \sqrt{3} \cdot 1.03 \cdot \frac{\lambda_0 d}{a \Delta\lambda} \approx 1.78 \cdot \frac{\lambda_0 d}{a \Delta\lambda}$$

$$\Rightarrow \text{From question: } \frac{\Delta\lambda}{a} = 30 \text{ nm} = 30 \times 10^{-9} \text{ m} \quad d = 200 \mu\text{m} = 200 \times 10^{-9} \text{ m}$$

$$a = 100 \mu\text{m} = 100 \times 10^{-9} \text{ m}$$

$$m = \frac{1.78 \times 525 \times 10^{-9} \times 200 \times 10^{-9}}{100 \times 10^{-9} \times 30 \times 10^{-9}} = 62.3$$

but should be more like 6.2 (extra  $m$   
so 7th order).

This provides a practical limit on how high a diffraction order can be reliably used: At low orders, spectral broadening is small, peaks are narrow & sharp. At high orders, angular dispersion scale with  $m$ , so finite LED Bandwidth causes each order to spread out more.

## Lab Session 1: Spatial Filter (Exploring the Equipments)

Date: Thursday, 08-Jan-2026, Lab Partner: Nathan  
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### 0. Prelab

1. Goal. a) Short Term goals b) Long Term Reach.
2. Apparatus
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8. Procedure
9. Post lab Reflections

### 1. Goals

#### a) Short Term goals:

- i) Create a good sketch of the overall setup
- ii) Set up the camera & Software, understand the gain & exposure parameters enough for a sharp image
- iii) Find the right position to place magnification lens for sharpening
- iv) Keep a look out for sources of uncertainty because this is a very sensitive experiment.

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- b) Long Term Vision
    - i) Complete Setup inside lab Setup 1, familiarize with equipment
    - ii) Familiar all information regarding the components in Pre lab Question 1.
    - iii) Explore real space imaging using the line grating test object
    - iv) Finish lab 1 Testing
    - v) Ensure beam & lens are centered also with camera
    - vi) Think about what we need for lab 2.
    - vii) Review Fraunhofer diffraction & relationships in Fourier transform
    - viii) Understand CMOS Camera factors (line exposure time, gain, -

## 2. Apparatus

Rail:

- ↳ Optic Rail & Saddles
  - ↳ Posts: 3", 4", 6"
  - ↳ Translational Stages (for microscope stage / fine positioning)
  - ↳ Sensors & Cameras:
    - ↳ LED Source ( $\lambda = 525\text{nm}$ ) (Bandwidth 25nm) LED S25L
    - ↳ Real-space camera (FLIR Blackfly) on 6" post  
Imaging / Illumination Optics
    - ↳ Magnifier lens ( $f \approx 300\text{ mm}$ , marked  $\infty$ ) Schott double lens
    - ↳ Objective lens ( $f = 150\text{ mm}$ ) → field lens ( $f = 50\text{ mm}$ ) plano-concave

Ackermann doublet

- ↳ Condenser lens ( $f \approx 50\text{ mm}$ ) ↳ 0.5" iris (small field stop)
  - ↳ 200  $\mu\text{m}$  pinhole on XY translation mount (aperture stop) LMIXY mount
  - ↳ large iris (Block stray light)
  - ↳ Lens tube, CCD cover disk

Test Object:

- Variables line grating (Thorlabs) !! Do not touch with Bare Hands !

## Software:

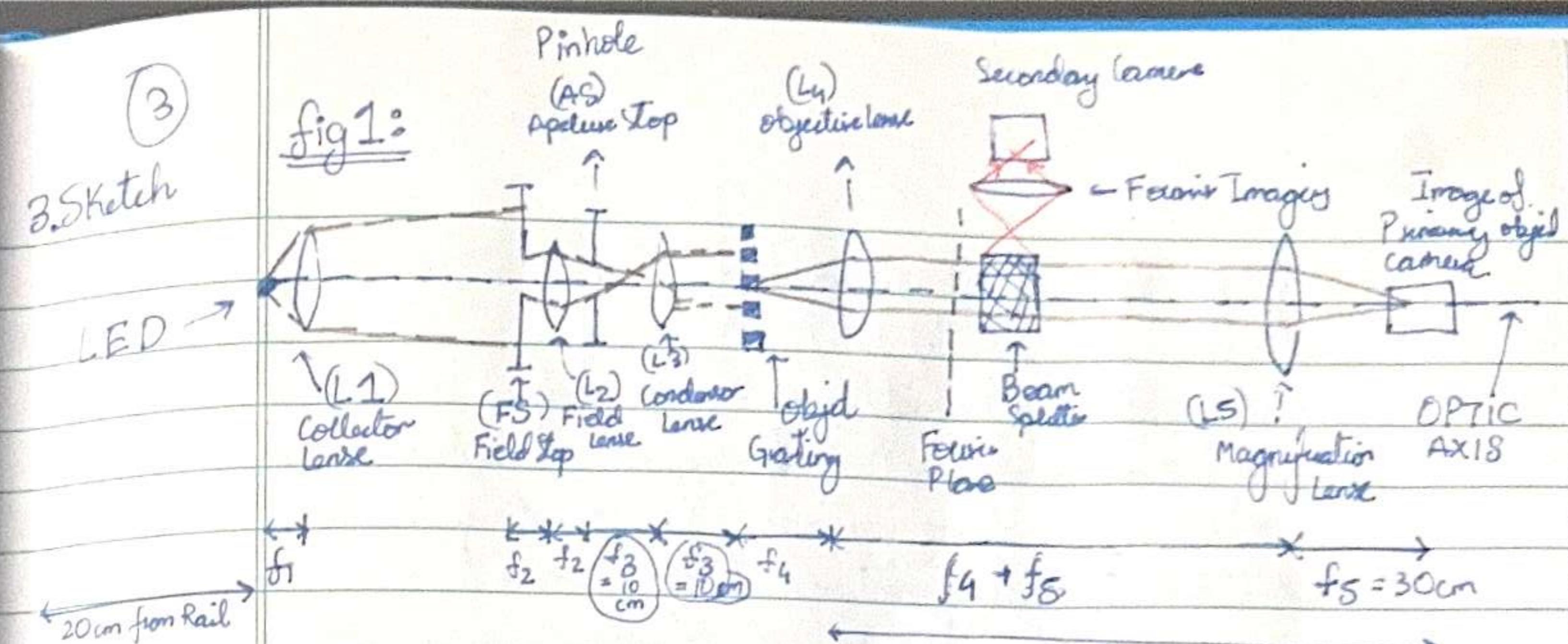
- ↳ NI Vision Assistant ↳ Lab View Program: Dual\_Camera\_Profile\_v2.

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### 3. Sketch

ED

LED



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## Key Distances Initial

- ↳ LED Distance from far rail end -  $20 \pm 0.05$  cm
  - ↳ LED Camera distance :  $\sim 150 \pm 0.05$  cm
  - ↳ Magnification lens  $\leftrightarrow$  Camera :  $\sim 30 \pm 0.05$
  - ↳ Objective lens  $\leftrightarrow$  Magnification lens :  $\sim 45 \pm 0.05$  cm
  - ↳ Condenser objective distance :  $\sim 10. \pm 0.05$  cm
  - ↳ Pin hole  $\leftrightarrow$  Condensor :  $\sim 10 \pm 0.05$  cm

S.  
Find me

# Demo for How to find Uncertainties

I could not find official documentation for the optois rail that talks about the calibration. The least count is  $1\text{mm} \approx 0.1\text{cm}$ . The uncertainty I use is half of that. ( $\pm 0.05$ ) cm

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## References

\*LabScript : PHYS 232 - Spatial filtering 2026, Jan 8. Edition

(4)

### 7. i) Some Useful Background Theory

\* Kohler Illumination Brief:

⇒ Field stop (controls illuminated area at object)

⇒ Pinhole (aperture stop) controls angular extent / coherence of illumination.

⇒ Field lens forms an image of LED onto aperture stop.

\* Diffraction grating relation:  $d \sin \theta_m = m \lambda$

$d$  = grating spacing (m),  $\theta_m$  = diffraction angle for order  $m$

$\lambda$  = LED emission wavelength

### ii) Background on the Variables in the lab.

Independent variables (we change):

→ Pinhole diameter (aperture stop) → Condenser lens position

→ Field stop iris (set illumination field) → Grating/object position

Dependent Variables (we expect to measure):

→ Max lp/mm we resolve on the grating (resolution limit)

→ Diffraction order Spacing

Control Variables (we keep fixed):

→ LED Source,  $\lambda = 525\text{nm}$  → Room light Blocked

→ lens choices

(5)

8.

### Detailed Procedure.

#### 8.1) Initial placement of LED + collimator lens.

Established the far end of the rail as the one near door to limit light from outside into the setup

Placed LED + collimator lens on far end of rail ( $\approx 20$  cm from end of rail). Measured using scale on railing

Set height of the LED source as  $21.5 \pm 0.05$  cm take into account for end of railing. Ensure LED source sits right over the center of the rail & that the beam propagates approx. on centre of line. ✓

Quickcheck:

To adjust the collimator, we adjust so the image of the LED chip is in clear focus when we flip the source & project onto a  $\sim 5\text{m}$  away wall it looks as sharp as we can. without a clear moist focus or along the rail.

No moist focus; so we diverge & never converge. Showing it is collimated enough. ✓

#### 8.2) Ensure Software is able to show image.

Verified the program on LabView, Rud-Camera-Line-Projekt v2.vi on the pc desktop.

It shows two panels.

Use Exposure 900ps, 1 Gamma & 18 gain

Mounted the Camera on a 6 inch pole, 30 cm on the other side (opposite side to LED).

TIP: the size of the base saddle is 3 cm. So if you want the camera to be at 30 cm. you must set 28.5 & 31.5 on either side

1.51pm

⑥

Quick Check:

Make Sure CCD face is exposed by removing the lens tube.

- \* Rotate the Source after Putting a post collar & adjust height of camera post  $21.5 \pm 0.05$  cm  
→ Used a Ruler to measure.

### 8.3) Aligning magnification lens

\* Magnification lens 30 cm in front of camera (Between Camera & Source). The lens is of  $300\text{mm} = f$ . Use "4" post

Move curved part of magnification lens toward the source.

The  $\infty$  symbol or lens is away from camera. After making the position of LED with empty saddle & Remove LED post.

We moved the magnification lens until the image is sharp on a white card at  $\approx 71.5 \pm 0.05$  cm on rail.

Success: We found a sharp focus with lens centered & equipment square to optic axis. The Image Confirms this ✓

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## 9. Post lab 1 Reflections :

\* We found it very difficult to focus the light through a minor Doto camera.

\* We spent too much time on set up so we now try to only do rough set up & then go back fine tune for accuracy

Goals Review: (Refer to Pg 1-2)

a) Short Term goals : Everything from sketch(i) to position of magnification lens was found (iii). But iv) the uncertainty we lost time and could only explore uncertainty of the optics rail. Must find more uncertainty next lab.

b) Long Term goals : Seems like we were a bit ambitious. The precision needed in the equipment set up meant we did we were slow to do the placement of and adjustments.

i) We did not finish Set up 1 ✗

ii) Partially familiarized with information needed for pre lab 1 -

iii) We explored real space imaging but only with half the set up -

iv) Could not Reach Testing ✗

v) Yes Beam, lens, camera were well aligned ✓

vi) Limited Thoughts on Lab 2, focus remains on Lab 1

vii) Learned Fraunhofer Diffraction but is only relevant for pre labs

viii) Understood CMOS (camera, features & exposure time ✓

(8)

## To do next lab :

Complete goals incomplete in last page

Move to the next part of lab Setup 1, specifically add objective lens, image grating object, place pin hole and as specified by the lab script while all the elements are co-linear and square to the rail.

(a)

1. Goals: i) Complete Lab Setup 1 following the post lab Reflections on (page 7-8) of lab notebook.

ii) Explore Uncertainty Sources. iii) Familiarize information for pre lab 1

iv) Explore real Space imaging but with full set up.

v) Reach & Do the Testing of the Setup to Qualitatively Verify the Set up.

vi) Add Objective lens, pin hole

v) Image the grating object & Resolve a grating  $> 10 \text{ lp/mm}$

2. Apparatus, sketch & Reference : Same as Lab Session 1 : Refer to page 2-3 of notebook.

3. Procedure conducted:

### 3.1 Verify the old set up & distances.

Focus on a new object & verified the distance of the focal length as recommended by lab script pg 30.

Objective lens at  $60.5 \pm 0.05 \text{ cm}$  from Start of rail.

Open the Dual-Camera-line-Profile-v2.vi or NI Vision Accretion Software. This is the default software file on the Desktop.

→ Set Gamma = 1

→ Disable Auto Gain, set gain as 18

→ Disable Exposure Auto,

→ To do this open Block Diagrams in NI Vision, click on Vision Accretion 1. Change the Value of Auto Gain & Auto Exposure as off.

Adjust and Set Sharpness & Contrast

Final: Exposure Time : 12000 ns

Gamma: 1 Grain is 18. (no need to change)

## Lab Session 2: Spatial Filtering (Finishing Set up 1)

Date: Thursday, 8-Jan-2026. Lab Partner: Nathan

### Table of Content:

#### 1. Goals

#### 2. Apparatus

#### 3. Procedure

##### 4.1 Error Identification for Uniform illumination

##### 4.2 Sosio theory & Explanation of Errors

##### 4.3 Conclusion made

##### 5) Post Lab 2 Reflection:

##### 6) Goal Evaluation & what to do next lab

(10)

- 2:15 PM Return LED Source to previous position on the Rail, at  $20 \pm 0.05$  cm away from end of Rail  
 ↳ Verify it is aligned to the centre of rail

### 3.2 Place Objective lens

- Place a new  $f = 150$  mm lens, at 45 cm from magnification lens to Right. Centre-to-centre  
 ↳ ie place new lens at 45 cm + 60.5 cm on the Rail  
 $\text{mark} = 105.5 \pm 0.05$  cm  
 ↳ Left Height of lens to make rays go through center of lens. Centre Horizontally & Vertically.  
 ↳ Note: The 150mm lens must be having a fine zoom control Silver colour on the lens.  
 ↳ Tip, look at the shadow with LED on, PL The camera must be co-centric to the lens aperture

### 3.3 Place Test object & View object on Screen

Place Variable line grating object on the translating microscope stage objective, facing the objective to the metallic coating on the grating. Saddle of "3".

(Test object)  
 The grating had a Thor Lab test on it, we try to focus on that!

The position of grating at best focus is  $123.5 \pm 0.05$  cm  
 Exposure time 3000 ps, Gamma = 1 & Gain is 18

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Now, adjust the vertical & horizontal fine course dial until you see  $> 10$  LP/mm.

Success: ↳ We were able to make  $12.5$  LP/mm.

### 3.4 Place Condenser lens

Placing Condenser lens  $f \approx 100$  mm, at 100 mm or 10 cm from the grating i.e. rail at  $134 \pm 0.05$  cm Centre the lens by ensuring the illuminated part of the object seen is centred in the camera mag. lens. Focus the object.

Need to use small Hex Ball driver to loosen the set screw on the lens mount for the Condenser lens to Centre the lens, retighten the screws to secure the position.

### 3.5 Place pin hole & Align with mirror

The 200pm pin hole is already on the LM1 XY translating mount & it is centred.

Place it Right of Condenser lens at  $10 \pm 0.05$  cm away from lens on the Source Side.

→ Ensure pin hole shadow is centred on Condenser lens using the X, Y knobs.

Tip place a white card after the Condenser lens to observe the image to Centre it

Place the Blue coated or one side mirror,  $10 \pm 0.05$  cm from the condenser lens & auto collimate, i.e., observe the blue reflection onto the pinhole. Make dots concentric.

### Quick Check

Make Sure: Illumination Beam remains centred on the line of the object. & stays centred on objective & CCD.

(12)

Insert  $f = 50\text{mm}$ , condensor lens to image LED source onto pinhole (focus it).

"LED image focused onto aperture stop. (pinhole)

→ Remove pinhole by uncoupling it from the mount  
But keeping the saddle, i.e.,  $144 \pm 0.05$  cm  
as rail.

→ Adjust field lens height to keep Beam centered at object & objective.

⇒ Real field lens is  $50\text{mm} = f$ , plano convex lens.

Replace pinhole & confirm LED image is focused onto pinhole

### 3.6 Place field Stop Iris

3:35 PM - Placed 0.5" iris (field stop) (ID 12, small diameter)  
as adjustable field stop.

⇒ Centered it on Beam.

⇒ Temporarily removed pinhole to focus the sharp edges of the iris on the camera image by sliding iris along rail.

This was closest to the  $50\text{mm}$  lens "field lens" we could get to.

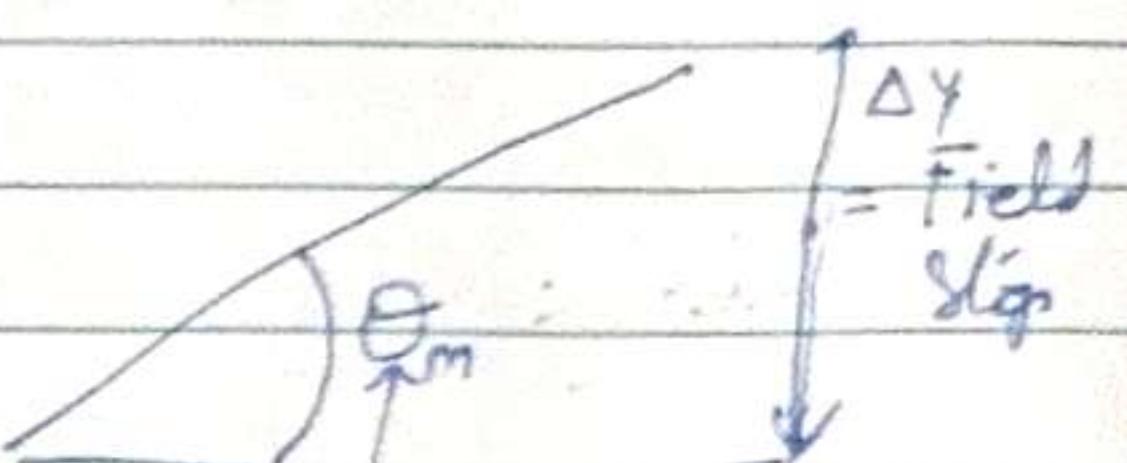
At smallest aperture, the centre of iris should be on the camera centered too.

Reduce the iris to get  $\sim 5\text{mm}$  illuminated field at the grating.  
Use a white black card to see this field of view.

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### Explaining Theory for our Observations (Note)

Note: Field stop controls illuminated area on the object, aperture stop controls the effective 'size' of the object lens.  
So control illumination angular exalt.



Aperture Stop

### 3.7 Final elements to Block stray light

Finally add a large mounted iris in front of the source side of the field iris to reduce stray LED light beams.

Add a lens tube to the camera to Block ambient room light

### 4.1 Error Identification for Uniform illumination

When Iris is reduced to  $\sim 5\text{mm}$  illumination on the grating.  
We did not observe uniform illumination.

→ On the top left corner There was a clear gradient.

We thought it was a screen glare from room but no even with dark door it remained.

Professor Paul assisted us,

→ We observed that even if we placed a white card after each element. We could see exactly where the non uniform illumination started.

Errors :

→ So, LS & L4 were pointing the wrong direction  
→ Because one lens was rotated too much, each element after that tried to correct it But this caused more & more error.

"Curious why this Makes non-uniform illumination" !! Sketch Behind →

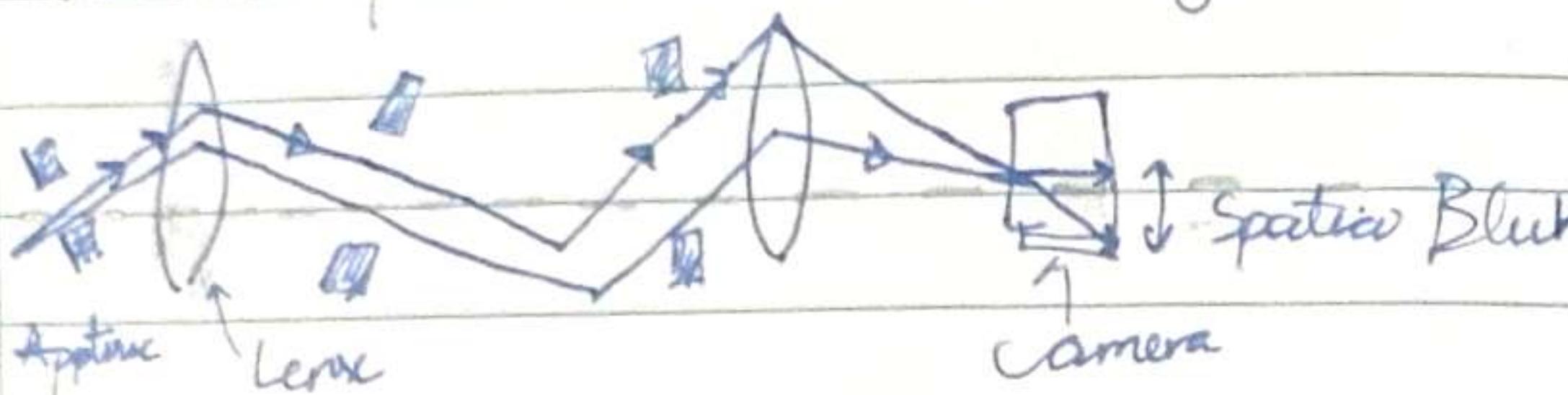
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4.2

## Sone Theory & Explanations of our Errors.

### Incorrect placement. Sketch (Rough & Inaccurate)

fig 2:



Observe How mis placed lenses & apertures cause some light to travel more. Optical path length changes so light focuses on different points!

This is what causes the non-uniform illumination

4.3

Correction: Make all of them aligned & co-centric

TIP:

Learnings

Do not need to remove all the elements & saddle!  
If the focus is right, the issue is just the rotation of the elements.

So, You can unscrew the element (like lens) from its holder mount while the post & saddle are in place.

So unscrew element by element towards the same until the illumination on a card is uniform.

4.4

Probable Some of errors:

lens focus points

Railing, it is really straight?

In proper lens position

camera Accuracy.

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5.

## Post lab 2 Reflection:

In Post lab 1 reflections (Pg ) we noticed that we were too slow & Behind expected Schedule. To compensate we tried to do rough placements this lab but as professor Paul noted this has led to some issues causing non square alignment of saddle.

DO:

We also noted that next lab, we should have a better sketch for the experiment. One that has Both the aspect rotation distances of components But also the direction they point in.

The main issue was that we had one aperture rotated off centre & that caused all following lenses & apertures to be rotated. But !! We learnt cool tricks to just remove the lens (unscrew it) from its holder & then go back to an earlier stage of the experiment. Super cool! I am impressed by how modular the optics lab is ! :)

To clarify

ASK →

Clarify the distances on the grating before next lab.

Ask →

How to speed up experiment?

Ask →

Documentation for the Rail Train

Ask →

I think I want the lens manufacturing documentation to find the errors in the lens. ??

Find →

Lab View & Camera Accuracy.

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## 6. Goal Evaluation & what to do next lab

- We completed the lab set up but we found errors.  
Next lab we must redo this set up strategically to correct this.
- We have found & thought of the sources of errors but not quantitatively. Try to do this next lab.
- We roughly explored the equipments needed for Pre lab 2 like Rabi Ruling.
- Explored Real Spacing with full set up
- Was not able to do the Testing, Next lab after doing corrections we will do this
- Added objective lens & pinhole elements ✓
- We imaged 12 lp/mm ✓ (max 11 and 10 lp/mm). We almost went to the 15 lp/mm but it was a little too blur

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For logistical Reasons, the next lab would be the "Lab Period 2" even though technically would be the third week of lab.

