(i)

lab 1 Session 1: SF

0. 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 lense (L2, $f_{Field} = 50mm$) and Condenser lens (L3, $f_{condenser} = 100mm$). This is the 4-f relay system

∴ Magnification, M_{field} (field stop → object) $= f_{condenser}/f_{field} = 100mm/50mm = \boxed{2}$

→ Illuminated diameter: $D_{obj} = M_{field} D_{Fieldstop}$

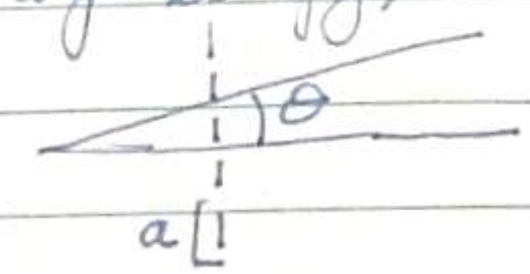
$$D_{FS} = \frac{D_{obj}}{M_{field}} = \frac{5mm}{2} = \boxed{2.5mm}$$ is the value we must set the iris diameter

Then fine tune while watching object illumination

ⓘⓘ

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 ≈ 1/10 of the spacing between adjacent orders?

⇒ For a grating of period a, the diffraction angle satisfy,



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

→ In the Back focal plane of objective / Fourier plane, transverse position is $x_m \approx f_4\,\theta_m \approx f_4 \frac{m\lambda}{a}$

So spacing between adjacent orders is:

$$\Delta x = x_{m+1} - x_m = f_4 \frac{\lambda}{a}(m+1) - f_4 \frac{\lambda}{a} m$$

$$\Delta x = \frac{f_4 \lambda}{a}(m+1-m) = \boxed{\frac{f_4 \lambda}{a}}$$

Recall: $f_4 = 150\,mm = 0.15\,m$, $\lambda = 525\,nm = 525\times10^{-9}\,m$

$a = 1\times10^{-4}\,m$

$$\therefore \Delta x = \frac{0.15 \times 525\times10^{-9}}{1\times10^{-4}} = 7.875\times10^{-4}\,m = 0.7875\,mm$$

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

⇒ Approximate the diffraction-limited spot size at fourier plane as the Airy disk FWHM for circular pin hole aperture: $FWHM_x \approx 1.03 \frac{\lambda f}{D_{pin\ hole}}$

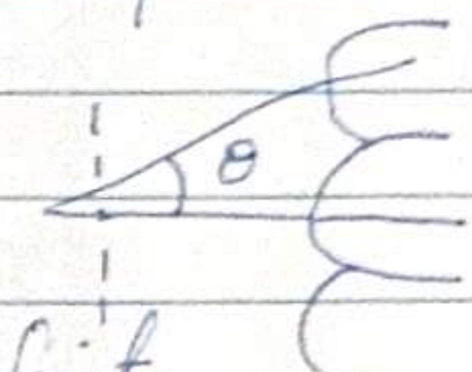
D_p

ⓘⓘⓘ

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 FWHM $\Delta\lambda$ around central λ_0, then the same diffraction order is produced at slightly different angles for different wavelengths.

For small Bandwidth, the angular spread is Approximately

$$\Delta\theta_{spec} \approx \left|\frac{\partial\theta_m}{\partial\lambda}\right|_{\lambda_0} \Delta\lambda \quad (1)$$

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

$$\therefore \frac{\partial\theta_m}{\partial\lambda} = \frac{m}{d\cos\theta_m} \quad \text{into (1)}$$

So spectral contribution to FWHM is:

$$\Delta\theta_{spec,m} \approx \frac{m}{d\cos\theta_m}\Delta\lambda$$

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

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

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 $\Delta\theta_{spec,m}$

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

⇒ To find m, $\Delta\theta_m = 2\Delta\theta_0$.

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

Plug $\Delta\theta_{spec,m}$: $\frac{m}{d\cos\theta_m}\Delta\lambda = \sqrt{3}\; 1.03 \times \frac{\lambda_0}{a}$

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

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

⇒ From question: $\Delta\lambda = 30nm = 30\times10^{-9}m$, $a = 100\mu m = 100\times10^{-9}m$ | $d = 200\mu m = 200\times10^{-9}m$

$$m = 1.78 \times \frac{525\times10^{-9}\times200\times10^{-9}}{100\times10^{-9}\times30\times10^{-9}} = 62.3$$

but should be more like 6.2 (extra zero 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 Band width causes each order to spread out more.

Lab Session 1: Spatial Filter (Exploring the Equipments)
Date: Thursday, 08-Jan-2026, Lab Partner: Nathan

Table of Content

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.