### D. Pre lab Question 2

\*Rabi Ruling consists of a series of long parallel slits (slit width,  $b$ ) & (period,  $a$ )

→ Monochromatic light incident on object diffracts & forms far-field (Fraunhofer) diffraction pattern

$$\Rightarrow \text{Eq. 32: } I(\theta) = I_0 \left( \frac{\sin B}{B} \right)^2 \left( \frac{\sin N\alpha}{N\sin \alpha} \right)^2$$

where  $\alpha = \frac{ka}{2} \sin \theta$ ,  $B = \frac{kb}{2} \sin \theta$ ,  $K = 2\pi$  (Source lab Script pg 11)

→ Starting from the lab Script's eq 30; in 1D Fraunhofer field at angle  $\theta$ , the field intensity is proportional to the Fourier transform of the aperture / mask function  $a(x')$  or  $f(x')$  or  $\Pi(x')$   
"This lab script uses  $a(x')$ , lesson uses  $f(x')$  while  $\Pi(x')$ "

$$\therefore \text{Eq. 30: } E(x) \propto \int_{-\infty}^{\infty} a(x') e^{i k x' x} dx'$$

$$\text{or using } u = K\theta x; E(\theta) \propto \int_{-\infty}^{\infty} a(x') e^{i K \theta x' x} dx'$$

In the paraxial approximation & small angle Regions (Remember we are quite far away from the mask)  $\theta_x \approx \sin \theta$  &  $u = K\theta_x \approx K \sin \theta$

$$\therefore E(\theta) \propto \int_{-\infty}^{\infty} a(x') e^{i K x' \sin \theta} dx'$$

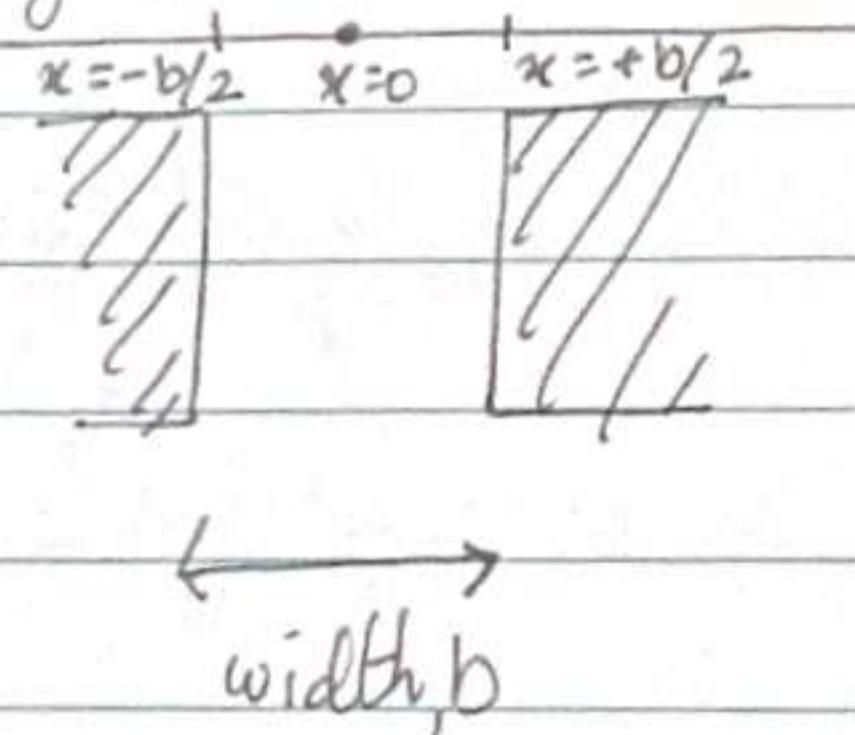
(18)

Now let a single slit of width  $b$  centered at  $x=0$ .  
Its single aperture function for transmission would be.

$$\Pi(x') = \begin{cases} 1, & |x'| \leq b/2 \\ 0, & \text{otherwise} \end{cases}$$

Do not panic! all this says is, if your light beam is positioned between the slit (ie it is not blocked by the slit, it passes through) otherwise it is blocked & no light

See here →



if you are between slit  
you pass.  
Sketch

Moving on,

The Fourier transform for a single slit would be the following. (we do a single slit Fourier transform instead of the full pattern because using a dual comb we can just later on use properties of F.T (Fourier Transform) to multiply.)  
Convolution in object space is multiplication in the Fourier space.

$$E_1(\theta) \propto \int_{-\infty}^{\infty} \Pi(x') e^{-i k x' \sin \theta} dx' = \int_{-b/2}^{b/2} e^{-i k x' \sin \theta} dx'$$

$$\text{Note: } \frac{e^{-i\theta} - e^{+i\theta}}{-i} = 2 \sin \theta \quad \text{use} \\ E_1(\theta) \propto \frac{2 \sin(Kb/2 \sin \theta)}{K \sin \theta}, \text{ now let } \beta = \frac{Kb \sin \theta}{2}$$

$$E_1(\theta) \propto \frac{b \sin(\beta)}{\beta}, \quad \beta = \frac{Kb \sin \theta}{2}$$

This is the envelope function

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Quoting Lipson (pg: 245 - 247)

A diffraction grating is given by

$$f(x) = a(x') \otimes \sum_{n=0}^{N-1} s(x-na) \quad (\text{eq 8.53 lipson})$$

↑  
Single Aperture Mask      ↓  
Diffraction of slits      ↑  
a, line spacing (period)  
N, Total nos of slits

The Intensity or the Diffraction Pattern is The F.T.

$$\Rightarrow I(u) = |E(u)|^2 = \mathcal{F}\{f(x)\}$$

$$\mathcal{F}\{f(x)\} = E_1(\theta) \times \sum_{n=0}^{N-1} e^{-iun\alpha} \quad (8.45) \quad u = \frac{2\pi}{\lambda} (\sin \theta - \sin \theta_i)$$

Note  $\sum_{n=0}^{N-1} e^{-iun\alpha}$ , as  $N \rightarrow \infty$ , the sum is,  $\sum_{m=-\infty}^{\infty} s(u - 2\pi m/a)$

The index  $m$  is called order of diffraction. When  $m=0$ ,  $N$  is first. The geometric series becomes,  $= \frac{1 - e^{-iuNa}}{1 - e^{-iua}} \quad (8.47 \text{ lipson})$

$$\text{The intensity, } I(u, v) = \left| \frac{1 - e^{-iuNa}}{1 - e^{-iua}} \right|^2 = \frac{\sin^2(u Na/2)}{\sin^2(u a/2)}$$

Now again  $\alpha = ka \sin \theta = ua$  is how we define in this lab (look at lab script pg → )  
Singl Slit Repeating Slits ↓

∴ The total Amplitude becomes:  $E(\theta) \propto \frac{\sin B}{B} \frac{\sin(Na)}{\sin(a)}$

$$\text{Total Intensity } I(\theta) \propto |E(\theta)|^2 \propto \left( \frac{\sin B}{B} \right)^2 \left( \frac{\sin(Na)}{\sin(a)} \right)^2$$

$$I(\theta) = I_0 \left( \frac{\sin B}{B} \right)^2 \left( \frac{\sin(Na)}{\sin(a)} \right)^2 \quad \text{If you let } N=2 \\ \text{Singl slit Envelope (Pattern)} \quad \text{You get Young double slit exp.}$$

## Pre-lab Question 2

Your Ronchi ruling consists of a series of long parallel slits (slit width  $b$ , period  $a$ ). Monochromatic light incident on the object diffracts and forms a far-field (Fraunhofer) diffraction pattern.

(a) Derive Eq. (32) for the far-field diffraction intensity pattern of  $N$  slits.

(b) Make sample plots for different values of  $N$  and  $a$ , and describe qualitatively how each parameter affects:

- the spacing between diffraction orders,
- the width of diffraction peaks,
- and the overall envelope of the pattern.

(c) Explore the effect of varying the duty cycle  $b/a$ . How does it affect the relative intensity of diffraction orders (including which orders may be suppressed)?

(d) In the experiment, diffraction orders will not be perfectly sharp and may broaden with order. Briefly explain at least two physical reasons why a real diffraction pattern may deviate from the ideal prediction of Eq. (32). (Hint: consider finite source size, finite spectral bandwidth, and imperfect alignment/aberrations.)

---

**Eq. (32):**

$$I(\theta) = I_0 \left( \frac{\sin \beta}{\beta} \right)^2 \left( \frac{\sin(N\alpha)}{N \sin(\alpha)} \right)^2$$

Where:

$$\alpha = \frac{k a \sin \theta}{2}, \quad \beta = \frac{k b \sin \theta}{2}, \quad k = \frac{2\pi}{\lambda}$$

**B)**

Make sample plots for different values of  $N$  and  $a$ , and describe qualitatively how each parameter affects:  
• the spacing between diffraction orders,  
• the width of diffraction peaks,  
• and the overall envelope of the pattern.

$$I(\theta) \propto \left( \frac{\sin(N\alpha)}{N \sin(\alpha)} \right)^2$$

```
In [9]: import matplotlib.pyplot as plt
plt.style.use('dark_background')
import numpy as np
```

Note:

Here  $a$  is the grating period of the Ronchi ruling and  $b$  is the slit width (close to  $b = a/2$ , but it may differ slightly). (LabScript: Pg 11)

```
In [10]: def I(theta, N, a, lam=None, I0=1.0):
    """
    theta : array of angles (rad)
    N    : number of slits
    a    : grating period (m)
    lam  : wavelength (m), default 525 nm
    I0   : overall I scale
    """

    lam = (lam or 525) # nm (Lab Script Pg 22)
    lam = lam * 10**(-9) # m
    b = a/2 # (Lab Script Pg 11 and inspired by code in Pg 12)

    k = 2*np.pi / lam
    alpha = 0.5 * k * a * np.sin(theta)
    beta = 0.5 * k * b * np.sin(theta)

    single_slit = (np.sin(beta) / beta)**2
    interference = (np.sin(N*alpha) / (N*np.sin(alpha)))**2

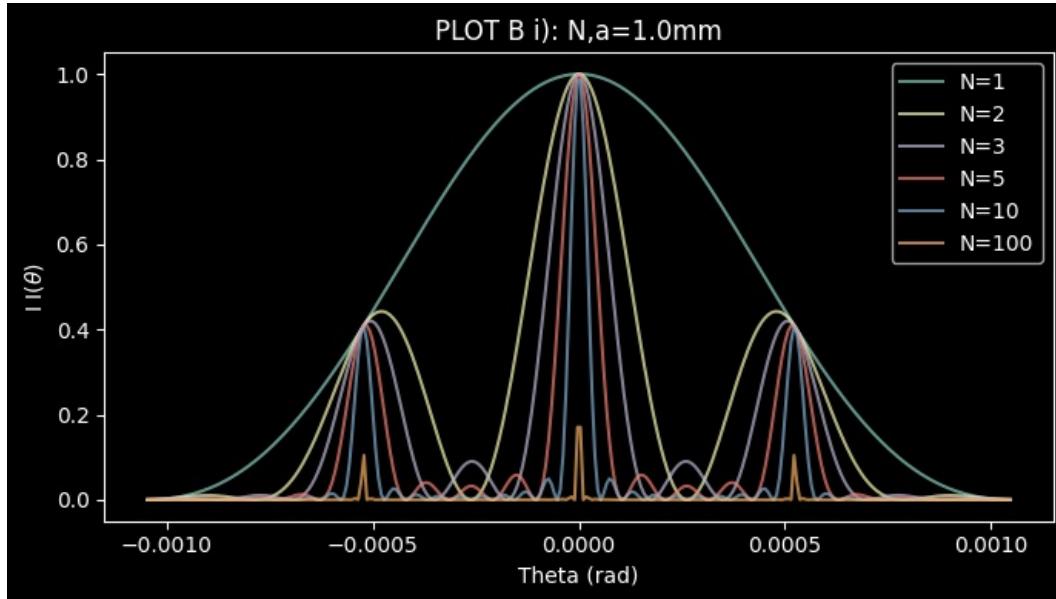
    return I0 * single_slit * interference
```

i) Keeping  $a$  constant, Changing  $N$

```
In [11]: theta = np.linspace(-np.pi/3000,np.pi/3000,3000)
N_lst = [1,2,3,5,10,100] # different numbers of slits
a_lst = [1,10,100,1000] # mm

# Keeping a constant, Changing N
#plt.subplot(1,2,1)
plt.figure(figsize=(7,4))
for i in range(len(N_lst)):
    a = a_lst[0]
    a = a * 10**(-3) # m
    #plt.subplot(len(N_lst),2,i+1)
    # sharex = True
    plt.plot(theta, I(theta,N=N_lst[i],a=a) , label=f"N={N_lst[i]}",alpha=0.7)

plt.title(f"PLOT B i): N,a={a*1000}mm")
plt.xlabel("Theta (rad)")
plt.ylabel(r"I I$(\theta)$")
plt.legend()
plt.tight_layout()
plt.show()
```



ii) Vary  $a$  at fixed  $N$

```
In [12]: theta = np.linspace(-np.pi/300,np.pi/300,3000)
plt.figure(figsize=(16,8))

N = N_lst[0]

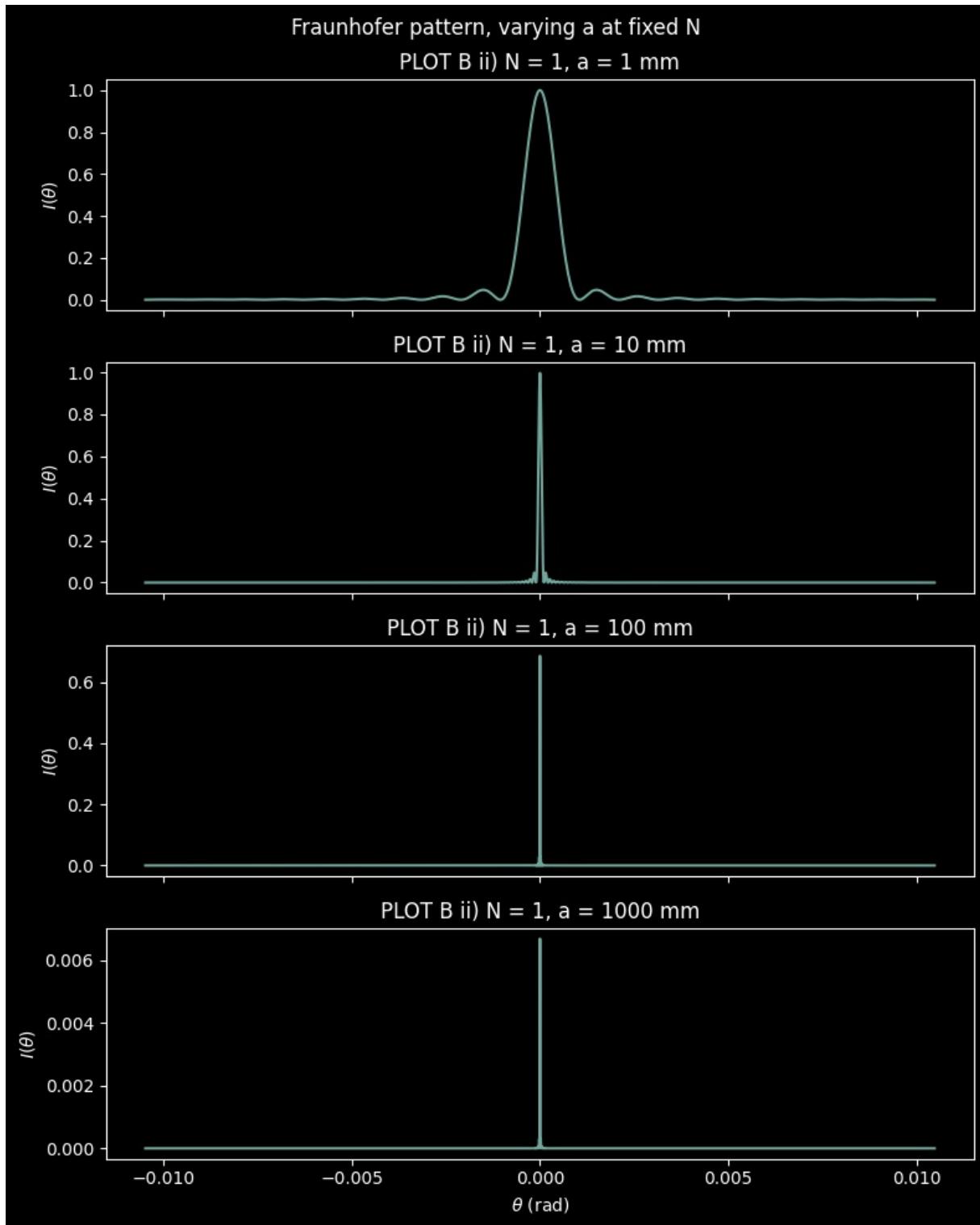
fig, axs = plt.subplots(len(a_lst), 1, figsize=(8, 10), sharex=True)

for i, a_mm in enumerate(a_lst):
    a = a_mm * 1e-3 # convert mm -> m
    I_vals = I(theta, N=N, a=a)

    axs[i].plot(theta, I_vals, alpha=0.8)
    axs[i].set_ylabel(r"$I(\theta)$")
    axs[i].set_title(f"PLOT B ii) N = {N}, a = {a_mm} mm")

axs[-1].set_xlabel(r"$\theta$ (rad)")
fig.suptitle("Fraunhofer pattern, varying a at fixed N", y=0.98)
fig.tight_layout()
plt.show()
```

<Figure size 1600x800 with 0 Axes>



iii) Grid

```
In [13]: # Angle range (rad) – chosen to show several diffraction orders
theta = np.linspace(-5e-3, 5e-3, 2000)    # ~±0.3 degrees

# Columns: different N
N_list = [2, 5, 10, 20]
```

```

# Rows: different grating periods a (in mm)
a_list_mm = [0.1, 0.2, 0.5, 1.0] # adjust to taste

# -----
# Create grid of plots: rows = a, cols = N
# -----


n_rows = len(a_list_mm)
n_cols = len(N_list)

# A4 in landscape: about 11.69 x 8.27 inches
fig, axes = plt.subplots(
    n_rows,
    n_cols,
    figsize=(11.69, 8.27),
    sharex=True,
    sharey=True
)

# If there's only one row/col, make axes always 2D-indexable
axes = np.atleast_2d(axes)

for i, a_mm in enumerate(a_list_mm):
    a_m = a_mm * 1e-3 # convert mm -> m
    for j, N in enumerate(N_list):

        ax = axes[i, j]
        I_vals = I(theta, N=N, a=a_m)

        ax.plot(theta, I_vals, lw=1.0)

        # Top row: label with N
        if i == 0:
            ax.set_title(f"N = {N}", fontsize=10)

        # First column: label with a
        if j == 0:
            ax.set_ylabel(f"a = {a_mm:.2f} mm\nI(\u03b8)", fontsize=9)

        # Keep ticks small so everything fits nicely
        ax.tick_params(axis='both', which='both', labelsize=8)

    # Common x-label
    fig.text(0.5, 0.04, r"\theta (rad)", ha='center', fontsize=11)

    # Optional overall title
    fig.suptitle("PLOT B iii) Fraunhofer Diffraction of a Ronchi Ruling\n(rows: a, columns: N)", fontsize=12)

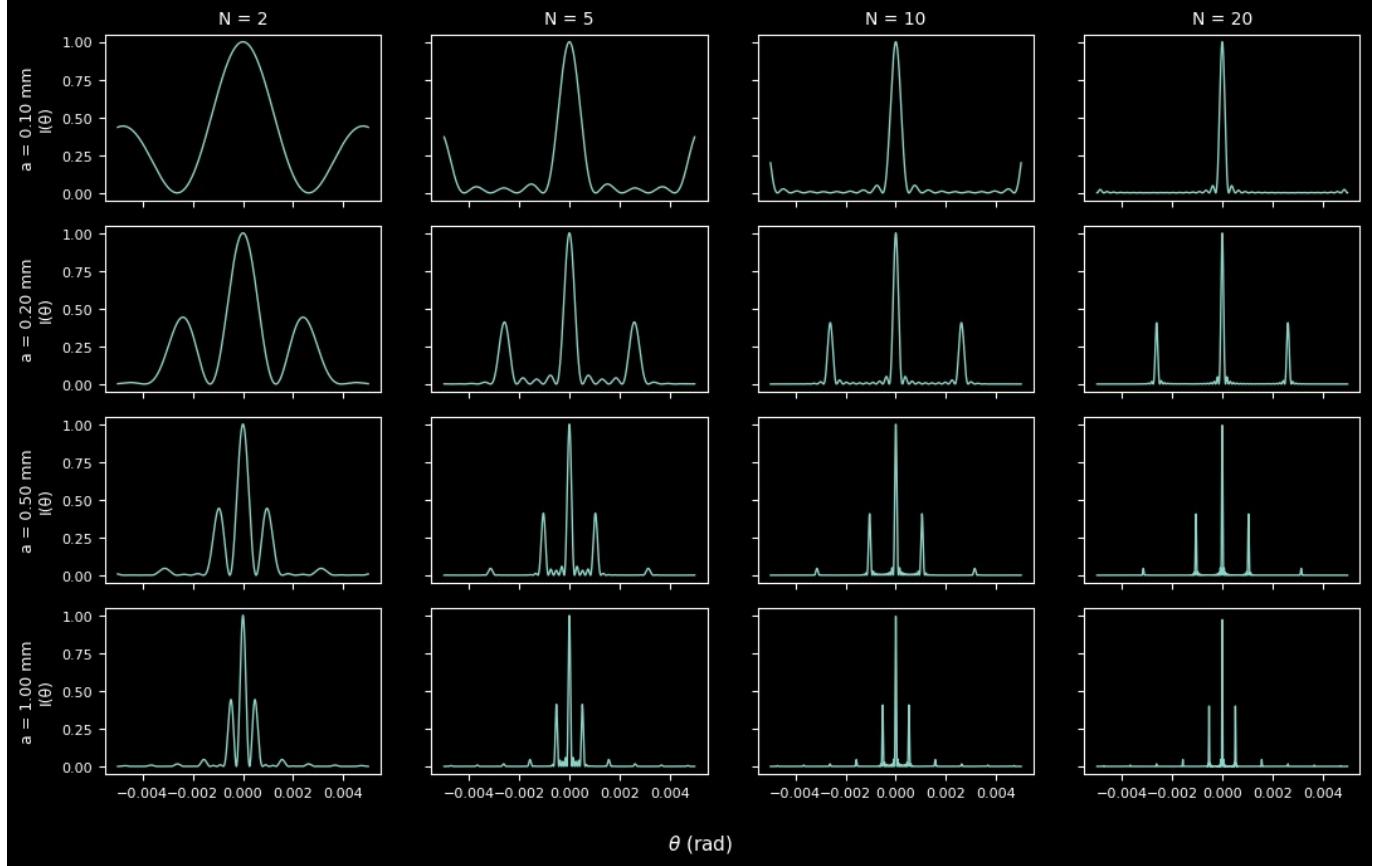
    # Make layout tight for A4 printing
    fig.tight_layout(rect=[0.03, 0.07, 0.97, 0.93])

    # Optional: save for printing
    # plt.savefig("ronchi_grid_A4.pdf", dpi=300, bbox_inches="tight")

plt.show()

```

PLOT B iii) Fraunhofer Diffraction of a Ronchi Ruling  
(rows: a, columns: N)



#### Fraunhofer Diffraction of a Ronchi Ruling: Effect of Slit Number $N$ and Period $a$

Each panel shows the normalized far-field intensity  $I(\theta)$  for a 1D Ronchi ruling, modeled as a grating of  $N$  identical slits with period  $a$  and duty cycle  $b/a = 0.5$  (i.e., slit width  $b = a/2$ ).

Rows correspond to different grating periods  $a$  (in mm), and columns correspond to different numbers of illuminated slits  $N$ . The diffraction pattern is computed from the standard  $N$ -slit Fraunhofer formula:

$$I(\theta) \propto \underbrace{\left[ \frac{\sin(\beta)}{\beta} \right]^2}_{\text{single-slit envelope}} \times \underbrace{\left[ \frac{\sin(N\alpha)}{N\sin(\alpha)} \right]^2}_{\text{N-slit interference}}$$

#### Variables Defined:

- $\alpha = \frac{1}{2}k\sin\theta$
- $\beta = \frac{1}{2}kbs\sin\theta$
- $k = 2\pi/\lambda$
- $\lambda = 525 \text{ nm}$

## Key Qualitative Features

- **Effect of increasing  $N$  (across columns):** The principal maxima become narrower and sharper, and the side lobes (subsidiary maxima) become more numerous but relatively weaker. This matches the behavior of the interference term:  $[\sin(N\alpha)/(Ns\sin\alpha)]^2$ .
- **Effect of increasing  $a$  (down rows):** The angular spacing between diffraction orders decreases approximately as  $\Delta\theta \sim \lambda/a$ . Larger periods produce more closely spaced peaks.
- **Single-slit envelope:** The overall envelope is set by  $[\sin(\beta)/\beta]^2$ . This broadens when  $b$  is smaller and narrows when  $b$  is larger. For a fixed duty cycle  $b = a/2$ , changing  $a$  simultaneously rescales both the order spacing and the envelope width.

## Assumptions and Simplifications

Category	Description
Regime	Fraunhofer (far-field): The pattern is the Fourier transform of the aperture; no Fresnel-region effects.

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b)

Plotting log in, Pseudo code

 $N = [1, 2, 3, 5, 10, 100], a = [1, 10, 100, 1000]$ For i in range list  $N$ :

- plt. subplot(2, len(N), i)
- plt. plot(theta, I(argument)) include  $i^{\circ}$  &  $a[0]$   
genet from np.linspace
- plt. title(f'N {i}')

try for a do with j.

<b>Geometry</b>	<b>Scalar &amp; 1D:</b> Polarization, finite slit height, and 2D structures are ignored.
<b>Light Source</b>	<b>Perfectly Coherent:</b> Single wavelength $\lambda = 525 \text{ nm}$ with no spectral bandwidth.
<b>Optics</b>	<b>Idealized:</b> No lens aberrations, misalignment, detector noise, or finite pixel size.
<b>Normalization</b>	<b>Per-subplot:</b> Intensities are normalized to their own maximum for shape comparison.

**Note:** Under these idealized assumptions, the plots isolate the pure dependence of the Fraunhofer diffraction pattern on the grating period  $a$  and the number of illuminated slits  $N$ .

c)

Effect of varying the duty cycle  $b/a$ . How it affects the relative intensity of diffraction orders (including which orders may be suppressed).

I will be Fixing the N at 5 and  $a=0.20\text{mm}$

and Vary the duty,  $b/a$

```
In [14]: import numpy as np
import matplotlib.pyplot as plt
from fractions import Fraction as frac

def I_var_ba(theta, N, a, b_by_a, lam_nm=525, I0=1.0):
    """
    Calculates Fraunhofer intensity using the np.sinc identity.
    np.sinc(x) is defined as sin(pi*x)/(pi*x).
    """
    lam = lam_nm * 1e-9
    # s is the 'order' coordinate: (a*sin(theta))/lambda
    # When s is an integer, we are at an interference maximum.
    s = (a * np.sin(theta)) / lam

    # 1. Single Slit Envelope
    # Nulls occur when (b*sin(theta))/lambda is an integer.
    # This is equivalent to s * (b/a) being an integer.
    envelope = np.sinc(s * b_by_a)**2

    # 2. Interference Pattern
    # This identity avoids division by zero at sin(theta) = 0.
    # It normalizes the peak height to 1.0.
    interference = (np.sinc(N * s) / np.sinc(s))**2

    return I0 * envelope * interference

# --- Parameters ---
lam_nm = 525
N      = 10
a_mm   = 0.20
a       = a_mm * 1e-3

# Define duty cycles (b/a). b must be <= a.
b_by_a_list = [1.0, 1/2, 1/3, 1/4, 1/5, 1/7]
theta = np.linspace(-np.pi/120, np.pi/120, 5000)

fig, axs = plt.subplots(len(b_by_a_list), 1, figsize=(8, 12), sharex=True)

for i, b_by_a in enumerate(b_by_a_list):
    I_vals = I_var_ba(theta, N, a, b_by_a, lam_nm)

    # Convert theta to 's' for the plot to see integer orders clearly
    s_vals = (a * np.sin(theta)) / (lam_nm * 1e-9)

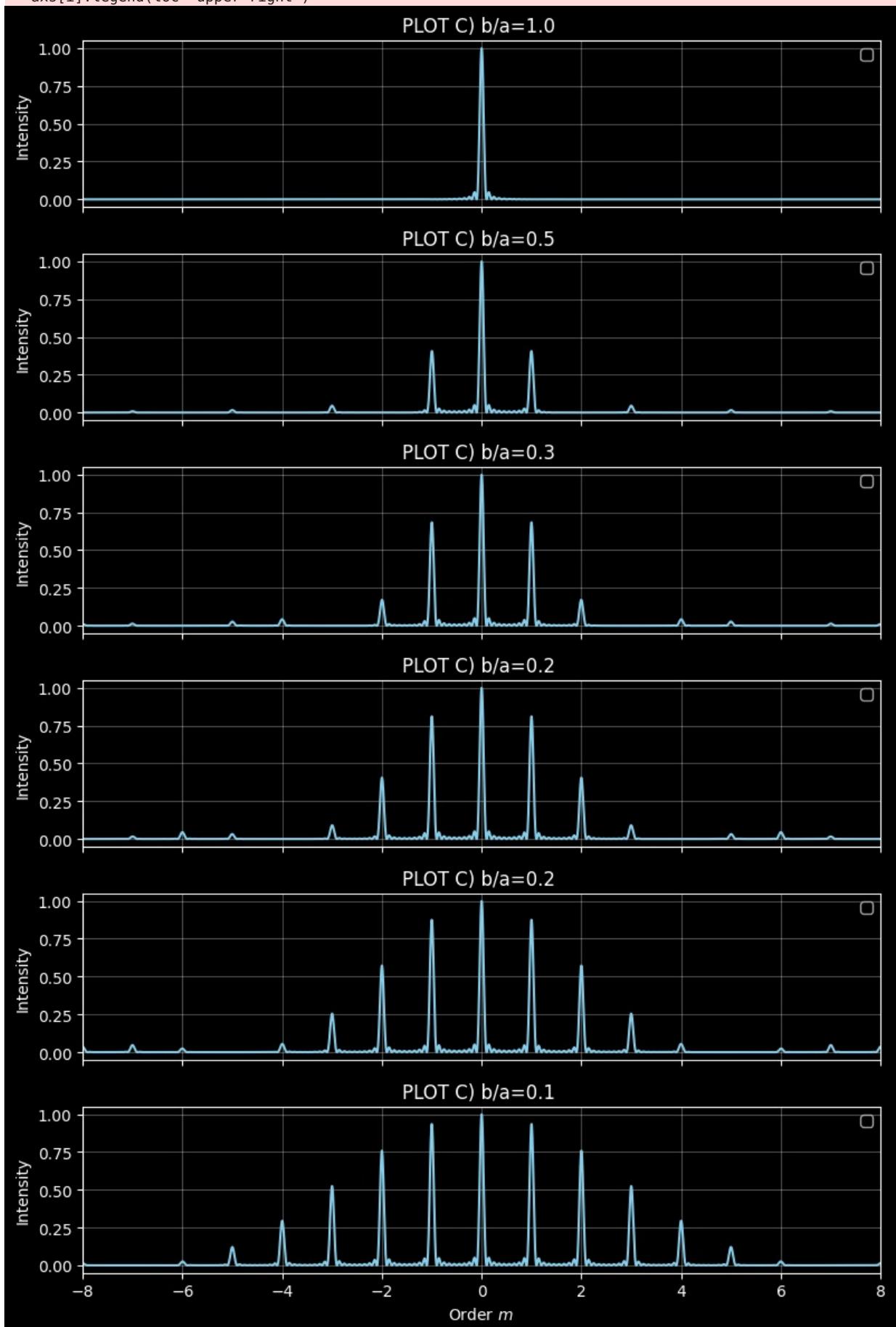
    axs[i].plot(s_vals, I_vals, color='skyblue')
    axs[i].set_ylabel("Intensity")
    axs[i].legend(loc='upper right')
    axs[i].grid(alpha=0.3)
    axs[i].set_title(f"PL0T C) b/a={b_by_a:.1f} ")

    # Highlight where orders SHOULD be (integer s)
    # If a peak is missing at an integer s, you've found a missing order!

axs[-1].set_xlabel(r"Order $m$")
plt.xlim(-8, 8)
plt.tight_layout()
plt.show()
```

```
C:\Users\ahila\AppData\Local\Temp\ipykernel_19348\677395210.py:48: UserWarning: No artists with labels found to put in legend. Note that artists whose label start with an underscore are ignored when legend() is called with no argument.
```

```
    axes[i].legend(loc='upper right')
```



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## Qualitative Explanations.

Spacing Between Orders:

As  $a$  increases, the diffraction order  $\lambda \sin \theta / \lambda$  length  
 $N$  has no effect

Width of Diffraction Peak

As  $N$  increases, diffraction peaks become narrower & sharper.

Overall Envelope

$\Rightarrow$  As  $b$  gets smaller, produces wider envelope, more diffraction orders are visible.

(22)

d) Effect of Varying  $b/a$ , the duty cycle, and how that affects the relative intensity.

$\Rightarrow$  Note the suppressed diffraction orders.

$\Rightarrow$  Let me do this to graphically.

= look at attached plot

We observe that as we decrease the duty cycle from 2 to  $1/100$ . The relative intensities of the  $\pm 1$  diffraction orders increases.

When  $b/a > 1$ , it is actually not even existant.

for  $b/a = 0.5$  to  $1/100$  do in excel

In the code, I was not observing missing orders initially, so I later on found out, the 0/0 value was not handled effectively, so I switched to using "np.sinc"

= Explanations:

As  $b/a$  decreases and the slit becomes narrow, the single slit diffraction pattern has more peaks, so i.e., more higher order retain intensity. More power is concentrated in higher order m's.

= Suppressing orders.

When our the numerator goes to zero, the intensity of the order is suppressed.

(23)

$$\sin\left(\frac{\pi m b}{a}\right) = 0, \text{ when } \frac{mb}{a} \pi = n\pi, n \in \mathbb{Z}$$

$$\therefore \text{at } \frac{mb}{a} = n,$$

for the rochi valley,  $b/a = 1/2$  even

$$\frac{Im}{Io} \propto \left[ \frac{\sin(\pi m/2)}{\pi m/2} \right]^2$$

when even m's,  $\pm 2, \pm 4, \pm 6 \dots$

$$\Rightarrow \pm 2\pi = n\pi, \pm 4\pi = n\pi, \pm 6\pi = n\pi \dots$$

so these become zeros. and hence are suppressed. while odd Powers remain

likly for rochi valley,  $b/a = 1/3$

when m's,  $\pm 3, \pm 6, \pm 9$  are suppressed.

(24)

d)

In experiments, diffraction orders will not be sharp & may blur.

The reasons boil down to what the physical reality is.

1) Finite source size

→ Realistically we will not have an infinite source, we would only have a finite extended source from our LED & aperture which we have a finite angular extent. So the grating is illuminated by a smaller range of incident angles  $\theta_i$ .

For each incident angle, the grating equation  $a(\sin\theta - \sin\theta_0) = m\lambda$  gives slightly different output angles  $\theta$  for the same  $m$ .

→ Measured intensity has a superposition (convolution) of many slightly shifted patterns. This leads to broader diffraction patterns of each order. Rather than being delta functions we have sinc functions.

→ It won't be sharp as the contrast decreases.

2) Finite spectral Bandwidth.

→ Now Eq 32 assumes an mono chromatic illumination  $\lambda$ . But although we have a largely mono chromatic source that is indistinguishable by eye, it still has a bandwidth of  $25\text{ nm}$  for a central wavelength of  $\lambda_0 = 525\text{ nm}$  (Refer to Lab Script Appendix : pg 22).

→ For a given order  $m$ , different wavelengths satisfy  $a \sin\theta_i \lambda = m\lambda$ . Some see slightly displaced peaks, an angular broadening & more blurring for high orders.

Lab Session 3: SF

Date: Thursday 15-Jan-2026,

Lab Partner: Natha

## Table of Content

- 1. Goal
- 2. Apparatus, References, i) Additional Apparatus ii) Additional References.
- 3. New sketch
- 4. Procedure
- 5. Testing the Set up
- 6. Analysis
- 7. Major Issues
- 8. Uncertainty Notes
- 9. Goal Evaluation
- 10. Reflection plan for Next lab

# Note: Since my lab partner isn't going to be here for a while, I've decided to work on some preparation & sketches I wanted to improve from last lab.

### 1. Goal:

- i) Correct & Make a better experiment sketch
- ii) Use methods from lab lab to go back & correct the optical configuration (pg: )
- iii) Do the testing from the lab Setup 1 & ensure we are getting expected Results
- iv) Fix & Complete Lab Setup 2. v) Place Fourier plane using mirror card & verify that a stable diffraction pattern can be observed
- vi) Place the camera at Fourier plane & record at least one set of diffraction - order positions for the 10lp/mm Ronchi ruling
- vii) Measure the imaging magnification for a real-space image of the grating &
- viii) Identify major limitations in illumination uniformity & document one check & Verification

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## 2. Apparatus, References

Refer one again to same

as (pg 2-3)

### i) Additional Apparatus to meet lab 3 :

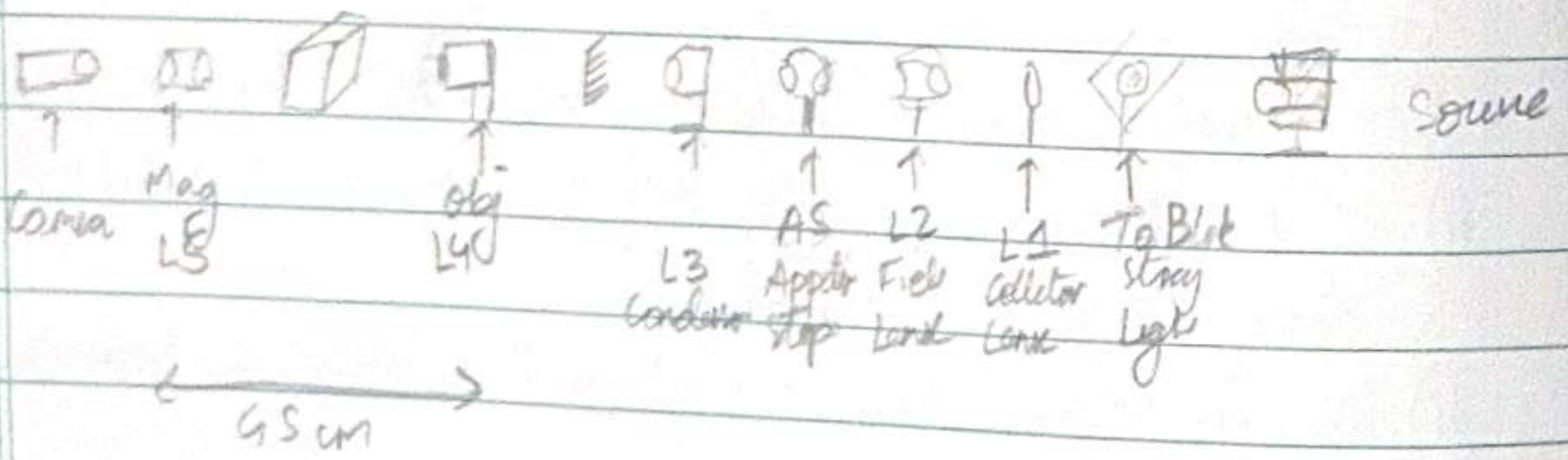
- \* Rondix Ruler & Camera BFS-03-1652M-CS
- \* Adjustable iris (field stop) & pinhole at aperture stop (200 μm)
- \* Paper to wedge the saddle & cover the pin hole stage

### ii) Additional References

- \* Hecht, Eugene, Textbook Optics (Library)
- \* Lipson, Modern Optic, 4th edition (Library)

3.

### Updated sketch: (Appendix Sketch to show lens Orientation)



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## 4. Procedure

### 4.1 Corrective measures :

Based on the figure we adjusted the direction the lens face in the sketch. Align all of the lenses square to the rail  
Nathan joined the lab

1:45 PM

### 4.2 Aligning Lense Alignment By working Backward Attempt 1

we trying to work Backward, remove the b4.

Then trying to decrease the pin hole size at

Using the small pin hole & the image on the camera, we are trying to align the placements of the lenses.

### 4.3) Restarting Configuration after Magnifying lens (Attempt 2)

We tried the above & this was difficult to align, so moving to different Method

Trying to Reset configuration after the magnification step

2:15 PM

(150mm)

Placed objective lens 45 ± 0.05 mm from magnification lens

Skip portion of grating, it is correct. The grating is moved to get 12 lp/mm in focus

There was ununiform illumination but it was from the outer rings of the aperture. Removing it fixed it.

We moved the mounted condenser lens by unscrewing it

Adjust the pin hole & the x-y dial. The image is centered. we verified with the aperture dot

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Attempt to wedge printer paper for pinhole saddle to align it

This did not help much. We just put a new saddle.  
This worked!

#### 4.4 Setup Check

- \* Verified optical train still assembled from Session 2
- \* Turned room lights down; confirmed lens tube installed to reduce ambient light

Quick Check: 4.5 Beam centering through the system

- \* Place a white card after each element (starting from source & towards camera side)
- \* Confirmed the beam stayed centered
- \* Overall largely uniform light! Yay!

Success!

#### 5. Testing the set up

Switched back on the NI acquisition software & the preset for this lab, stored at the desktop. (Just like referring to page 5, lab Session 1, Section 8.2)

Using the virtual dial on the grating object mount, center the image on the software such that the 10 lp/mm grating is on the center well illuminated.

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#### Testing

Using the line tool on the Image Panel, we make a line over the diffraction pattern over a length of 1mm. (converting pixel 255 to B28 on x axis)

Camera has a pixel of  $1440 \times 1080$  (Given on the Software itself)  
(cross checked by viewing the Bottom Right corner)

BFS-03-16S2M-CS documentation on canvas says each pixel is  $3.45 \mu\text{m}$

∴ image size is,  $(1328 - 225) \text{ pixel} \times 3.45$

The grating we used was 10 lines per 1 mm.

∴ we obtained 24 lines.

The object distance is:

$$\begin{aligned} 10 &: 1 \text{ mm} \\ 24 &: x \end{aligned}$$

$$\Rightarrow 10/x = \frac{24}{10} = 2.4 \text{ mm}$$

2.4 mm on object gives  $(1328 - 225) = 1103 \text{ pixels}$

$$\therefore 1103 \times 3.45 \mu\text{m} = 1103 \times 0.00345 \text{ mm}$$

$$M = \frac{i}{o} = \frac{1103 \times 0.00345}{2.4} = 1.585 \text{ magnification}$$

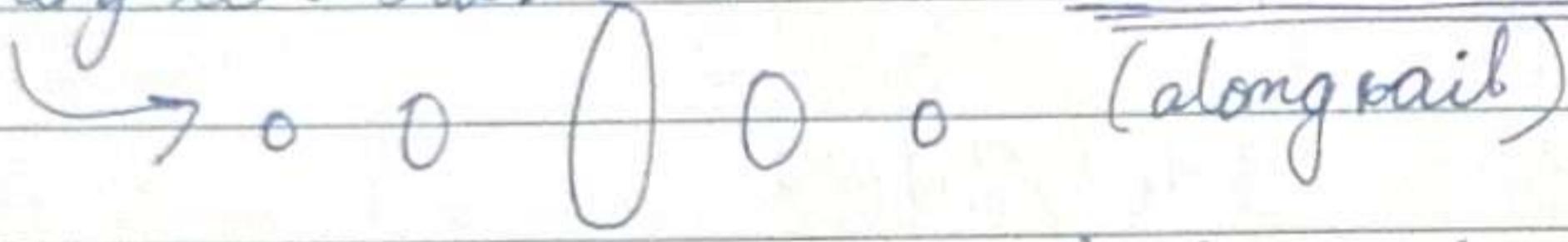
We are below it, we needed a magnification of 2 (Prelab 2)  
only  $\approx 1.6$ .

$$\text{This is from the 4-f relay: } M = \frac{\text{image distance}}{\text{object distance}} = \frac{300}{150} = 2$$

30

adjusted the field stop in such that we see only about 15 lines in full good illumination.

Moved a white card along the camera side of the objective region to find plane where sharp order peaks appeared.

Something like this. at  $\approx 94 \pm 0.05$  cm  


Place a camera on this plane, & fine adjusted the base. This spot was on camera side after the  $L_4$  lens.  
 at  $93.5 \pm 0.05$  mm.

Taking measurements of the diffraction pattern on LabView  
 Exposure: 1500 μs; Gain: 1, Gamma: 15. Auto exposure off.

Data: 0 0 0  
 390 674 953 : Pixel  
 $\frac{284}{2} \frac{279}{2}$

$$\text{avg pixel } \frac{284 + 279}{2} = 281.5 \text{ pixels}$$

$$\text{dagain } 281.5 \text{ pixels} \times 0.00345 \text{ mm} \\ = 0.971175 \pm 0.05 \text{ mm}$$

This is distance between the central & the first maxima.

Even, Hot spots on the camera formed a strong central dot.

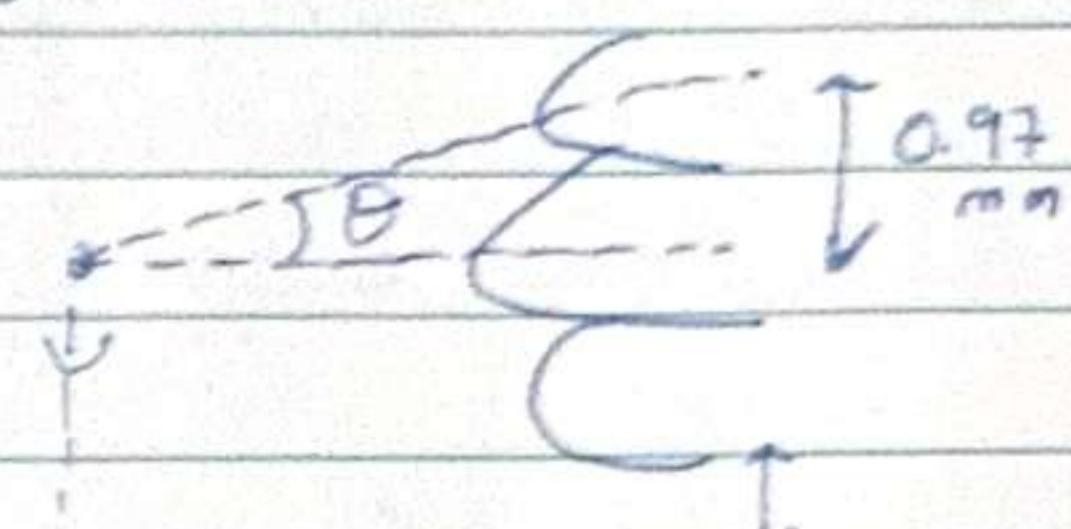
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### b. Analysis

To find the angle

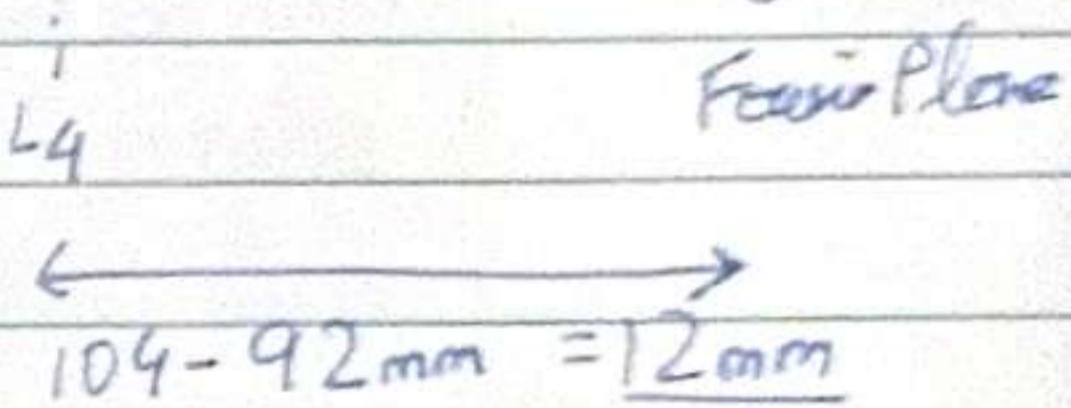
Under Small angle approximation  $\sin \theta \approx \theta$

$$\therefore \theta = \frac{0.97}{12} = 0.080833 \text{ rad}$$



The Labscript also suggests:

$$\sin \theta = \frac{\lambda}{d} = \frac{525}{12 \text{ mm}}$$



We took an image of the Fourier image using the "Save figure" button on the panel.

→ Saved it to canvas on: "Ahilan & Nathan Group/Lab 1-Spatial filtering/  
 Session 3/2026-01-15\_SF S3\_Fourier Imaging\_01.tiff"

Figure  
Saved

## 7. Major Issues:

- ISSUE 1) Found Very Bright spots equally in the centre. Made it harder to see exactly where the centre is (Reflected Image in canvas, look in last page.)
- ISSUE 2) Fine alignment of Rail & Saddle but this was easily mitigated with different Saddle. Keep this in mind for future labs.

## 8. Uncertainty notes:

- ⇒ Pixel measurement:  $\pm 1-2$  pixels, But each pixel is  $3.45 \mu\text{m}$  size, we have an uncertainty of  $\pm (3.45-6.9) \mu\text{m}$  to the spacing in diffraction pattern. Hence to the  $\theta$  angle as well.
- \* ⇒ In future lab, we should find this value!

## 9. Good Evaluation

- 1) locate Fourier plane ✓
- 2) Camera at Fourier plane + recorded image ✓
- 3) Magnification measurement + comparison ✓
- 4) Noted limitations ✓

## 10. Reflections & Plan for next lab:

- 1) After coming home & looking at the Fourier diffraction pattern image, I realized it might not be camera hot spot! whenever reloaded the default preset, we did not spend too much time on the exposure & gain values! Our notes on (Pg ) confirm this!
- ⇒ Next lab; control & decrease exposure values & see if that helps.
- ⇒ Zach, our TA suggested to about the over exposure at the lab actually, & told us we could use a "gaussian distribution" to further help identify the center. If time permits after the project for this lab. We will explore this.
- 2) We could improve the Fourier-plane placement & also make the magnification accuracy more close to 2. But Because of how much time we spent in this, maybe I want to move on & improve accuracy in lab 6-8.
- 3) We should have taken images of the Image Panel! Next lab we should have it too.
- 4) Explore the use of Git hub for file sharing. (TA Zach said to format better)

## Lab 1 Session 4 SF

Prelab Question 3.

1. Let the grating be periodic in  $x$  with period  $d$ .

Over one period, model its amplitude transmittance as a rectangular pulse:

$$t(x) = \begin{cases} 1 & , 0 \leq x \leq \omega \\ 0 & \omega \leq x \leq d \end{cases}, \text{ period with period } d$$

$$\Rightarrow \text{Duty Cycle; } f = \frac{\omega}{d} \quad (0 < f < 1)$$

Fourier Series form:

$$t(x) = \sum_{n=-\infty}^{\infty} c_n e^{i 2\pi n x / d}$$

$$\begin{aligned} \text{& fourier coeffnts: } c_n &= \frac{1}{d} \int_0^d t(u) e^{-i 2\pi n u / d} du \\ &= \frac{1}{d} \int_0^\omega e^{-i 2\pi n u / d} du \end{aligned}$$

$$\text{DC offset term, } c_0 = f$$

for  $n \neq 0$

$$c_n = \frac{1}{d} \left[ \frac{e^{-i 2\pi n \omega / d}}{-i 2\pi n / d} \right]_0^\omega = \frac{-1}{i 2\pi n} (e^{-i 2\pi n f} - 1)$$

$$c_n = \frac{\sin(\pi n f)}{\pi n} e^{i 2\pi n f} \quad (n \neq 0)$$

2) In a 4f imaging system, Fourier plane contains discrete diffraction orders with complex amplitudes proportional to  $C_n$ . A spatial filter modifies these orders by a complex factor  $M_n$  (amplitude & phase)

Filter is modelled as:

$$E(x) = \sum_{n=-N}^N (C_n M_n) e^{i 2\pi n x / d}$$

Assumed,  $I = |E(x)|^2 = E(x) E^*(x)$   
 $\approx$  complex conjugate

Code Below:

## Pre-lab Question 3

January 20, 2026

Ahilan Kumaresan

```
[4]: import numpy as np
import matplotlib.pyplot as plt

[15]: def ronchi_coeffs(N, duty_cycle):

    f = duty_cycle
    n = np.arange(-N, N+1, dtype=int)

    c = np.zeros_like(n, dtype=complex)

    # n=0
    c[n == 0] = f

    # n != 0
    nz = (n != 0)
    nn = n[nz].astype(float)
    c[nz] = (np.sin(np.pi * nn * f) / (np.pi * nn)) * np.exp(-1j * np.pi * nn * f)

    return n, c

def make_mask(n, mode="", **kwargs):

    M = np.ones_like(n, dtype=complex)

    if mode == "":
        return M

    if mode == "block_dc":
        M[n == 0] = 0
        return M

    if mode == "keep_orders":

        keep = set(kwargs.get("keep", []))
        M[:] = 0
```

```

for k in keep:
    M[n == k] = 1
return M

if mode == "lowpass":
    nmax = int(kwargs.get("nmax", 1))
    M[np.abs(n) > nmax] = 0
return M

if mode == "attenuate":
    scale = kwargs.get("scale", {})
    for k, s in scale.items():
        M[n == int(k)] *= complex(s)
    return M

if mode == "phase_shift":

    phase = kwargs.get("phase", {})
    for k, ph in phase.items():
        M[n == int(k)] *= np.exp(1j * float(ph))
    return M

raise ValueError(f"Unknown mode: {mode}")

def field_and_intensity(d, duty_cycle, N, x, mask=None):
    n, c = ronchi_coeffs(N, duty_cycle)

    if mask is None:
        M = np.ones_like(c, dtype=complex)
    else:
        M = mask

    # Build exp(i 2 n x/d) efficiently: shape (num_orders, num_x)
    phase = np.exp(1j * 2*np.pi * np.outer(n, x) / d)
    E = np.sum((c * M)[:, None] * phase, axis=0)
    I = np.abs(E)**2
    return n, c, M, E, I

def normalize(I):
    return I / np.max(I)

# PARAMETERS
d = 100e-6 # period [m] (example: 10 lp/mm => d=0.1 mm = 100 μm)
f = 0.50      # duty cycle (open fraction); use your measured/assumed value
N = 15       # truncation order
x = np.linspace(-2*d, 2*d, 4000) # evaluate over several periods

```

```

# EXAMPLE
cases = [
    ("No filter",                      make_mask(np.arange(-N, N+1), mode="")),
    ("Low-pass abs(n)<=1",            make_mask(np.arange(-N, N+1), mode="lowpass", nmax=1)),
    ("Block DC (dark-field-ish)",      make_mask(np.arange(-N, N+1), mode="block_dc")),
    ("Keep only 1 (edge-ish)",         make_mask(np.arange(-N, N+1), mode="keep_orders", keep=[-1, 1])),
    ("Atten + / - 1 to 0.2",          make_mask(np.arange(-N, N+1), mode="attenuate", scale={-1:0.2, 1:0.2})),
]

```

A4\_WIDTH = 8.27  
A4\_HEIGHT = 11.69

```

fig, axs = plt.subplots(4, 3, figsize=(A4_WIDTH, A4_HEIGHT),
                       layout='constrained', sharex=True, sharey=True)

for (label, M), ax in zip(cases, axs.flat):
    n, c, M, E, I = field_and_intensity(d=d, duty_cycle=f, N=N, x=x, mask=M)

    ax.plot(x*1e6, normalize(I))

    ax.set_title(label, fontsize=10)
    ax.set_xlabel("x [μm]", fontsize=8)
    ax.set_ylabel("I/max(I)", fontsize=8)
    ax.grid(True, alpha=0.3)

for ax in axs.flat[len(cases):]:
    ax.set_visible(False) # Hiding other non printing plots

fig.suptitle(f"Optical Fourier Filtering (N={N}, f={f})", fontsize=14)

plt.show()

```

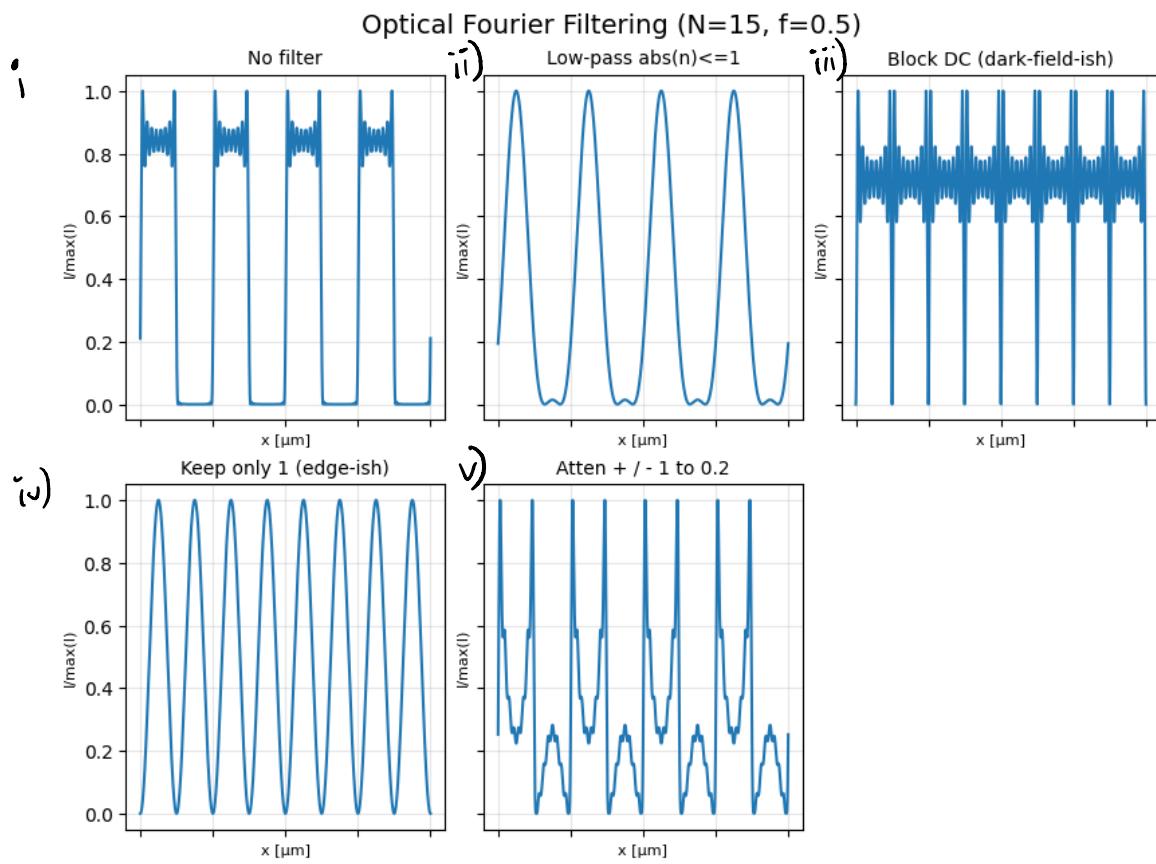


Figure i-v)

## Table of Contents (For Session 4, 5, 6 & 7)

- I. Session 4 (completing Setup 2 and Testing 1 and 2)
  1. Goals
  2. Apparatus
  3. Sketch
  4. References
  5. Useful Background
  6. Procedure
  7. Testing
  8. Post lab reflections and Sources of errors.

## II. Session 5 (Redo Test Two and Refine Set up for Data Collection)

1. Goals
2. Background/Theory
3. Procedure:
4. Post lab analysis

## III. Session 6 (Frauhofer Diffraction and making masks)

- |                          |                        |
|--------------------------|------------------------|
| 1. Goals                 | 6. Procedure           |
| 2. References            | 7. Discussion          |
| 3. Variables             | 8. Uncertainties       |
| 4. Apparatus             | 9. Session Reflections |
| 5. Additional background |                        |

## IV. Session 7(Doing Part B3 and Project )

1. Goals
2. Apparatus
3. Sketch
4. References
5. Background Information (from labscript)
6. Procedure
7. Testing
8. Conclusions



Lab 1 Session 4: SF (Completing Setup 1 & Testing Image)  
Date: 20 - Jan - 2026 Lab Partner: Absent   

### 1. Goals

- Capture an image for the real panel, also one image of the real panel after the beam splitter is installed. For seeing the reduced intensity.
- Adjust exposure to have better contrast and visibility in the real plane.
- Complete Lab Set up 1 and Testing

## 2. Apparatus

### Optics / mounts

- Beam splitter
- $90^\circ$  short optical rail + feet (leveled)
- 2 irises/apertures for alignment on  $90^\circ$  rail
- Fourier imaging lens: 50 mm,  $f = 100$  mm
- Lens tube for Fourier camera
- (Later) transverse translation stage + iris for Fourier plane filtering (confirm clearance)

### Cameras

- Fourier camera (FLIR Blackfly): mounted on transverse translation stage (XY)
- Real-space camera already aligned from Setup

### Part 1

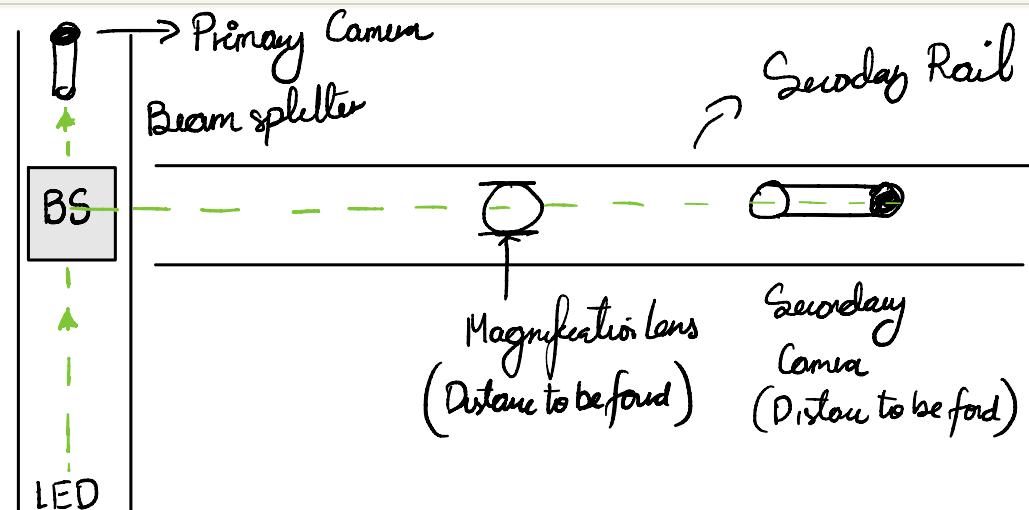
### Tools

- Alignment cap with central dot
- Viewing card (white card / paper)
- Hex drivers, ball driver, post collars, spare saddles/posts (3", 4", 6")

### Software

- LabVIEW: Dual\_Camera\_Line\_Profile\_v2.vi
- NI Vision Assistant (optional, but close it before LabVIEW)

## 3. Sketch:



Sketch1: Top View of Secondary Rail &amp; Elements Set up

## 4. References:

- Optical Systems Guide J.M. McGuirk
- An Introduction to Optics. Lipson
- Spatial Filtering Lab Script

## 5. Useful Background

Field Plane Conjugates (image of light source structure):

Field Stop → Object → Real-space Camera

Field stop controls illuminated area (field of view)

Changing field iris changes FOV but NOT resolution

Aperture Plane Conjugates (image of source angular distribution):

Aperture Stop → Fourier Plane → (determines resolution)

## 6. Detailed Procedure

### i) Verified Beam Splitter Insertion and 90° Rail Alignment

Place beam splitter in main beam

- Verified beam splitter is approx. 22 cm downstream of objective lens (L4).

Verify:

This spacing must leave room between BS and Fourier plane for a transverse translation stage with iris (spatial filter later).

- Visually confirm clearance: stage can mount on a saddle and sit near BS without collision.

Record

- Objective lens reference point: 104 ± 0.05 cm
- BS placed at: 82 ± 0.05 cm downstream of objective (target 22 cm)
- Clearance check for future iris/stage: /

Notes:

There is space but I do not see the Fourier Plane image

Issue:

ii) Rotate BS (using a collar) so that the reflected beam propagates straight on one arm and away from the edge on the other.

- Place the smaller rail with the secondary camera perpendicular to the beam splitter, so that the ray from the beam splitter hits the camera.
- Use Iris and Apperture to verify the centre.

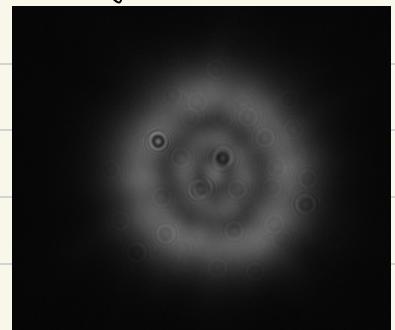
USE the white card and the raw from the BS to see and align the Camera Sensor to the light.

**Expected:**

I expected to see a diffraction pattern, just as before in page ()

Saved Image at Session4/Notes/

Name: Fourier-Image-Pinhole.tiff



Check  
2:20

**Image 1: Fourier Image Through a Pin hole.**

Could not see a diffraction pattern, maybe we are out of focus? There seems to be some blurring. Perhaps the BS is unclean, too.

However, Success! As I slide the card along the rail, the beam always stays within the Secondary Rail (with secondary camera)

1. Fourier imaging lens and Fourier camera
2. Placed the Fourier Lens (FL) (50 mm diameter,  $f = 100$  mm) in the secondary rail. Ensure correct placement by facing the side with the infinity symbol towards the BS.

This was the last lens available, so it matches the description, giving confidence that our lenses are being used correctly.

Check :

iii) Verified that the Fourier camera is on the translational stage and added a lens tube in front to block stray light from the room.

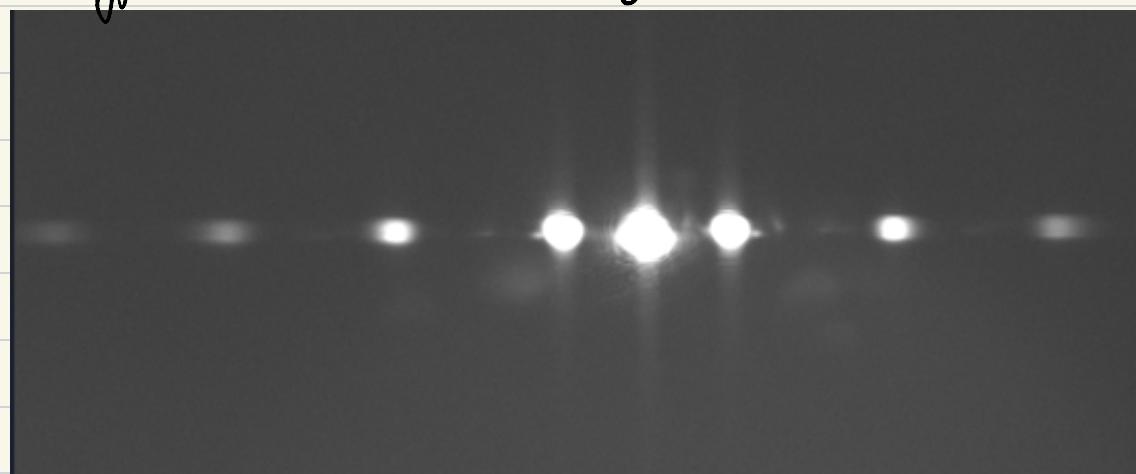
Imagine the Fourier plane onto the Fourier camera so that up to the 7th diffraction orders fit on the CCD for a 10 Lp/mm grating on the test object. ()

Adjusted the Fourier Lens (FL) along the rail until we finally saw the diffraction pattern, for Best Focus!!  
Yay!! FL pos: 29cm along secondary rail

Manually adjusted the railing a little, just the centre, to diffuse the pattern better.

Saved Image at Session 4/Notes/  
Name: diffraction-pattern-secondary-rail-01.tiff.

Image 2: Diffraction Pattern from Secondary rail Camera



Issue: Can only see 4 diffraction orders, There is probably more as when we adjust the mirror horizontally, we can see more but. How do I make all of them visible?

I tried to full the Camera and Lense Set up towards the BS, that did not work too well, it only got zoomed in.

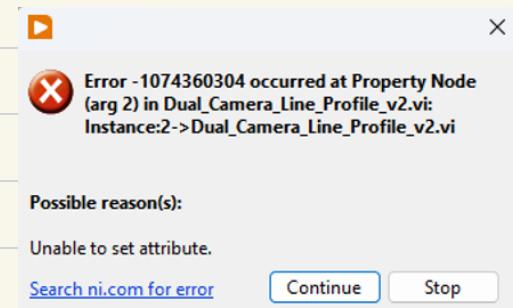
Asked Zack (TA) for help, the idea was to either pull as we did before or take multiple images with different exposure times to get the lower intensity images.

something new was the error happening in adjusting the Exposure,

error message: "Error - Occured at Property Node"

Screenshot saved at Session4/Notes

Name: error-changing-exposure.png



3:00

The fix is: go to BOTH camera Acusiation in the Block Diagram for the Preset and Switch off the Auto Gain and Exporeusre. We had done it.

Success: The diffraction patter is Centro Symmetrical, Sharp and Can see multiple orders.

iv) Final Notes for Set up 2:

**Goal Met:** We have a dual-camera spatial filtering setup. LabView shows the Fourier and Image Plane.

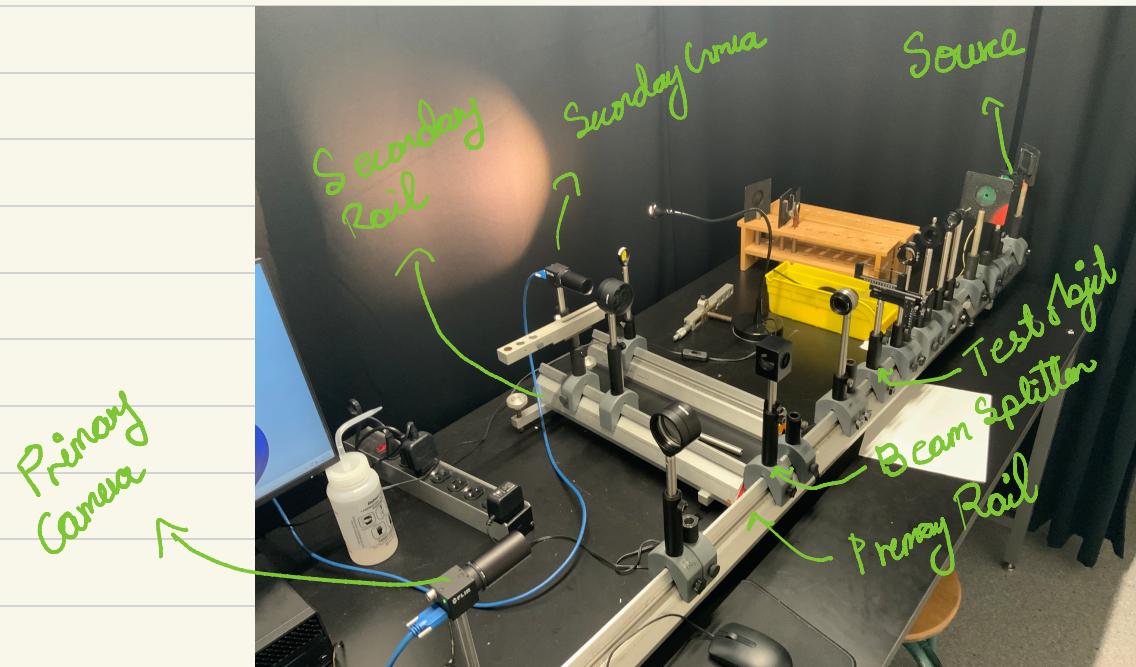


Image 4, Our Optics Setup

Added cross sections on both the Panels and explored the Live intensity profile.

Save images and a screenshot of the setup.

in Session 4/Notes

Name: labView - Set up - Screenshot.png

That is the line  
Intensity Pattern!  
Wow!

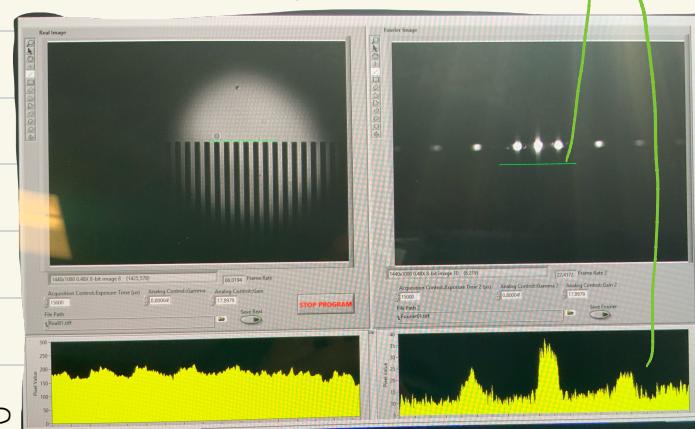


Image 5, Our LabView Setup

## 7. Testing

### i) Test 1

Observed 3 things simultaneously

1. The Fourier Camera image
2. The real-space image
3. With a card, the illuminated region or obj

3:25 PM

Did test 1 on (pg 36) of Lab NoteBook.

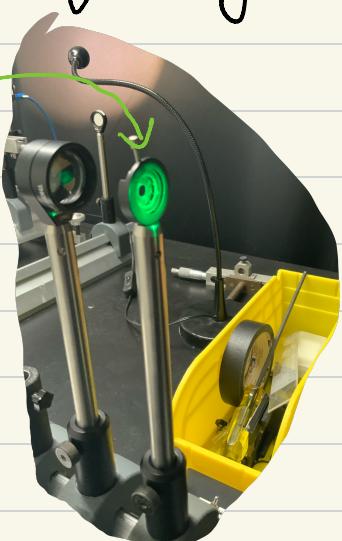
⇒ Varying field stop (field iris), pupil size

Expectation

⇒ We observed area on object & camera field of view change on images.

⇒ On Fourier Camera: Spot Size stays same but Intensity increases with more light let in.  
We actually see more orders & more blurring actually

image: Field Iris



Searched images in Session 4/Notes

Searched 3 images of 3 different heuristic pupil size.

"Smallest-pupil-field-iris.tiff", "1-10th-pupil-field-iris.tiff"  
& "2-10th-pupil-field-iris.tiff"

New Approach to Note Taking:

Zach, our TA recommended only refining procedure from our sources (like lab script) and writing only that is new and our personal notes.

This changes everything!  
Athilan Kumaresan

## ii) Test 2

\* Test 2 procedure on (pg 36) of Lab Script

Varying Aperture Stop using an iris at Aperture stop plane.

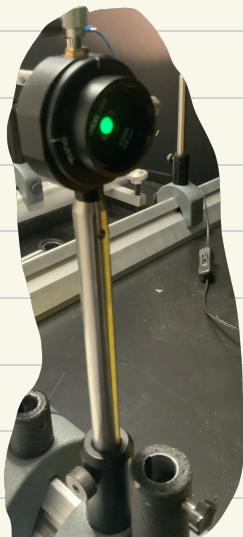


The Zeroth order on the Four Camera  
is at pixel (713, 508)

↳ Marked the Zeroth order with a line

↳ Using a adjoint Saddle & remove the  
(AS) pinhole & insert an iris at aperture stop plane

As usual make sure it is square & wing a up  
stream pin hole; it is central.



Aperture Stop (Pin hole)  
Image 7:

4:06 PM

Facing an **error** because the new iris is not fully on the centre of the screen.

Looking at the light train, looks like the problem might be downstream too! Using a white card & another pinhole.  
Trying to fix light train, making it aligned to optical rail.

Put Back the pinhole & trouble shooting.

Resolved:

4:21 PM

Finally!! The issue was on (L3) Condenser lens

Adjusting Secondary Rail elements for centered lens.  
new centre (709, 620) pixel.

How ever something changed, its more teardrop shaped  
Sand image in Session 4/ Notes

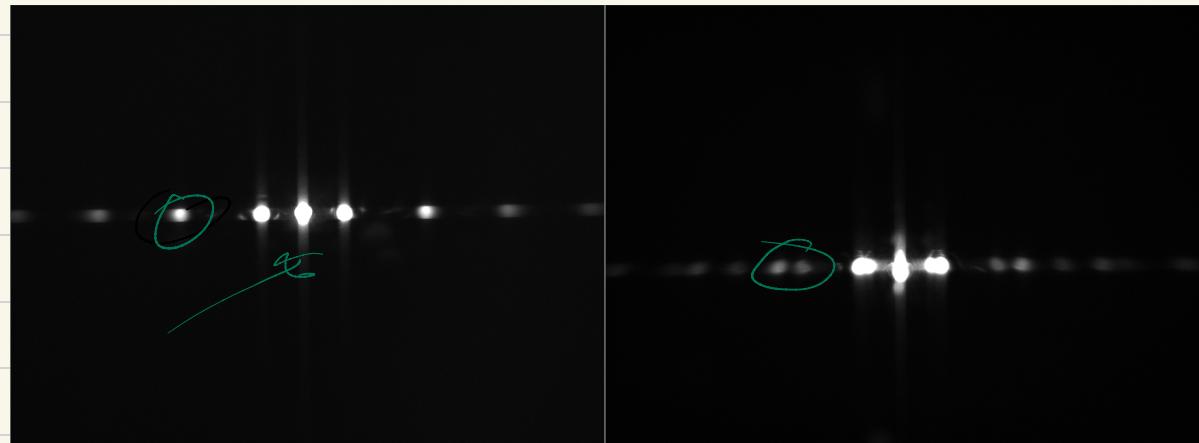
Name: new-diffraction-pattern.tiff (See below)

### 8. Post Lab Reflection:

I made some significant headway, a lot of the accumulated errors were resolved:

- 1) Optics element mis alignment
- 2) Errors in Lab View Exposure Settings

How ever some new errors popped up:



old diffraction pattern

New diffraction pattern

Probably this shows some unclean lenses?

### i) Goal Standing

Goal 1: Capture real-space image before/after beam splitter → MET ✓

- Successfully observed intensity reduction after BS insertion
- Adjusted exposure to compensate

Goal 2: Adjusted Exposure and got a better understanding of exposure settings. MET

Goal 3: Take image of real plane and upload it.

Yes Done.

Goal 4: Complete Lab set up 2 and Testing. Partially. Testing to be redone next lab.

### ii) Learnings:

1. Alignment is critical - small misalignments cause visible artifacts
2. The Fourier plane location can be found by sliding a card along the beam path - first you see real-space image, then diffraction patt
3. LabVIEW errors often require checking BOTH camera setting
4. The intensity cross-section tool is very useful for quick alignm

### iii) What I Would Do Differently:

Record more quantitative measurements (pixel positions, peak widths)

- Take systematic images at each alignment step for comparison
- Note iris/aperture settings when taking images

### iv) Questions to Investigate in Session 5:

1. Why are diffraction spots teardrop-shaped instead of circular?
2. Can I see all 7 orders for 10 lp/mm as expected?
3. What happens when I vary the field iris vs aperture iris?

## Lab 1 Session 5:

## Spatial Filtering (Finishing Setup 2 &amp; Improving diffraction image resolution)

Date: 22-Jan-2026

Lab Partner: Nathan Unku

FOR TABLE OF CONTENTS, REFER TO SESSION 4 pg 40

1. Goals:

- i) Labscript procedure testing after setup
- ii) Error correction during setup
- iii) Understand how the Fourier plane spots are formed and how "sharpness" or "detail" shows up as one spot while brightness shows up as another

## 2. Background Information Physical intuition (no math)

- i) Light behaves like a wave. A wave cannot make an abrupt change without involving many different directions of motion.

11:46 AM

- ii) A sharp edge is like telling the wave: "Go from zero to full amplitude instantly." The only way a wave can do that is by combining many plane waves at different angles.
  - Few angles → smooth variation
  - Many angles → sharp transitions;

55

### iii) Slit intuition (classic example)

- A wide slit ;(smooth spatial variation) → narrow diffraction pattern
- A narrow slit ;(sharp spatial confinement) → wide diffraction pattern

This is the same reason:

- Fine details → large angles
- Coarse features → small angles

#### iv) Filtering methods:

- Low pass filter: removes noise
- High pass filter: sharpness improvement
- Band-pass filtering: specific frequencies selected to show texture/patterns otherwise hidden by bright or sharp detail
- Directional filtering: orthogonal structures removed (only vertical or horizontal features)
- Notch filtering: removing specific noise
- Phase-contrast filtering: shifting frequencies to make transparent objects more visible
- Dark-field filtering: Reduce white highlights to see dark/small features
- Amplitude filtering: changes contrast
- Spatial frequency weighting: custom contrast for spec. freq.
- Order selection: resolution control
- Spacial differentiation: for edge/feature detection
- Holographic and correlation filtering (advanced): pattern recognition in real time

### 3. Detailed Procedure

#### i) Image Doubling: Trouble Shooting

We got a suggestion to use a filter paper that is translucent. Go through the different elements and try to determine which element starts the double first.

The issue could be the back reflection from one of the shiny parts of the elements.

However, My hunch is some miss alignments of the equipments.

Looking at the current state, maybe this issue isn't too bad. The intensity pattern definitely show multiple values. But Maybe this isn't too bad ???

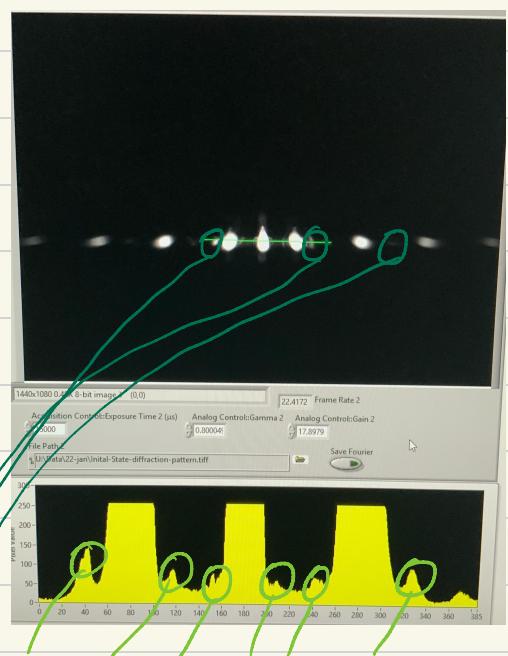
Saved as initial-state - diffraction pattern.tif

Observation

I can say that because there is both more dots on the fourier image but also, the intensity patterns send multiple small peaks.

These are not diffraction orders.

Image 1: Initial State Snapshot



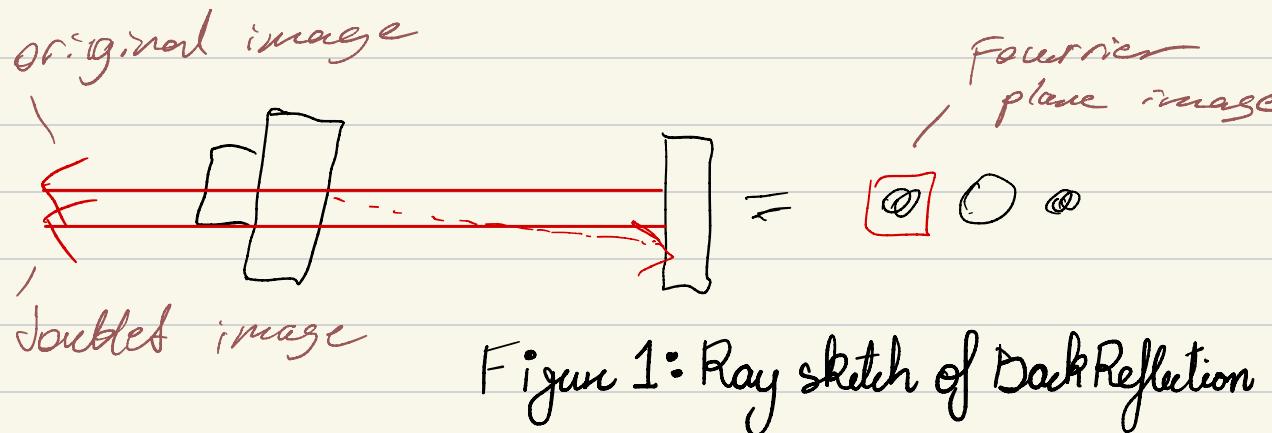
Clearly There are multiple reflections

1:42 PM

## ii) Correction of Lense

Correction of error (image is off center and doubling of forrier plane spots)

- Starting from test step 2 in setup 2 of labscrip  
(vary the aperature)
- Placing a paper filter behind condensor lens  
fixed the doubling, concluding that the doubling  
was cause by misalignment of either incoming  
light onto condensor or condesor alignment.  
Realigning the condensor lens should correct this.
- Fixed doubling by pitching lens forward on track  
and right very slightly.



## iii) Correcting Fersnel Fridnges

New Issue: Fersnel Fridnges on the real Image,  
This makes it clear that our has been image is out  
of focus! This could explain the doubling of our  
diffraction pattern! So my previous hunch of an "Un  
clean lense" is incorrect.

Saved this image as: fersnel-frindge-issue.tiff under  
Sessions5/Notes

## Observation

Noticed how there are fringes around the letters we are focusing on.

Previously we thought this was insignificant but this seems to matter more for resolution as we move towards more tests.

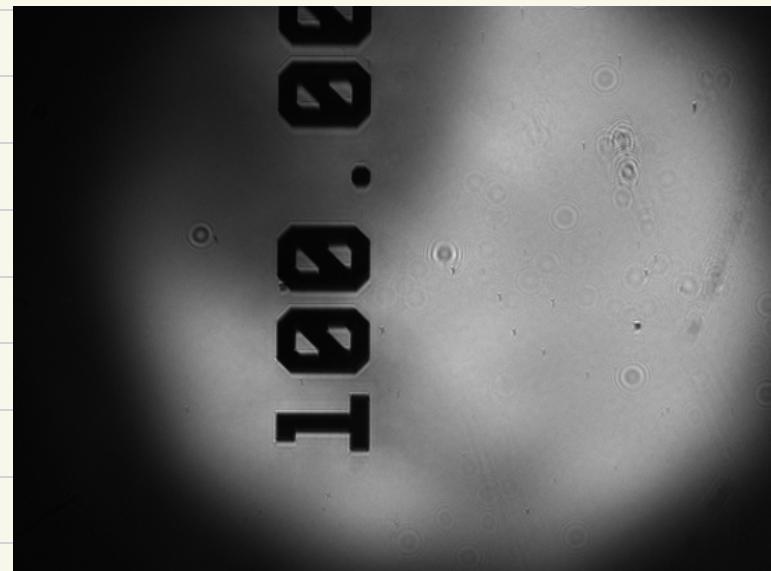


Image 2: Fresnel Fringes on Image

## Tip

When trying to focus & eliminate Fresnel fringes try to focus on a small defect on the test object & make it sharp.

iii) Continuing with Test 2 again

- added the aperture stop before the forrier plane splitter, closing the aperture blocked the outer diffraction orders which blurs the image (outer orders at higher frequency contain the sharp detail information)
- Position of 0-order: 819, 655 pixels (zeroth-order-image.tiff) saved at session 4 notes
- Removed the pinhole temporarily and added the iris aperture in its place. This changed the brightness of the image without changing the illumination area much.
- Moved the small iris back toward the LED source and make the image edges sharper
- Saved Image: Correct-iris-position.tiff

Image3:

• Corrected sharp real  
Image after comoving iris

Compared to our  
previous image the  
edges are way  
sharper!

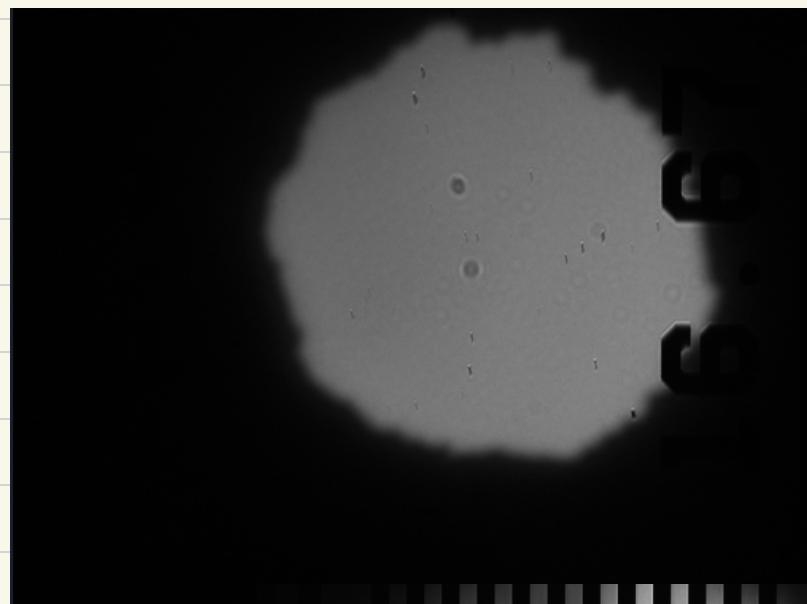
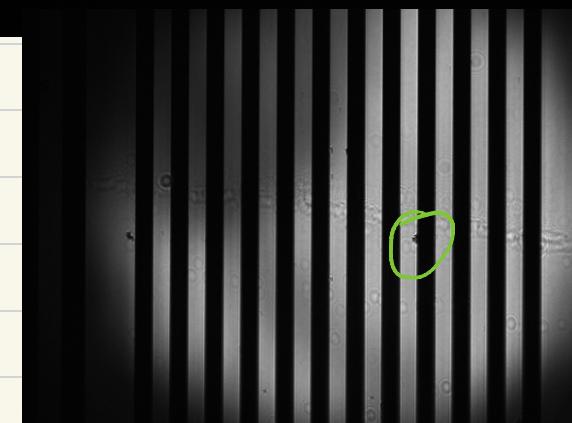


Image4: Showing an example  
of a defect on grating we  
focused on



- inserted 10nm band filter in front of LED, eliminated the non-zero order diffraction patterns (collapsed to single frequency peak with black image)

iv) Resolution Test:

started with 10 lp/mm grading. With increased exposure and 10nm filter image is clearer (original wavelength is 525 ± 35 nm)

Recorded images of 12 and 16.67 lp/mm. Spacing between 16 (0th → 1st order) is 202 pixels. Spacing for 12 is 132 pixels

(space below for calculation of magnification level)

$$\theta_i = \sin^{-1} \left( \frac{\lambda}{f} \right) = \left( \frac{525 \cdot 10^{-9}}{16.67 \cdot 1000} \right)$$

$$= 0.501^\circ$$

$$202 \text{ pxl} \div 0.501^\circ = 403 \text{ pxl/deg.}$$

$$f_{\text{eff}} = \frac{\Delta x}{\theta_i} = \frac{202 \text{ pxl} \cdot 3.45 \mu\text{m}pxl}{0.501^\circ}$$

$$= 139 \text{ mm}$$

## v) Resolution test

- chose 26 and 50 lp/mm (easy and difficult to resolve)
- Prediction: closing the apperature iris slightly should block the higher order diffraction spots tied to the finner line spacing, blurring that section without blurring the coarse line spacing.
- Added an iris at the forrier plane. Reducing aperature eliminates higher order diffraction spots, reducing fine detail first (high frequencies = finest detail = farthest diffraction orders)
- Closed the iris halfway to make the finner grading lines blurred while the coarser ones still sharp (insert image of blured fine lines and sharp coarse lines)

Second order      1st order      Zeroth order      First order

Image 5 :  
26 lp/mm

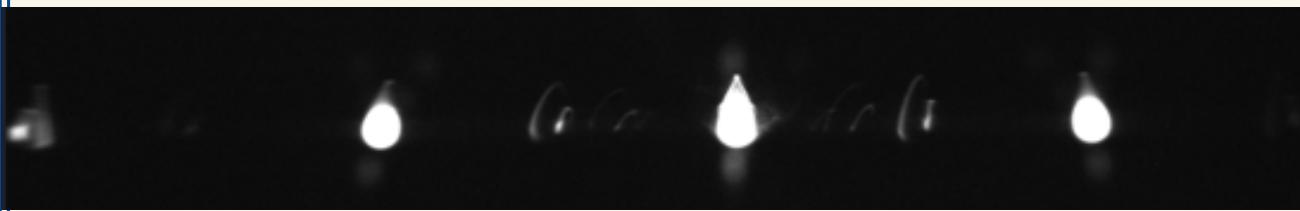
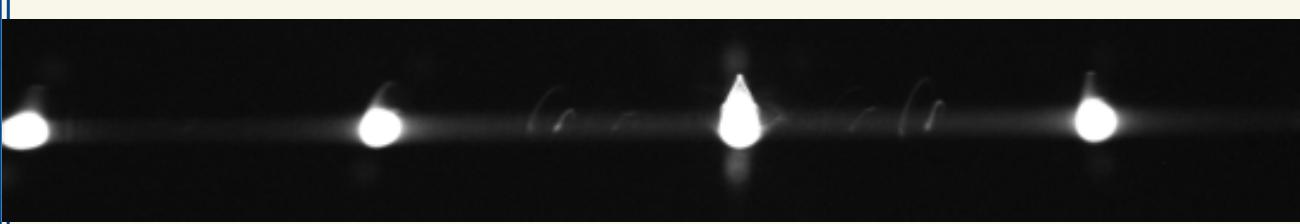


Image 6 :  
50 lp/mm



Image 7 :  
26 and 50 lp/mm



All files saved under Session 5/Notes

Name : "26lp mm - fourier.tif"  
"50lp mm - fourier.tif"  
"26 - 50lpmm - fourier.tif"

**Observation:** We notice how in the 26lp/mm Grating, the first Order is very clear and bright. While Higher Orders are dim

On the 50 lp/mm we observe the second order bright while the first order is relatively dim.

We can see that when we position the grating such that the field of view has 26lp/mm on one side and 50 lp/mm on the other, we get a combined pattern! This is pretty cool!

Success! :

confirmed overlap between fourier images of 26 and 50 lp/mm diffraction orders.

## 5) Post Lab Reflection and Suggestions for next Lab

The Diffraction Pattern (Page 63) was illuminating.

1) We were not able to see higher diffraction orders.

A solution we recommend is to tilt the Fourier camera so that the 0th order goes to one end. That way, we could imagine more orders.

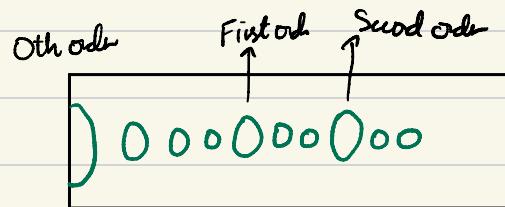


Figure 2: Fourier Image Idea

2) While our image light illumination has dark spots, it is decently in focus after making some alignment corrections, and we are now able to see the effects of altering the fourier diffraction orders on the image results. We achieved our intial goals of correcting the focus and alignment of the fourier plane peaks. Our setup is sufficient to proceed with Ronchi ruling next session.

3) This lab fundamentally changed how I conceptualize image formation. Rather than thinking of lenses as simply "focusing light," I now understand them as performing spatial Fourier transforms, with the image plane representing the inverse transform of filtered frequency components. The ability to physically manipulate frequency content by placing objects in the Fourier plane --- and immediately see the effect on the image --- made abstract mathematical concepts concrete and intuitive.

# Lab Notebook Submission Summaries

Spatial Filtering Lab (Lab 1) – Sessions 4 & 5

PHYS 332

## Week 1 Submission: Session 4

### Session Overview

**Date:** 20-Jan-2026      **Lab Partner:** Absent      **Pages:** 40–53 **Objective:** Complete Setup 2 by adding beam splitter and secondary (Fourier) camera arm; perform initial testing of field and aperture stop effects.

[View Next Page: Format Error](#)

Item	Page
<b><i>Preparation</i></b>	
Table of Contents for Sessions 4 & 5	40
Goals: capture real-space images before/after BS; adjust exposure; complete Setup 2	41
Apparatus List (optics, cameras, tools, software)	42
Experimental Setup Sketch (top view of secondary rail configuration)	43
References and Background: Field & Aperture Plane Conjugates	43–44
<b><i>Procedure &amp; Data Collection</i></b>	
Beam Splitter Insertion & Rail Alignment — placed BS at $82 \pm 0.05$ cm	44
Secondary Rail Setup — rotated BS, used white card to trace beam path	45
Fourier Lens Placement ( $f = 100$ mm) — adjusted until diffraction pattern focused	45–46
Diffraction Pattern Acquisition — initially only 4 orders visible, adjusted mirror	46–47
LabVIEW Error Resolution — disabled Auto Gain/Exposure in Block Diagram	47
Final Setup Verification — dual-camera system confirmed operational (Images 4, 5)	48
<b><i>Testing</i></b>	
Test 1: Field Stop Variation — varied field iris, observed FOV change on real-space <i>camera while Fourier spot size stayed constant (intensity changed)</i>	49
Test 2: Aperture Stop Variation — zeroth order at pixel (713, 508)	50
Troubleshooting: Iris centering issue traced to condenser lens (L3) misalignment	50–51
<b><i>Post-Lab Analysis</i></b>	
New Issue: Diffraction spots became teardrop-shaped after adjustments	51
Errors Resolved: (1) optical element misalignment, (2) LabVIEW exposure settings	51–52
Goal Status: Goals 1–3 MET; Goal 4 (testing) PARTIAL	52
Key Learnings (alignment, Fourier plane location, LabVIEW, intensity cross-section)	52
What I Would Do Differently; Questions for Session 5	53

**Key Files Saved:**

- Fourier-Image-Pinhole.tiff
- diffraction-pattern-secondary-rail-01.tiff
- error-changing-exposure.png
- LabView-Setup-Screenshot.png
- new-diffraction-pattern.tiff
- Smallest-pupil-field-iris.tiff
- 1-10th-pupil-field-iris.tiff
- 2-10th-pupil-field-iris.tiff

## Week 2 Submission: Session 5

### Session Overview

**Date:** 22-Jan-2026      **Lab Partner:** Nathan Unhm      **Pages:** 54–64

**Objective:** Resolve image doubling and focus issues from Session 4; understand physical relationship between Fourier plane spots and image sharpness; perform resolution tests with multiple gratings.

Item	Page
<b><i>Preparation &amp; Background</i></b>	
Goals: complete testing, correct errors, understand sharpness vs. brightness in Fourier plane	54
Physical Intuition: wave behavior, sharp edges require many plane wave components	54–55
Slit Diffraction: wide slit → narrow pattern; fine details → large angles	55
Filtering Methods Overview (11 methods documented)	56
<b><i>Procedure &amp; Troubleshooting</i></b>	
Image Doubling Diagnosis — used filter paper to trace source; multiple intensity peaks	57–58
Resolution: misalignment of light onto condenser; fixed by pitching lens forward/right	58
Fresnel Fringes Issue — fringes around text indicate out-of-focus image	58–59
Focus Tip: focus on small defect on test object and make it sharp	59
<b><i>Testing &amp; Data Collection</i></b>	
Test 2 Continued: Aperture stop blocks outer orders → blurs image (high-freq info lost)	60
10 nm Band Filter Insertion — eliminated diffraction spreading, cleaner pattern	61
Resolution Test (10, 12, 16.67 lp/mm) — measured pixel spacings between orders	61
Diffraction Angle Calculation: $\theta_1 = \sin^{-1}(\lambda/d) = 0.501 = 0.00874$ rad	61
Resolution Test (26, 50 lp/mm) — predicted and confirmed selective blurring	62–63
<i>Closing iris halfway: fine lines (50 lp/mm) blur, coarse lines (26 lp/mm) stay sharp</i>	
Combined Grating Pattern — positioned FOV to capture both frequencies simultaneously	63
<b><i>Post-Lab Analysis</i></b>	
Reflection: diffraction pattern images illuminating; could not see all higher orders	64
Suggestion: tilt Fourier camera so 0th order at edge to fit more orders on sensor	64

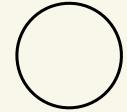
**Key Files Saved:**

- initial-state-diffraction-pattern.tiff
- fersnel-fringe-issue.tiff
- Correct-iris-position.tiff
- zeroth-order-image.tiff
- 26lp-mm-fourier.tiff
- 50lp-mm-fourier.tiff
- 26-50lpmm-fourier.tiff

**Key Measurements:**

Parameter	Value	Notes
LED wavelength	525 nm	Bandwidth 35 nm
Zeroth order (initial)	(819, 655) px	Before correction
Zeroth order (corrected)	(709, 620) px	After condenser fix
16.67 lp/mm spacing	202 pixels	0th to 1st order
12 lp/mm spacing	132 pixels	0th to 1st order
$\theta_1$ (16.67 lp/mm)	0.501°	Calculated

**Equipment:** Fourier lens (50 mm dia,  $f = 100$  mm), FLIR Blackfly camera on XY stage, 10 nm band filter, resolution target (10–50 lp/mm gratings).



6S

## Lab 1 Session 6: Spatial Filtering (Fraunhofer Diffraction and Making Masks)

Date: 27 January 2026

Lab Partner: Nathan Unruh

For Table of Contents, refer to session 4,

Pg 40

### 1. Session Goals

- i) Compare diffraction pattern to theory
- ii) Calibrate the Ronchi ruling (slit spacing  $a$  and slit width  $b$ )
- iii) Establish a quantitative baseline for spatial filtering 4. Complete
- iv) spatial filtering mask cases (a), (b), (d), (e), (f), (j), (k)

### 2. Reference: Pages 39-43 (Part A: Fraunhofer Diffraction, Part B: Spatial)

### 3. Variables

**Independent:** Mask configuration (orders transmitted) **Dependent:** Real-space image intensity profile, Fourier-space diffraction pattern

**Control:** Camera settings (gain, exposure, gamma), LED wavelength, grating period, optical alignment

### 4. Apparatus:

In Addition to the Material listed on Pg 2-3. We need

- i) Additional Translational Stage
- ii) Wires, Black Tape, Allen Key of different size
- iii) A rectangular Frame with a Post and Saddle

### 5. Additional Background Variables.

where:  $m$  = diffraction order ( $0, \pm 1, \pm 2, \dots$ )  $\lambda$  = wavelength = 525 nm  $d$  = grating period = 100  $\mu\text{m}$  (for 10 lp/mm).

$\Theta_1$  = first order angle  $\Delta p_1$  = pixel spacing to first order

### 6. Procedure:

#### A: Fraunhofer Diffraction

Following procedure on Lab Script pg. 39-40 3.1 Procedure 1.

- Replaced variable diffraction grating with 10 lp/mm Ronchi ruling

## microscope slide

- Set camera parameters: Exposure = 43000, Gamma = 1, Gain = 18
- Focused on "ZERO" lettering on Ronchi ruling for coarse focus
- Fine focused on blemishes (chipped metal on lettering) for optimal sharpness
- Inserted 10 nm bandpass filter in front of LED
- Verified Fourier image centro-symmetry
- Recorded real space and Fourier space images
- Extracted line profiles for calibration measurements

Despite turning the dial on the condenser lens, the focus appeared to change unexpectedly. Fine focusing required locating small defects (chipped metal) on the ruling surface rather than the grating lines themselves. This provides sharper focus targets than the periodic structure due to the Talbot effect creating multiple focal planes for periodic objects.

## Observation:

## Observation:

The Fourier image was centro-symmetrical, confirming that the optical elements are properly aligned square to the optical axis. This symmetry verification is essential before quantitative measurements.

## Calibrate the Real image:

10 lines on the camera is from 602 px  $\rightarrow$  1150 px

Pixel span 1150 - 602 = 548 pixel for 10 period

$$\text{Scale factor} = \frac{a}{\text{Pixel per period}} = \frac{100 \mu\text{m}}{54.8 \text{ px}} = 1.82 \mu\text{m/pixel}$$

With the Real space camera having a pixel size  $\Delta_{\text{Pixel}} = 3.45 \mu\text{m}$ .

$$M_{\text{real}} = \frac{\text{image scale}}{\text{pixel size}} = \frac{54.8 \times 3.45 \mu\text{m}}{100 \mu\text{m}} = \frac{189 \mu\text{m}}{100 \mu\text{m}} = 1.89 \times$$

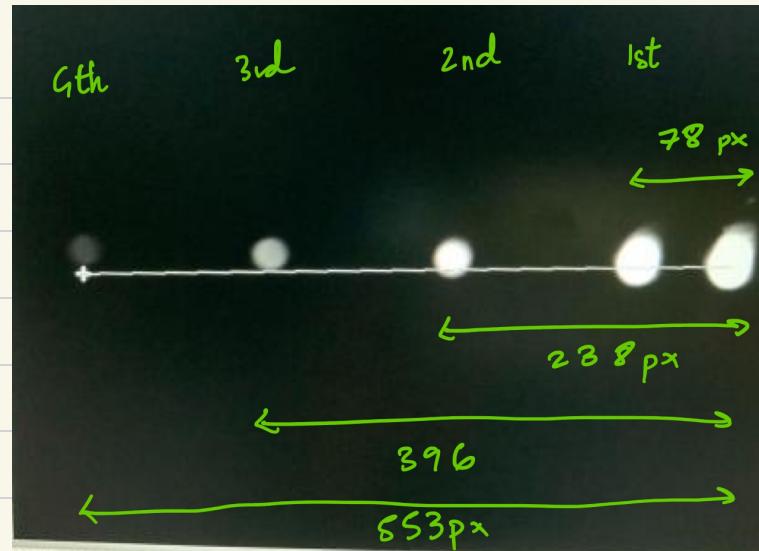
$$\text{Expected magnification} = \frac{f_s}{f_u} = \frac{300}{150} = 2.0 \times$$

The values are close, but the difference is from the lens position not being exactly at focal length

## Calibration for Fourier Image:

6b b

Figure 6.1: Diffraction Pattern



We note that we only see odd orders, = 1.3.5.7

This is what we observe from a 50% Duty Cycle Ronchi Ruling.

The even orders ( $m = 2, 4, 6, \dots$ ) are suppressed because :

$$\sin\left(m\pi \frac{b}{a}\right) = \sin\left(\frac{m\pi}{2}\right) = 0 \text{ for even } m \text{ when } \frac{b}{a} = \frac{1}{2}$$

### Fourier Camera Calibration :

$$\Theta_m = \frac{m\lambda}{a} = \frac{m \times 525 \times 10^{-9}}{100 \times 10^{-6}} = m \times 5.2 \text{ rad}$$

$$K_{cal} = \frac{\Theta_m}{\Delta P_i} = \frac{5.25 \text{ m}}{78 \text{ px}} = 0.0673 \text{ rad/pixel}$$

(For variable Definitions go to Section 5)

Order m	Measured (px)	Theory: $m \times 78 \text{ px}$	Discrepancy
1	78	78	0% (reference)
3	238	234	+1.7%
5	396	390	+1.5%
7	553	546	+1.3%

Table 6.1: Measured vs theoretical diffraction order patterns

Excellent linearity! The small systematic offset ( $\sim 1.5\%$ ) could be due to:

- Slight deviation from small-angle approximation at higher orders
- Minor lens aberrations
- Grating period slightly different from nominal 100  $\mu\text{m}$

$\Rightarrow$  Extrapolating Grating Period

$$\Delta p = \frac{78 + 238/3 + 396/5 + 553/7}{4} = \frac{78 + 79.8 + 79.2 + 79.0}{4} \\ = 78.9 \text{ px/order}$$

$$a = \frac{\lambda f_{obj}}{\Delta x} = \frac{\lambda}{\theta_i} = \frac{525 \text{ nm}}{5.25 \text{ m rad}} = 100 \mu\text{m}$$

## B. Spatial Filtering

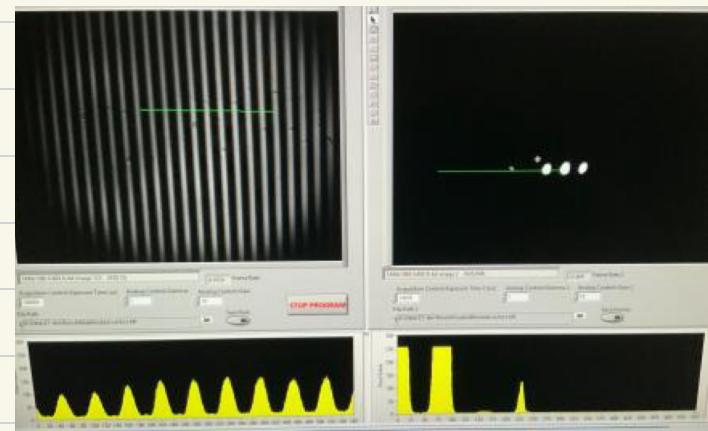
Following procedure on Lab Script pg. 41—43

- 1. Verified Fourier patterns are symmetrical and well focused
- 2. Placed mask post at Fourier plane (after condenser lens, before beam splitter)
- 3. Mounted translational stage for precise mask positioning

Saved as file: Default-and-blocked-ve1to1.tif

Images below

a) Default - Blocked half



b) Normal

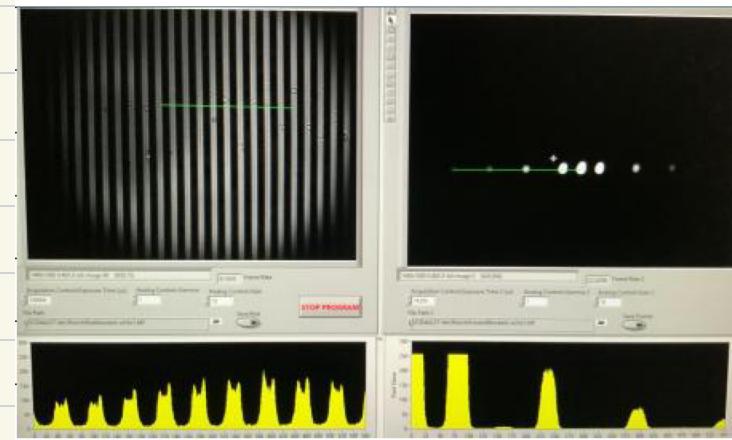


Figure 6.2: LabView Screenshots. a & b

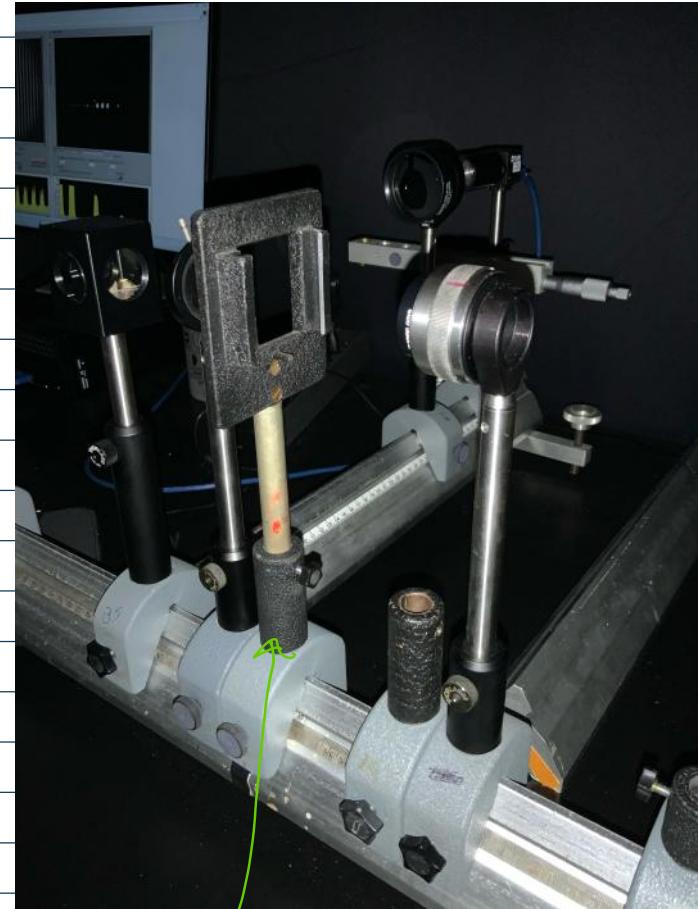
(69)

ATC

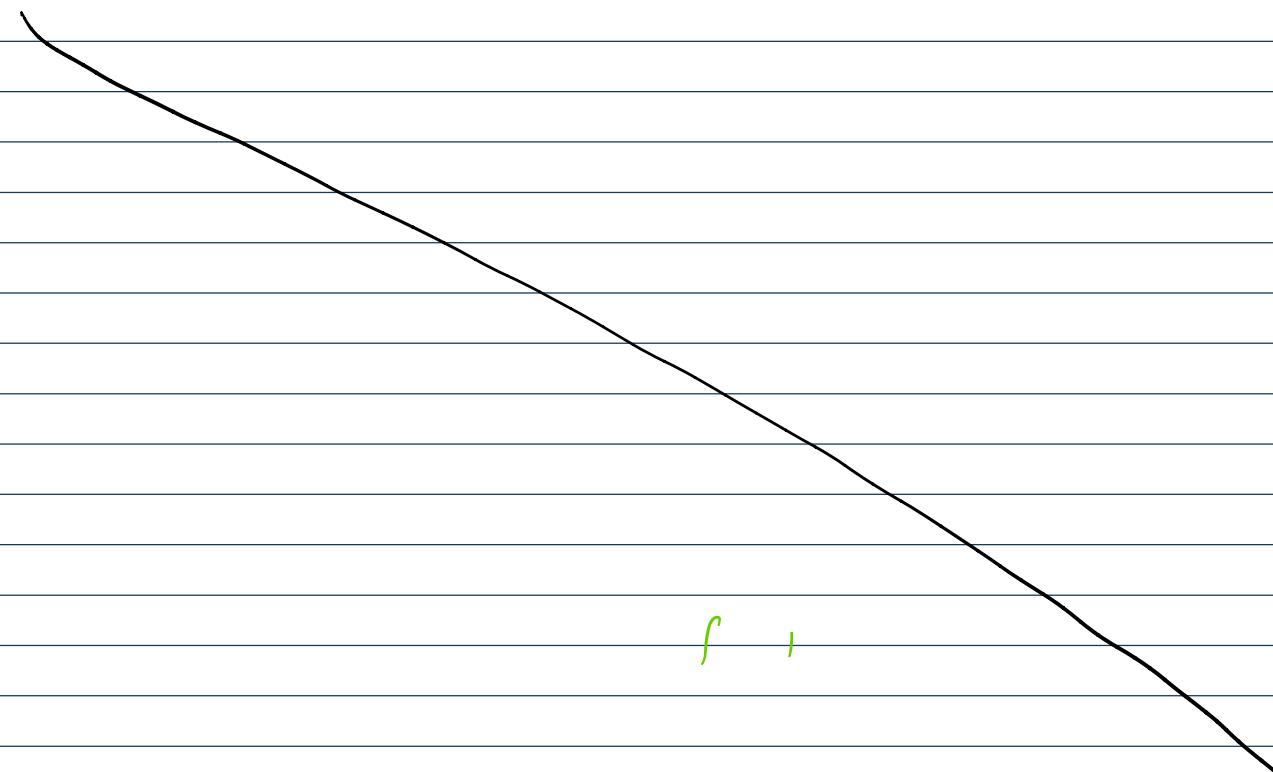
At the Fourier Plane, after  
that condenser Lense,  
before the Beam Splitter.  
We placed a post, on this  
post we are making  
masks to block different  
diffraction patterns.

TIP: We are using an  
hellen screw with a  
translational stage. This  
works very very well!

Fig.6.3: Set up of four  
Mask



placing the four mask  
after the condenser lense.  
at the source plane



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### case (a) All orders (reference case)

Saved Images as "RonchiReal-A.tiff"

"RonchiFourier-A.tiff"

Default image. Looks bright and the real image is all well illuminated

We accidentally increased the Iris so new images as

Saved Images as "RonchiReal-A2.tiff"

"RonchiFourier-A2.tiff"

**Observation:** Image is bright and well illuminated.  
Real-space image shows sharp, well-defined grating lines with high contrast. This serves as the reference for all subsequent filtering cases.

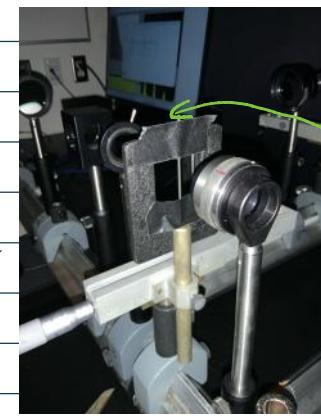


Fig 6.4a):  
Allen Key mask

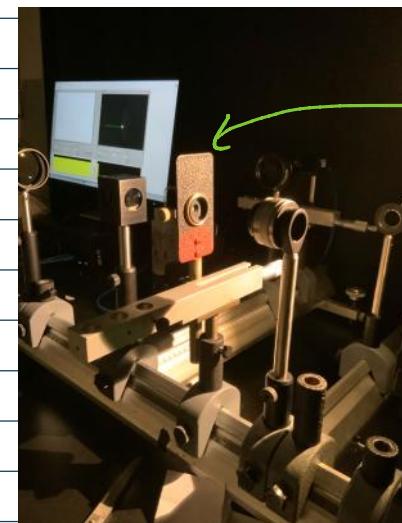


Fig 6.4 b)  
Iris Mask

### case (b) Zero order only:

Orders transmitted:  $m = 0$  only

Orders blocked: All  $m \neq 0$

**Observation:** Intensity significantly reduced. Real space image shows uniform illumination with NO spatial variation — the grating lines completely disappear.

File Name: "RonchiReal-B.tiff" and  
"RonchiFourier-B.tiff"

Physical Interpretation: Zero Order Only

The zeroth order carries only the DC (average) component of the image.

Blocking all other orders

removes all spatial frequency information, resulting in a uniform gray field:

(71)

field:

$$I(x) = |C_0|^2 = \left(\frac{1}{2}\right)^2 = 0.25$$

This demonstrates why at least one non-zero order is required to resolve any periodic structure.

Case(d) 0, +1 (Abbe minimal criterion):

Orders transmitted:  $m = 0, +1$

Orders blocked: All negative orders,  $m \geq 2$

Mask adjustment: Moved mask forward to make effective aperture larger, then slid on translational stage to select 0 and +1 only.

FileName: "RonchiReal-D.tiff" and "RonchiFourier-D.tiff"

**Observation:** More noticeable lines appear in between each solid white line.

The image

shows periodic structure but with reduced contrast and asymmetric appearance.

Explanation: Abbe Minimal Criterion

This is the minimum requirement to resolve a periodic structure. With only 0 and +1:

$$E(x) = C_0 + C_1 e^{i k_0 x} = \frac{1}{2} + \frac{1}{\pi} e^{i k_0 x}$$

The intensity shows periodicity at the fundamental frequency, but the asymmetric order selection produces a "traveling wave" appearance with reduced contrast compared to symmetric filtering.

More noticeable lines in between each solid white line

case(e) +1, 0, -1:

Orders transmitted:  $m = -1, 0, +1$

Orders blocked:  $|m| \geq 3$

Mask: Larger Allen key taped to translational stage. (Smart Move :)

**Observation:** Intensity further reduced compared to reference. Image shows sinusoidal variation — the sharp square-wave edges are replaced by smooth, rounded transitions. Focus and sharpness are lost; peaks on line profile become rounded.

**Physical Interpretation:** Low Pass with  $m_{\max}$  With symmetric  $\pm 1$  and 0:

$$E(x) = \frac{1}{2} + \frac{2}{\pi} \cos(K_0 x)$$

This produces a pure sinusoidal intensity modulation. All high-frequency content (sharp edges) is removed, demonstrating that edge sharpness requires higher-order Fourier components.

Case (f): Orders  $+1, -1$  Only (Zero Blocked)

Orders transmitted:  $m = +1, -1$

Orders blocked:  $m = 0$  and  $|m| \geq 3$

Mask: Thinnest Allen key + similar-sized screwdriver

Files: RonchiReal-F.tiff, RonchiFourier-F.tiff

**Observation:** Very low intensity. Real-space image shows frequency doubling — the apparent period is half the original grating period.

**Explanation:** Frequency Doubling Effect

Blocking the zero order while transmitting  $\pm 1$ :

$$E(x) = \frac{1}{\pi} (e^{ik_0 x} + e^{-ik_0 x}) = \frac{2}{\pi} \cos(K_0 x)$$

$$I(x) = \frac{4}{\pi^2} \cos^2(K_0 x) = \frac{2}{\pi^2} (1 + \cos 2K_0 x)$$

73

The intensity varies at frequency  $2k_0$ , producing an image with twice the spatial frequency (half the period) of the original grating. This is a classic demonstration of how phase information affects image reconstruction.

#### case (j): All Orders Except Zero (Dark-Field)

Orders transmitted: All  $m \neq 0$

Orders blocked:  $m = 0$  only

Mask: Slit mask blocking central maximum only

**Observation:** Real-space image appears as a uniform dark screen with very faint edge features barely visible.

Dark-Field Imaging

Files: RonchiReal-J.tiff, RonchiFourier-J.tiff

Explanation: Blocking only the zero order removes the DC background:

$$I(x) = \left| \sum_{m=0} C_m e^{imk_0 x} \right|^2 = |f(x) - C_0|^2$$

For a square wave, this enhances edges while suppressing uniform regions. However, for a well-focused grating, the result appears very dark because most energy is in the zero order. Dark-field imaging is more effective for phase objects or objects with defects.

#### Case (k): Low-Pass Filtering ( $m_{\text{max}} = 2$ )

Orders transmitted:  $m = -2, -1, 0, +1, +2$  (effectively  $-1, 0, +1$  since even orders absent)

Orders blocked:  $|m| \geq 3$

Files: RonchiReal-K2.tiff, RonchiFourier-K2.tiff

**Observation:** Similar to case (e) since  $m = \pm 2$  orders are naturally suppressed for 50% duty cycle grating. Image shows sinusoidal profile with rounded edges.

### Summary of Spatial Filtering Results

Case	Orders Transmitted	Contrast	Period	Key Observation
(a)	All (reference)	High	$a$	Sharp square wave, well-defined edges
(b)	0 only	None	N/A	Uniform gray — no spatial variation
(d)	0, +1	Medium	$a$	Asymmetric, extra lines between peaks
(e)	-1, 0, +1	Medium	$a$	Sinusoidal, rounded edges, reduced sharpness
(f)	+1, -1	Low	$a/2$	<b>Frequency doubling</b> — period halved
(j)	All except 0	Very low	$a$	Uniform dark screen, faint edges
(k)	$ m  \leq 2$	Medium	$a$	Same as (e) due to absent even orders

Table 6.2 : Summary of Spatial Filter Results

## Figures: model function overlay with the

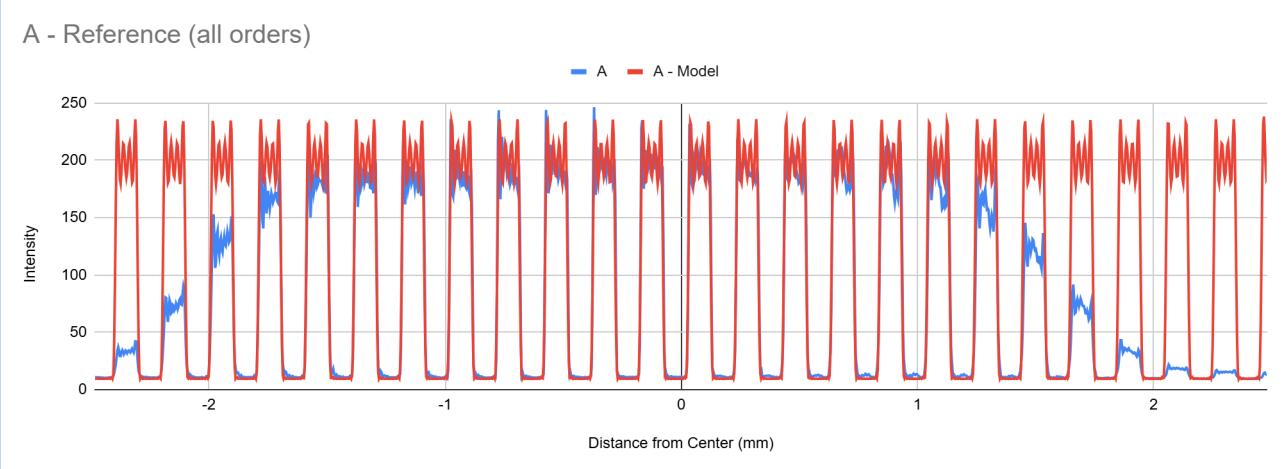


Figure A.1: Case (a) — All Orders (Reference)

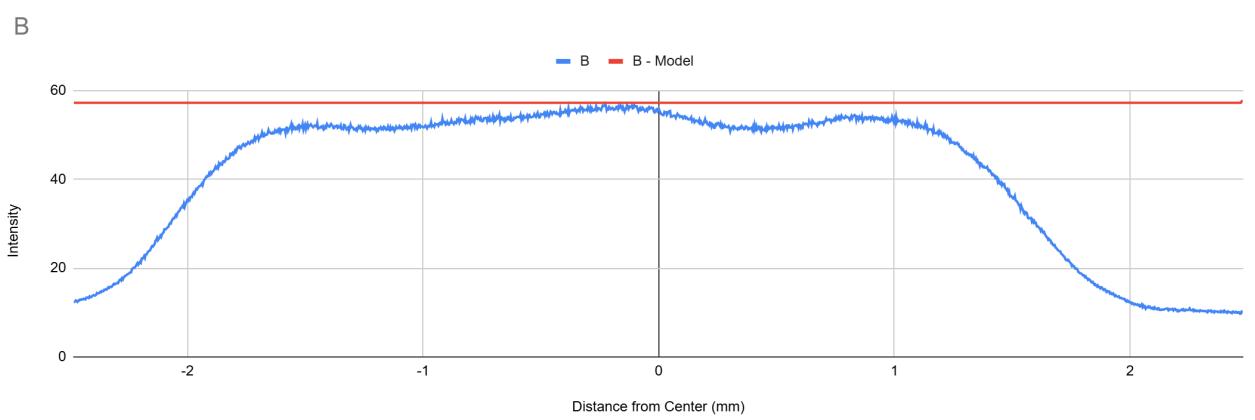


Figure A.2: Case (b) — Zero Order Only

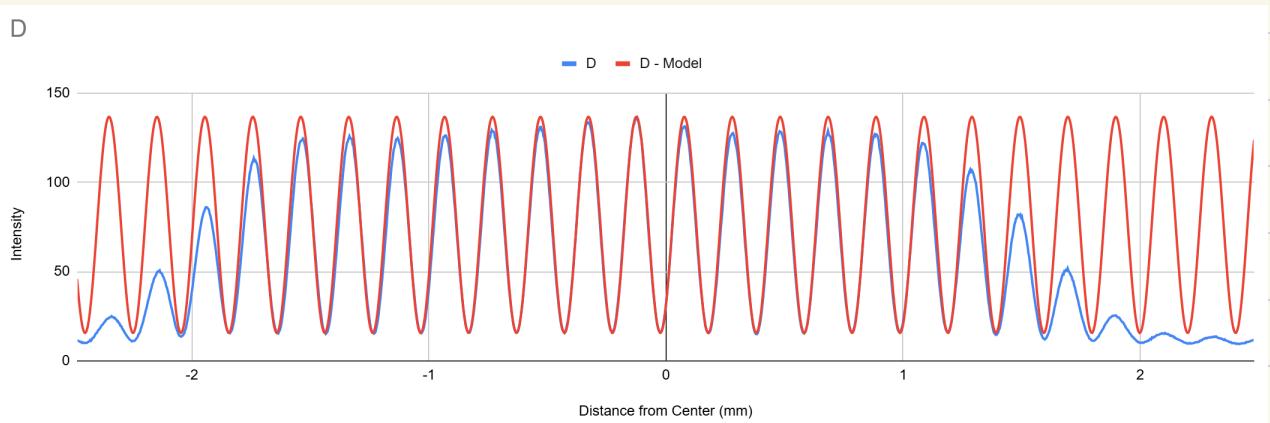


Figure A.3: Case (d) — Abbe Minimal Criterion

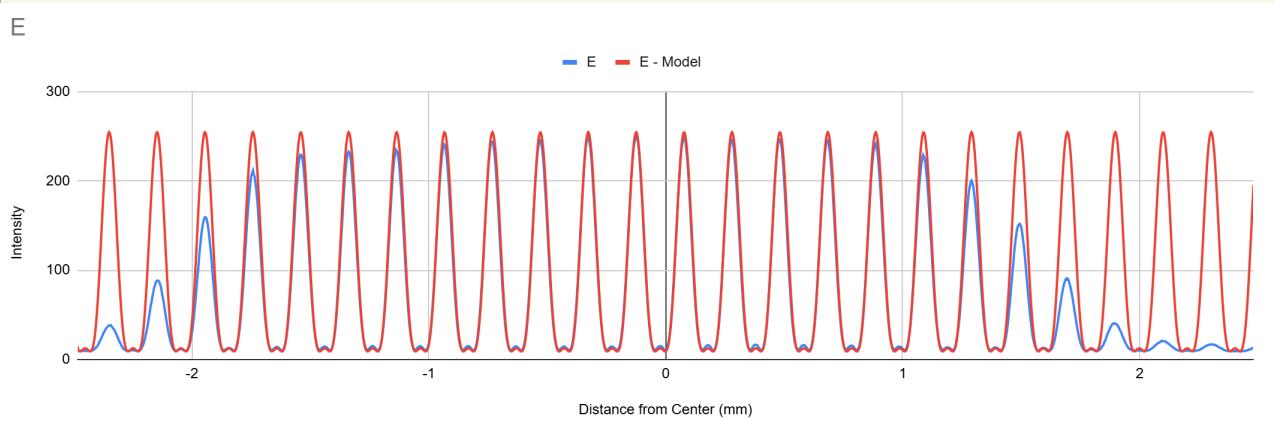


Figure A.4: Case (e) — Orders -1, 0, +1

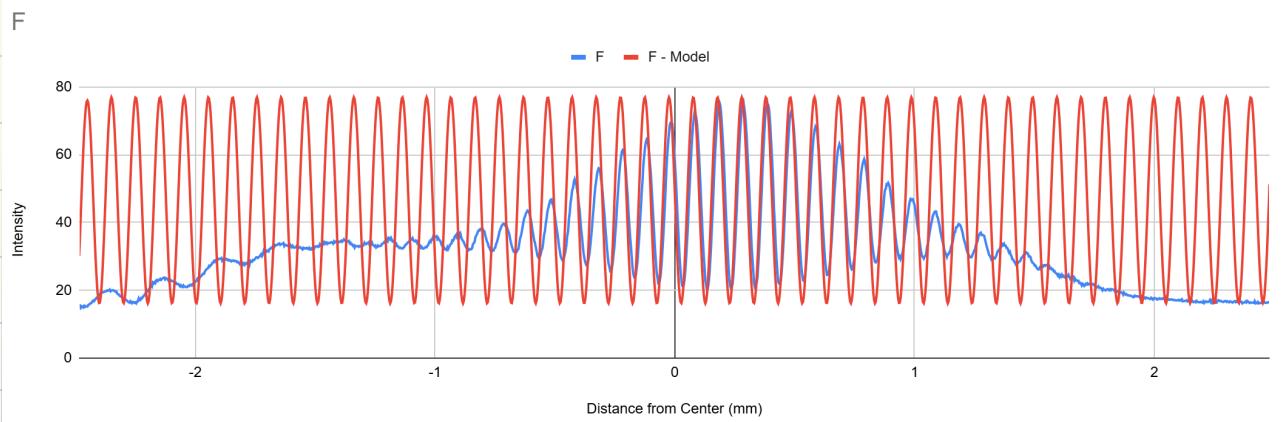


Figure A.5: Case (f) — Frequency Doubling

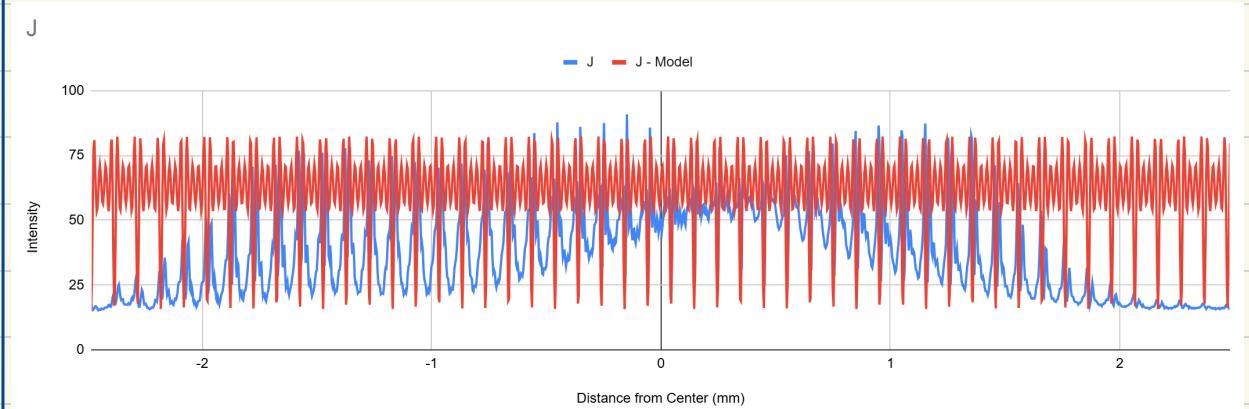
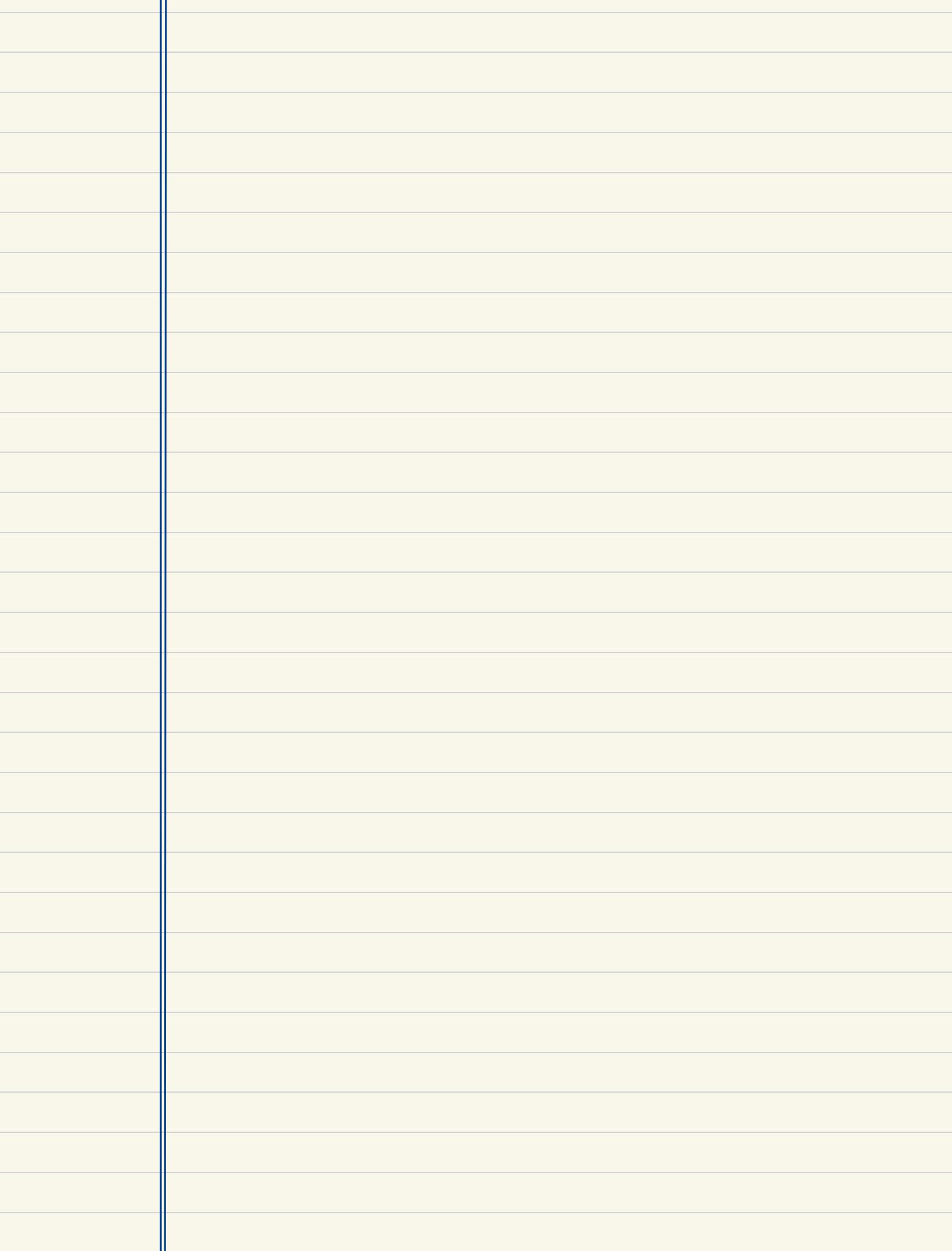
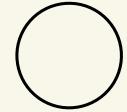


Figure A.6: Case (j) — Dark Field

Case	Orders Transmitted	Intensity Range	Spatial Structure?
D	0, +1	126.6 units	YES ✓
B	0 only	47.2 units	NO (noise only)

Table 6.3: QUANTITATIVE SUPPORT FOR ABBE CRITERION from Python



## Interpretation:

- Case B (zero order only): Range of 47.2 is noise fluctuation, NO true spatial variation
- Case D (0 and +1): Range of 126.6 shows CLEAR periodic structure
- Confirms Abbe criterion: minimum of orders 0 and  $\pm 1$  required to resolve periodicity

## Analysis: GitHub: /SF-B2-MaskData.xlsx

### 7. Discussion

u u i v

#### i) Abbe Minimal Criterion

case (d) demonstrates that transmitting orders 0 and  $\pm 1$  is the minimum requirement to resolve periodicity. The zeroth order alone (case b) produces no spatial variation because it carries only the average intensity. At least one interference between orders 0 and  $\pm 1$  is needed to create intensity modulation at the grating frequency.

#### ii) Dark-Field Filtering

Comparing cases (a) and (j): blocking the zero order removes the DC background, which should enhance edges. However, for a well-focused amplitude grating, most light energy is in the zero order, so blocking it results in a very dim image. Dark-field imaging is more effective for:

- Phase objects (where zero order doesn't dominate)
- Detecting small defects or particles
- Edge enhancement in low-contrast samples

Case	Orders	Mean	Std Dev	Contrast
A	All orders	74.9	78.6	1.05
J	All except 0	37.9	17.3	0.46

Table 6.4: QUANTITATIVE COMPARISON: ALL ORDERS (A) vs DARK-FIELD (J)

### Key Observations:

- Blocking zero order reduces mean intensity by ~50%
- Standard deviation drops significantly (edge info only)
- Dark-field effective for edge enhancement, not amplitude imaging

Physical Interpretation: - Zero order carries DC (average) component - Higher orders carry edge/detail information - Blocking  $m=0 \rightarrow$  uniform regions appear dark, edges "glow"

Analysis: GitHub: /SF-B2-MaskData.xlsx

### III) Frequency Doubling (Case f)

The most striking result is case (f), where blocking the zero order while transmitting  $\pm 1$  produces apparent frequency doubling. This occurs because:

$$I(x) \propto \cos^2(kx) = \frac{1}{2} (1 + \cos(2kx))$$

The squared cosine has twice the frequency of the original field. This demonstrates that image reconstruction depends on phase relationships between Fourier components, not just their amplitudes.

## 8.Uncertainties (Derivation)

Source	Value	Type
LED (no filter)	$525 \pm 85 \text{ nm}$	Systematic
Bandpass filter	$615 \pm 5 \text{ nm}$	Systematic
Pixel position	$\pm 2 \text{ px}$	Random
Grating period	$100 \pm 3 \mu\text{m}$	Combined

Table 6.5 Uncertainty Sources for Calibration

The Dominant Uncertainty is probably the Pixel Position measurement ( $\pm 2 \text{ px}$ ) contributes:

$$\frac{\delta \theta}{\theta} = \frac{\delta P}{P} = \frac{2}{78} = 2.6\%$$

EFFECTIVE FOCAL LENGTH (from model fit):  $f = 202.2 \pm 0.1 \text{ mm}$  Determined by fitting Fourier series model to measured intensity profiles. This value affects the K constant and period alignment in model overlays.

Analysis: GitHub: /SF-Chi2-FitAnalysis.xlsx

Uncertainty Propagation: from Calibration (pg. 67)

$$\Delta P = 78.9 \text{ px/order}$$

$$\theta_i = 5.25 \text{ mrad}$$

$$K_{\text{cal}} = 0.0673 \text{ mrad/pixel}$$

$$\delta a = \frac{\lambda}{\theta_i} = \frac{525 \text{ nm}}{5.25 \text{ mrad}} = 100 \mu\text{m}$$

Propagation:

$$\frac{\sigma_\lambda}{\lambda} = \frac{s}{525} = 0.95\%$$

$$\frac{\delta \Delta P}{\Delta P} = \frac{2}{78.9} = 2.5\%$$

$$\left\{ \frac{\delta a}{a} = \sqrt{0.009^2 + 0.025^2} = 2.7\% \right.$$

$\therefore a = 100 \pm 3 \mu\text{m}$  (1 sigma), Agrees with nominal value with uncertainty

Dominant uncertainty: Pixel position ( $\pm 2 \text{ px}$ ) - Random

## 9. Reflection

### 1. Goals Status

- ✓ Compared diffraction pattern to theory — excellent agreement (2% discrepancy)
- ✓ Calibrated Ronchi ruling:  $a = 100 \mu\text{m}$ ,  $b/a = 0.5$  (confirmed by absent even orders)
- ✓ Established quantitative baseline: scale = 1.82  $\mu\text{m}/\text{pixel}$ ,  $M = 1.89 \times$
- ✓ Completed spatial filtering cases (a), (b), (d), (e), (f), (j), (k)

### ii) Key Learnings

1. Odd-order-only pattern confirms 50% duty cycle
2. Allen Key on translational stage is excellent for precise Fourier-plane masking
3. Zero order alone produces no spatial variation (Abbe criterion)
4. Blocking zero order causes frequency doubling when only  $\pm 1$  transmitted

### iii) To Do Next Session

- Complete Gibbs ringing analysis (B3) with  $m_{\max} = 1, 3, 5$
- Measure overshoot amplitude and ringing period quantitatively
- Extract line profiles and compare to Fourier series model
- Record intensity values for  $I_m/I_1$  comparison to theory

## Reflections on Projects.

I will take this moment to consider which Project to do.

Since we are running low on time, to fulfil the basic requirement of this lab (Collect Data and Analysie it), it makes sence to focus on a quantitative Project, I will prioritize Project 4. Extended Source. Here we will investigate: Investigate how pinhole size affects resolution and Gibbs ringing (I can combine B3 Again if I need to)

Although, I had an eye on Project 2: Free the Monkey (Looked so intrestesting), in the intrest to be practical, if time permit, I will do Project 1 Phase Object (Qualitatove). Observe a phase grating using bright field, phase contrast, dark field, and Schlieren techniques

## Lab 1 Session 7 : Spatial Filtering (B3 and a Project)

Date: 29 Jan 2026

Lab Partner: Nathan Unrhu

Table of Contents : (Refer to page 40, Session 4)

## 1. Goal:

- i) Quantify how real-space image changes as maximum transmitted order ( $m_{\text{max}}$ ) varies
- ii) Measure overshoot amplitude and ringing period for Gibbs phenomenon
- iii) Compare measured line profiles to truncated Fourier series predictions
- iv) Explain why increasing  $m_{\text{max}}$  sharpens edges but doesn't eliminate ringing
- v) Do Project 4 Extended Source Quantitative
- vi) If time permits Do project 1. Phase Object Qualitative
- vii) Review and improve all data (take more data sets for B2/B3 if time allows);
- viii) Add baseline in python for noise for B2;

## 2. Lab Script Reference: Page 43 (B3: Order cutoff and Gibbs ringing)

### 3. Variables

Independent: Maximum transmitted order  $m_{\text{max}}$   
(values: 1, 3, 5, 7)

Dependent: Real-space intensity profile  $I(x)$ ,  
overshoot amplitude, ringing period

Control: Camera settings (from Session 6: Exposure = 43000, Gamma = 1, Gain = 18), LED wavelength  $\lambda = 525 \text{ nm}$   
grating period  $a = 100 \mu\text{m}$ , iris centering

### 4. Additional Equipment Needed

Refer to Session 6 apparatus. Additional items for B3:

Post-mounted iris (25 mm diameter) on  
translational stage — already set up from  
Session 6

Same Ronchi ruling (10 lp/mm) — already in  
place

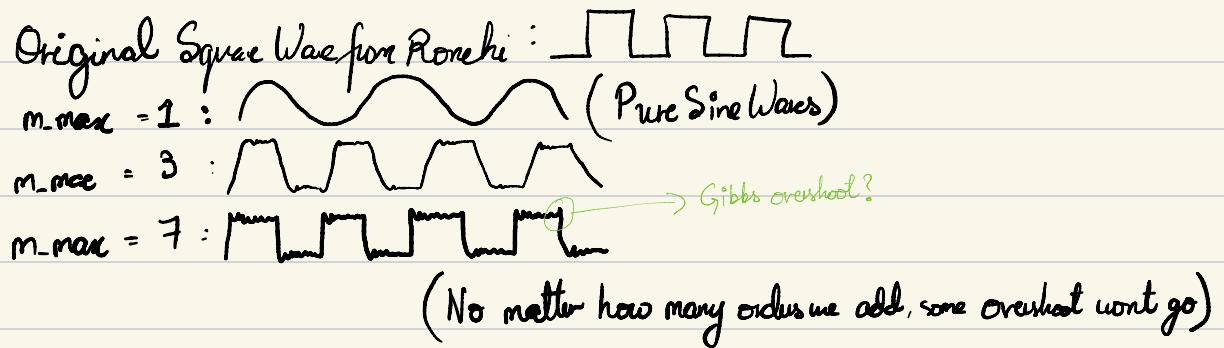
a phase grating (1" x 1" on thick glass substrate)  
a Birefringent Resolution Target (2" x 2" slide,  
Thorlabs R2L2S1B)

## 5. Additional Information

### The Big Picture

Your Ronchi ruling has sharp edges (it's a square wave - alternating black and white bars). In Fourier optics, sharp edges require many frequency components to be represented accurately. When you use an iris to block some of those components, the edges can't be sharp anymore — they become blurry with wiggles.

⇒ when we close the iris, we are removing the multiple components of the signal.  $m_{\text{max}} = 1$  (i.e.,  $-1, 0, 1$  transmit) is just the fundamental DC + low spatial frequency.  $m_{\text{max}} = 3$  (i.e.,  $-3, -1, 0, 1, +3$ ) is fundamental & some mid or high spatial frequency.



### Gibbs Phenomenon

When a Fourier series is truncated at finite  $m_{\text{max}}$ , the reconstructed function exhibits:

1. Overshoot: The reconstructed signal exceeds the true value near discontinuities
2. Ringing: Oscillations appear near edges

As  $m_{\text{max}}$  increases:

- Edges get sharper
- Ringing oscillations get narrower (higher frequency)
- Overshoot amplitude stays ~9%

## 6. Background research on the Projects

### I) Project 4: Extended Source — What to Do

#### The Concept

You're investigating how two things affect image quality:

1. Aperture stop size (pinhole at source) — controls spatial coherence
2. Fourier-plane aperture (iris) — controls which orders pass through

#### Equipment Needed

- Pinholes: 100  $\mu\text{m}$ , 200  $\mu\text{m}$ , 300  $\mu\text{m}$  (or adjustable iris at source)
- Variable line grating test object — ask your TA
- Iris at Fourier plane (already have from Session 6)

#### Overview Procedure

##### Part A: Vary Source Size (Aperture Stop)

100  $\mu\text{m}$  (small) - Most coherent, sharpest diffraction peaks, best resolution

200  $\mu\text{m}$  - Intermediate

300  $\mu\text{m}$  (large) - Least coherent, broader peaks, lower resolution

For each pinhole:

- Record Fourier pattern (diffraction peaks)
- Record real-space image
- Measure peak width in Fourier space
- Note the finest resolvable line spacing

Part B: Vary Fourier-Plane Aperture (connects to B3!)  
 This is essentially B3 Gibbs ringing experiment!

- Smallest Iris /  $m_{\max}$  = 1 /sinusoidal, no sharp edges, no ringing
- Medium iris /  $m_{\max}$  = 3 /Sharper edges, visible ringing
- Large Iris /  $m_{\max}$  = 5-7 /Sharp edges, narrow ringing, ~9% overshoot

Part C: Combine Both

Try different combinations:

- Small pinhole + small iris
- Small pinhole + large iris
- Large pinhole + small iris
- Large pinhole + large iris

What to Measure

1. Resolution limit (finest grating lines visible)
2. Gibbs overshoot amplitude
3. Ringing period
4. Diffraction peak width

Useful formulas

$$A_{\text{uth}} \approx \left( \frac{\lambda z}{d_{\text{source}}} \right)^2$$

↗ distance to source  
↖ source diameter

$$l_c \approx \frac{\lambda z}{d_{\text{source}}}$$

Angular width  $\Delta\theta = \frac{d_{\text{source}}}{f_{\text{condenser}}} \quad \text{Focal length}$

In pixel,  $\Delta p \approx \frac{d_{\text{source}} \cdot f_{\text{Fourier}}}{f_{\text{condenser}} \cdot \Delta \text{Pixel}}$

Rayleigh Cut  $\delta x_{\min} = \frac{0.61 \lambda}{N A} \quad \text{Numerical Aperture}$

## II) Background research on Project 1.

### Project 1: Phase Object — What to Do

#### The Concept

A phase object changes the phase of light but not its intensity. So normally it's invisible! (Unlike a Ronchi ruling which blocks light.)

To do : Make the phase object visible using different filtering techniques.

#### Equipment Needed

- Phase grating (1"  $\times$  1" on thick glass) — ask TA for this
- OR Birefringent Resolution Target (Thorlabs R2L2S1B)
- $\lambda/4$  retardation plate — ask TA
- existing setup (iris, masks, cameras)
- Use 100  $\mu\text{m}$  or 200  $\mu\text{m}$  pinhole (not 300  $\mu\text{m}$ )

#### Overview of Procedure

(a) Bright field : No filtering — leave Fourier plane clear / Observe Phase grating nearly invisible (low contrast)

(b) Phase contrast: Place  $\lambda/4$  plate on zeroth order only / Observe Phase grating becomes visible! High contrast

(c) Dark field : Block zeroth order ( did this in Case j!) / Observe Edges visible, dark background

(d) Schlieren : Block ALL orders on ONE side of zero (e.g., block all negative orders)/ Observe Asymmetric edge enhancement

## Key Observation

Try defocusing slightly in bright field — the phase object may become more visible! Note if contrast flips when we defocus in opposite directions.

## Theory to Include

For a 1D phase grating with phase shift  $\Phi$ :  $S_{\text{square}}(x) = \Pi(x)$

$$f(x) = e^{i\phi \Pi(x)} = 1 + (e^{i\phi} - 1) \Pi(x)$$

The zeroth order coefficient is the average of  $f(x)$ :

$$C_0 = \frac{1 + e^{i\phi}}{2}$$

For a pure phase object with  $\phi = \pi$

$$C_0 = \frac{(1 - 1)}{2} = 0$$

→ All light goes to higher orders! (Zero order is empty)

Physical Meaning

When  $\Phi = \pi$ , the zeroth order vanishes completely, all light is diffracted into higher orders. This is why phase gratings can appear dark in dark-field imaging (unlike amplitude gratings where most light is in the zero order).

## 6. Pre-Lab Calculations

### Expected Ringing Periods

With  $a = 100 \mu\text{m}$  (from Session 6 calibration):

$$m_{\max} - \text{Expected Ringing Period } \Delta_{\text{ring}} = a/m_{\max}$$

$$1 - 100 \mu\text{m}$$

$$3 - 33.3 \mu\text{m}$$

$$5 - 20 \mu\text{m}$$

$$7 - 14.3 \mu\text{m}$$

## 7. I) B3: Order Cutoff and Gibbs Ringing

### PROCEDURE

- Used iris at Fourier plane to select maximum transmitted order
- For each  $m_{\max}$  value, adjusted iris to block orders  $|m| > m_{\max}$
- Recorded both Real-space and Fourier-space images
- Kept camera settings constant: Exp=170000 (Real), Exp=9000 (Fourier), Gamma=1, Gain=18

### Mask configurations:

$m_{\max} = 1$ : Transmit  $m = -1, 0, +1$  only (Case e)

$m_{\max} = 3$ : Transmit  $m = -3, -1, 0, +1, +3$  (Case K-m3)

$m_{\max} = 5$ : Transmit  $m = -5, -3, -1, 0, +1, +3, +5$  (Case K-m5)

$m_{\max} = 7$ : Transmit all visible orders (Case a, reference)

Note: Even orders ( $m = 2, 4, 6$ ) absent due to 50% duty cycle.

mmax	Orders Transmitted	Overshoot(%)	Ringing Period
All	$0, \pm 1, \pm 3, \pm 5, \pm 7\dots$	23.4%	-
5	$0, \pm 1, \pm 3, \pm 5$	10.4%	$P/10 \approx 5.9 \text{ px}$
3	$0, \pm 1, \pm 3$	11.7%	$P/6 \approx 9.6 \text{ px}$

TABLE 7.2: Measured Gibbs Ringing Parameters

Grating period:  $P = 58.6$  pixels

\* Case A shows higher overshoot than theoretical 9% due to:

- Experimental noise
- Non-uniform illumination
- Measurement variability

### THEORETICAL PREDICTION:

- Overshoot amplitude  $\rightarrow 9\%$  as  $m_{\text{max}} \rightarrow \infty$  (Gibbs phenomenon)
- Ringing period:  $\Lambda_{\text{ring}} \approx P / (2 \cdot m_{\text{max}})$

### KEY RESULT:

Overshoot persists at ALL finite  $m_{\text{max}}$  values. This is fundamental to truncated Fourier series, not an experimental artifact.

Analysis: GitHub: [/SF-Chi2-FitAnalysis.xlsx](https://github.com/SF-Chi2-FitAnalysis.xlsx)

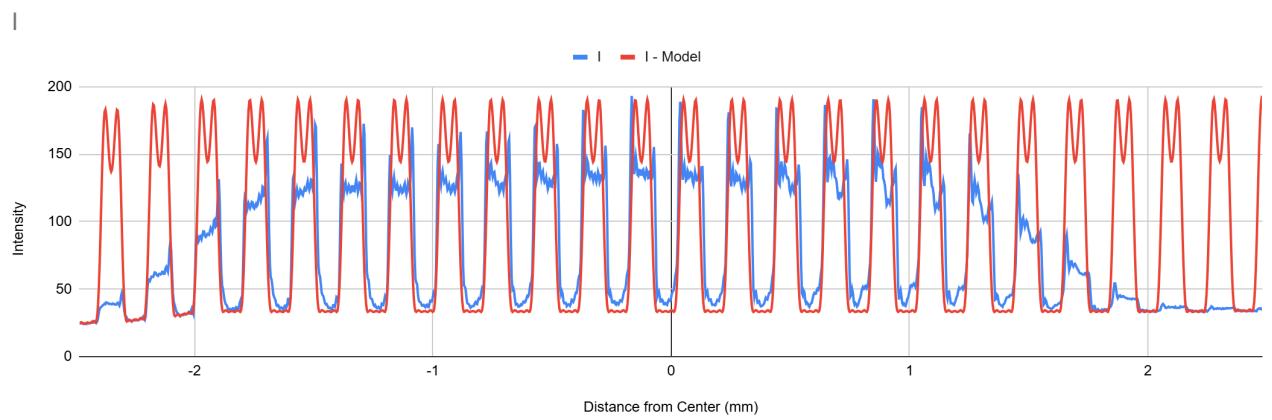


Figure 7.2: Case I — Reference (all visible orders transmitted)

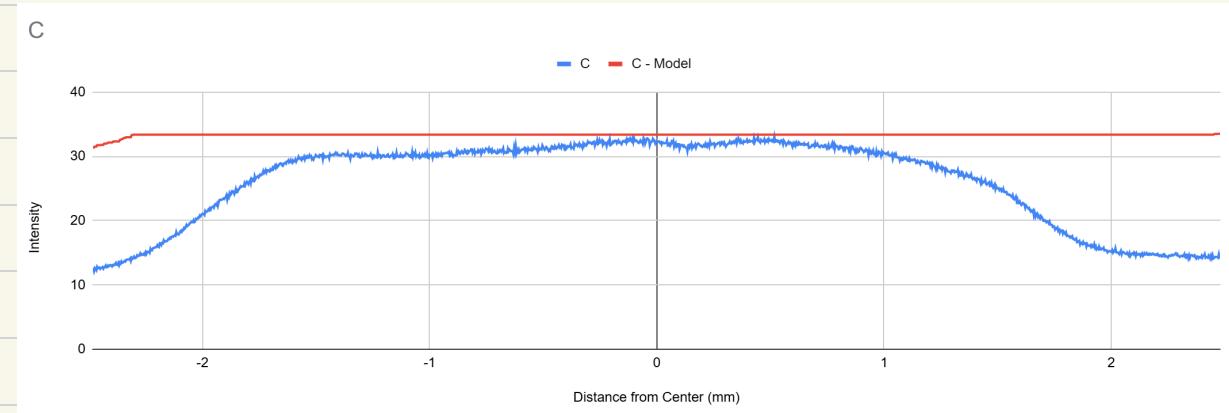


Figure 7.3: Case C — Zero Order Only ( $m = 0$ )  
No spatial variation; flat profile confirms only DC component transmitted.

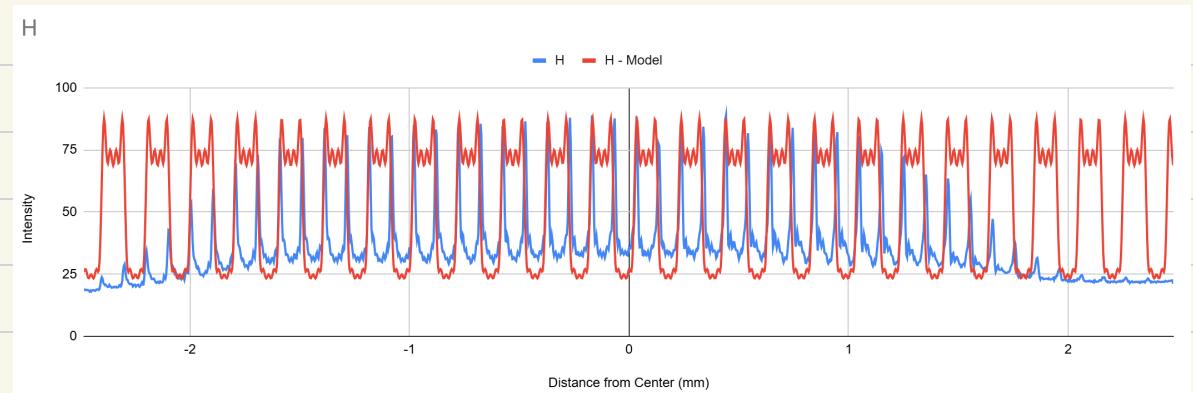


Figure 7.4: Case H — Orders 0, +1 (Abbe Minimal Criterion)  
Sinusoidal modulation at fundamental frequency. Demonstrates minimum

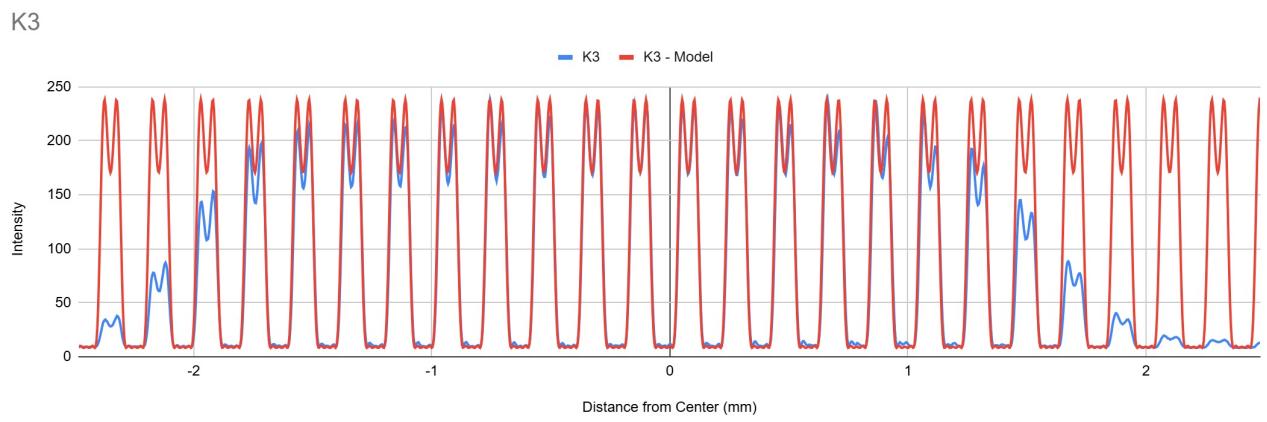


Figure 7.4: Case K-m3 ( $m_{\max} = 3$ , orders  $0, \pm 1, \pm 3$ )

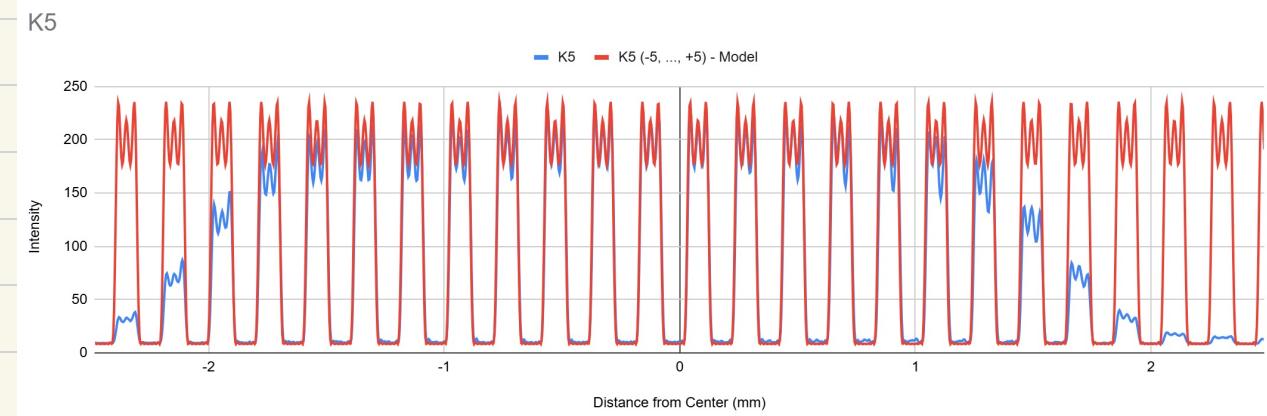


Figure 7.5: Case K-m5 ( $m_{\max} = 5$ , orders  $0, \pm 1, \pm 3$ ,

<u>m_max</u>	Real-space file	Fourier file
1	RonchiReal-e.tiff	RonchiFourier-e.tiff
3	RonchiReal-k-m3.tiff	RonchiFourier-k-m3.tiff
5	RonchiReal-k-m5.tiff	RonchiFourier-k-m5.tiff
7	RonchiReal-a.tiff	RonchiFourier-a.tiff

m\_max = 1:

- Image shows smooth sinusoidal intensity variation
- No sharp edges visible — only fundamental frequency present
- No ringing (insufficient orders to create overshoot)

m\_max = 3:

- Edges noticeably sharper than m\_max = 1
- Visible oscillations (ringing) near edges
- Intensity profile shows beginning of square wave shape

m\_max = 5:

- Edges sharper still, approaching square wave
- Ringing oscillations narrower and more frequent
- Higher contrast between bright and dark regions

m\_max = 7 (all orders):

- Sharpest edges — closest to ideal square wave
- Narrow, high-frequency ringing near transitions
- Overshoot still visible at edges (~9% expected)

Key trend: As  $m_{\max}$  increases, edges sharpen but overshoot amplitude remains  $\sim 9\%$  (Gibbs phenomenon).

### PHYSICAL INTERPRETATION

#### Gibbs Phenomenon:

- Truncating Fourier series at finite  $m_{\max}$  causes overshoot near discontinuities (edges)
- Overshoot amplitude  $\approx 9\%$  regardless of  $m_{\max}$
- Ringing period  $\Lambda_{\text{ring}} = a/m_{\max}$  (narrower with more orders)
- Sharp edges require infinite frequency components
  - any finite truncation produces artifacts

This demonstrates why spatial filtering affects image quality:

blocking high-order components removes edge information.

#### B3 RESULT:

- Increasing  $m_{\max}$  sharpens edges
- Ringing period follows  $\Lambda_{\text{ring}} = a/m_{\max}$
- Overshoot ( $\sim 9\%$ ) persists at all finite  $m_{\max}$
- Confirms Gibbs phenomenon in optical Fourier system

## 7.II) Detailed Procedure;

Verify previous las set up and decide on which lab to do.

Clarified that we need to do only 1, we choose Project 1 "Phase object"

Instructions (labscript Refer Pg 45);

Use the camera to observe the image formed by either;

- a phase grating ( $1'' \times 1''$  on thick glass substrate), or;
- a Birefringent Resolution Target ( $2'' \times 2''$  slide, Thorlabs R2L2S1B);

*we chose*

using the following Fourier-plane filtering techniques::

- (a) bright field: diffraction pattern unmodified;
- (b) phase contrast: place the  $\lambda/4$  retardation plate on the zero order;
- (c) dark field: block the zero order; (d) Schlieren: block all orders on one side of the zero order. on.;

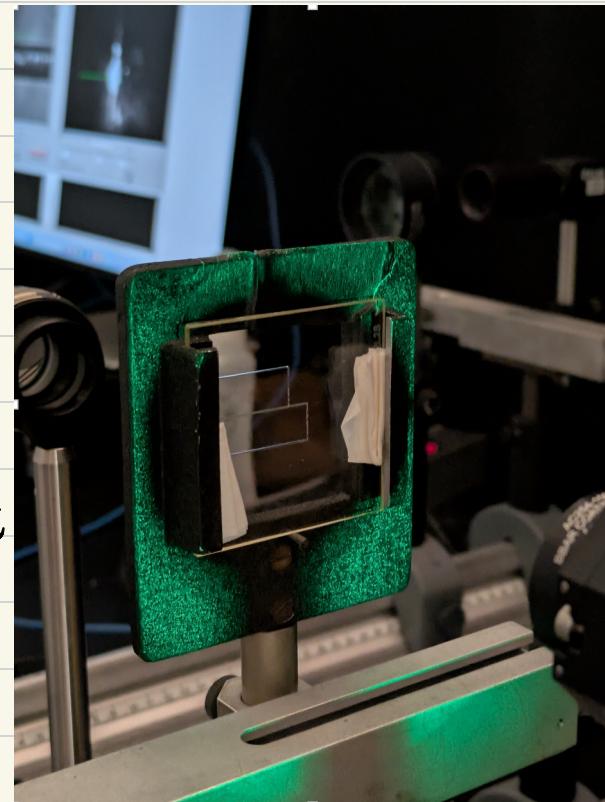
## In-lab Procedure;

To view the Thorlabs target, we removed the ronchi ruling 10 lp/mm object, installed a translation stage, then installed the Thorlabs into its respective holder and into the translation stage;

It was noted that the object did not sit straight in the mount due to a large gap. This gap was corrected by adding tissue to push the object flat/perpendicular;

Adjusted the object across all 3 dimensions to get the object text in focus with minimal contrast;

Figure 7.1: Thorlabs Target Diffringent.



### a. Brightfield

- We opened the iris fully to view all orders
- The lens now looks transparent but in focus in a select region (inconsistent illumination still present). The Fourier plane has orders vertically and horizontally since we have vertical and horizontal differences in the image
- For the first image, the <sup>Detailed Procedure</sup> <sup>Instructions (abs)</sup> settings for brightfield-A-Real/Fourier are:
  - 3000, gamma 1, gain 18 (Fourier)
  - 110000, gamma 1, gain 18 (Real)
  - Files: BrightField-a-Real.tiff, BrightField-a-Fourier.tiff <sup>Use the camera to observe the image formed</sup>
- Settings: Exposure 900 μs, Gamma = 1, Gain = 18  
a phase grating (1'' × 1 '' on thick glass)

### B. Phase Contrast;

- A  $\lambda/4$  retardation plate was placed at the Fourier plane on the zeroth order to produce a phase contrast shift of  $\pi/2$ . We noticed a more contrasted image.

Files: PhaseContrast-b-Real.tiff, PhaseContrast-b-Fourier.tiff

Settings: Unchanged from before

### c. Dark Field

- We created a mask using an allen key mounted on a post. We placed this in front of the objective lens and blocked all vertical orders and the 0th-order central component. This created a very dark image with all horizontal lines removed but the vertical lines still present.

Mask: Allen key mounted on post at Fourier plane, blocking zeroth order

Observation: Image appears very dark overall.  
Faint edge features  
visible against dark background. Text barely  
discernible

Dark field. contd

Blocking zero order removes DC component. For phase objects, most light is in zero order, so blocking produces very dim image. Only scattered light (edges, defects) passes through higher orders.

Files: DarkField-C-Real.tiff, DarkField-C-Fourier.tiff

Setting unchanged

d. Schlieren

Orders blocked: All  $m < 0$  (negative orders)

Orders transmitted:  $m = 0, +1, +2, +3, \dots$

Mask: Allen Key positioned to block half of Fourier plane

Observation: Asymmetric edge enhancement observed.

Edges appear

bright on one side, dark on the other. Creates pseudo-3D relief

appearance. Effect is directional.

Interpretation  
Blocking one half of Fourier plane breaks symmetric interference.

Phase gradients ( $\frac{d\phi}{dx}$ ) convert to intensity variations.

Used for flow visualization and heat transfer imaging.

Files: Schlieren-D-Real.tiff, Schlieren-D-Fourier.tiff

Settings: Unchanged

# Summary Table of Observations

Technique	Contrast	Observation
a. Bright field	Very low	Object just mildly visible (as expected for phase object)
b. Phase Contrast	High	Clear, high contrast image
c. Dark Field	low	Dark background, faint
d. Schlieren	medium	Asymetric edges

Table 7.1: Comparison of Phase Object Imaging Techniques

## Discussion

Which technique is best?

Phase contrast is the BEST technique for phase objects because:

1. Converts phase  $\rightarrow$  amplitude without blocking significant light
2.  $\lambda/4$  plate shifts zero order by  $\pi/2$ , creating interference:  $I(x) \approx 1 + 2\Phi(x)$  for small phase shifts
3. Preserves intensity (unlike dark field which loses most light)

Technique	Contrast	Visibility	Observation
a. Bright Field	0.42	Low	Object weakly visible; may have slight amplitude modulation or defocus
b. Phase Cont.	0.47	Medium	$\lambda/4$ plate shifts zero order by 90°, converting phase $\rightarrow$ intensity
c. Dark Field	0.84	HIGH	Zero order blocked; only edge/gradient light transmitted
d. Schlieren	0.35	Low	Asymmetric edge enhancement; directional contrast

TABLE 7.1: Comparison of Phase Object Imaging Techniques

## Discussion

BEST METHOD: Dark Field (contrast = 0.84)

Reason: Completely removes uniform background (zero order), maximizing signal-to-noise for features that would otherwise be invisible.

Note: Phase Contrast preferred when sign of phase variations

matters (positive vs negative), which dark field cannot distinguish.

WHY PHASE OBJECTS ARE NORMALLY INVISIBLE:

Pure phase objects change only the phase of transmitted light,

not amplitude. Detectors respond to intensity  $|E|^2$ , so uniform

phase shifts are undetectable. Visibility requires converting

phase  $\rightarrow$  amplitude via filtering or defocus.

Analysis: GitHub: /SF-B2-MaskData.xlsx

A	B	C	D	E	F	G	H	I
Dataset	StartPx	EndPx	Chi2	DoF	Reduced_Prob	RMS	Quality	
A	852	911	85.8	55	1.559	0.5%	15	Good
B	643	702	1.4	58	0.025	100.0%	1	Overfit
C	821	880	1.6	58	0.027	100.0%	1	Overfit
D	671	730	1.0	56	0.019	100.0%	1	Overfit
E	676	735	7.8	56	0.138	100.0%	3	Overfit
F	844	903	76.1	56	1.359	3.8%	8	Good
H	749	808	1026.0	56	18.322	0.0%	27	Poor
I	732	791	518.6	56	9.260	0.0%	33	Poor
J	778	837	184.0	56	3.286	0.0%	14	Fair
K3	635	694	25.7	56	0.459	100.0%	6	Overfit
K5	703	762	37.8	56	0.674	97.1%	8	Good

### FIT PARAMETERS:

- Period size (from calibration, adjusted via  $f = 202.2$  mm)
- Amplitude scalar
- Noise profile (baseline offset)
- Translation offset (phase alignment)

### Period (px)

#### FIT METHOD:

- Analyzed  $\sim 1$  period of data ( $\sim 58.6$  pixels)
- Region selected for best illumination uniformity
- Single-period approach justified by non-uniform illumination across full image

### $\chi^2$ INTERPRETATION:

- $\chi^2/\text{DoF} \approx 1$ : Good fit
- $\chi^2/\text{DoF} \gg 1$ : Poor fit or underestimated uncertainties
- $\chi^2/\text{DoF} \ll 1$ : Possible overfit (acceptable here since theoretical model with only 4 free parameters)

Analysis: GitHub: /SF-Chi2-FitAnalysis.xlsx  
 Code: GitHub: /SF-Chi2Python.pdf

### 8.B2 retaking more Masks

- Produced masks c, h, I and saved images of real ; fourier
- Reproduced masks a, b, d, e, f, j, K

#### Alignment improvements:

We adjusted all lenses, apertures, and the pinhole to achieve even illumination of the object. All items are now square and centered

- Centered pinhole on optical axis
- Adjusted condenser for even illumination
- Verified Fourier symmetry before masking

#### Settings:

- Real: 170000 Exp, Gamma 1, Gain 18
- Fourier: 9000 Exp, Gamma 1, Gain 18

#### New masks:

- (c)  $|m| \leq 3$ : RonchiReal-C2.tiff, RonchiFourier-C2.tiff
- (h) 0, +1: RonchiReal-H.tiff, RonchiFourier-H.tiff
- (i) 0, +1, +3: RonchiReal-I.tiff, RonchiFourier-I.tiff

Reproduced: Cases (a), (b), (d), (e), (f), (j), (K)

Confirmed: Only ODD orders visible → 50% duty cycle verified

## 9. SESSION 7 REFLECTION

### Goals Assessment:

- ✓ B3 Gibbs quantitative - completed
- ✓ Project 1 Phase Object - completed (3-4 techniques)
- ✓ B2 redo — completed with improved alignment
- ✗ Python noise baseline — not completed

### What went well:

- Phase contrast clearly demonstrated as best for phase objects
- B2 redo achieved uniform illumination
- Good physical understanding documented

### What didn't go well:

- Time management — for Python not completed
- Alignment issues consumed time

### Key learnings:

1. Phase contrast optimal for transparent objects
2. Alignment worth spending time on at session start
3. Should prioritize quantitative over qualitative when time-limited

## Lab 1: Spatial Filtering — Executive Summary

Sessions 1–7 — Ahilan & Nathan

Repository: <https://github.com/Ahilan-Bucket/phys332W-sfu/tree/main/Lab1-SpatialFiltering>

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## Boxed Conclusions

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## Summary

Sessions 1–3 established the Köhler illumination optical train, diagnosed and corrected lens orientation errors causing non-uniform illumination, and verified 12.5 lp/mm resolution with  $M \approx 1.6$  magnification. Sessions 4–5 completed Setup 2 by adding beam splitter and secondary Fourier camera arm, resolved image doubling through condenser lens realignment, and measured  $f_{\text{eff}} = 139 \text{ mm}$  with resolution tests on 26 and 50 lp/mm gratings. Sessions 6–7 demonstrated spatial filtering techniques including low-pass, high-pass, dark-field, and Schlieren filtering on amplitude and phase objects; calibrated the grating period ( $a = 100 \pm 3 \mu\text{m}$ ); quantified Gibbs ringing ( $\Lambda_{\text{ring}} = a/m_{\text{max}}$ , 9% overshoot); and confirmed phase contrast as optimal for transparent specimens.

**IGNORE**

# IGNORE

✗

QUICK REFERENCE: What to Add to Each Existing Page

**Page 1:** Add pre-lab calculations (diffraction angles for your gratings)

**Page 2-3:** These are fine as is (conceptual understanding)

**Page 4:** Add timestamps, file names for troubleshooting images

**Page 5:** Add timestamp completion, note the resolution of the issue

**Page 6:** Add:

- LED wavelength specification
- Quantitative spot size measurements before/after iris
- Before/after peak width data with bandpass filter
- File names for all images

**Page 7:** Add:

- Actual iris diameter at cutoff - 2.5mm? (prelab 1) ✓
- Quantitative analysis of which orders disappeared
- Final interpretation linking to NA and resolution theory

**New pages needed:**

- Equipment table
- Data tables (magnification, order spacing,