(2)

b) Long Term Vision

i) Complete Setup inside lab Setup 1, familiarize with equipment
ii) Familiarize 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 & lense 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 features like exposure time, gain, _

2. Apparatus

Rail:
↳ Optic Rail & Saddles
↳ Posts: 3", 4", 6"
↳ Translational Stages (for microscope stage / fine positioning)

Sources & Cameras:
↳ LED Source (λ = 525 nm) (Bandwidth 25 nm) LED525L
↳ Real-space camera (FLIR Blackfly) on 6" post

Imaging / Illumination Optics
↳ Magnification lense ($f \approx 300$ mm, marked ∞) Achromatic double lense
↳ Objective lense ($f \approx 150$ mm) ↳ field lens ($f = 50$ mm) plano-convex
achromatic doublet ↳ Condenser lense ($f \approx 50$ mm) ↳ 0.5" iris (small field stop)
↳ 200 μm pin hole on XY Translation mount (aperture stop) LM1XY mount
↳ large iris (Block stray light)
↳ Lens tube, CCD cover disk

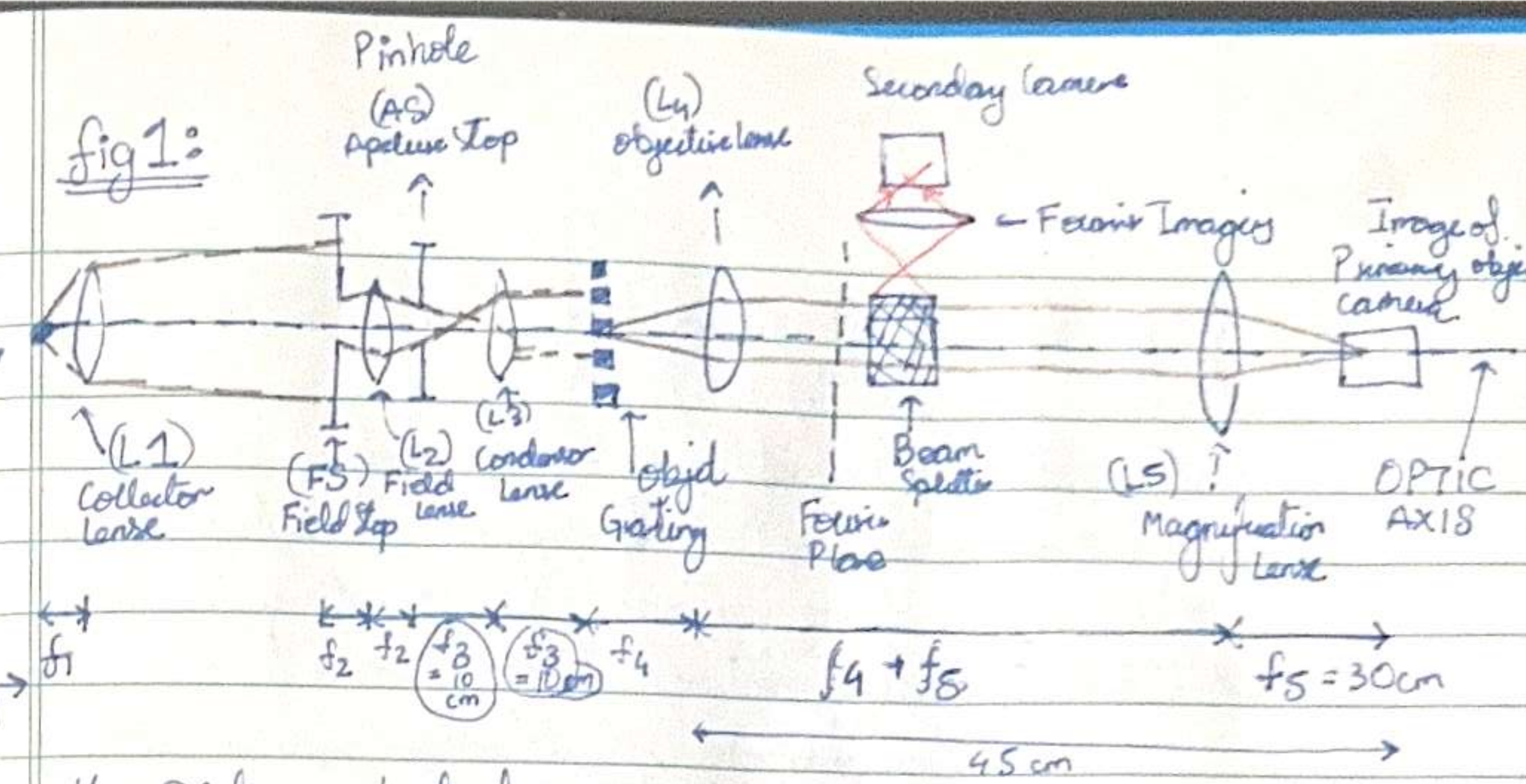
Test Object:
↳ Variable line grating (Thorlabs) !! Do not touch with Bare Hands !!

Software:
↳ NI Vision Assistant ↳ LabView Program: Dual_Camera_Line_Profile_v2.vi

(3)

3. Sketch

fig 1:



4. Key Distances Initial

↳ LED Distance from far rail end ~ 20 ± 0.05 cm
↳ LED Camera distance : ~ 150 ± 0.05 cm
↳ Magnification lense ↔ Camera : ~ 30 ± 0.05
↳ Objective lense ↔ Magnification lense : ~ 45 ± 0.05 cm
↳ Condenser objective distance : ~ 10 ± 0.05 cm
↳ Pin hole ↔ Condensor : ~ 10 ± 0.05 cm

5. Demo for How to find Uncertainties

Find more

I could not find official documentation for the optics rail that talks about the calibration. The least Count is 1 mm ≈ 0.1 cm. ∴ The uncertainty I use is half of that. (± 0.05) cm

6. References:

*Lab Script : PHYS 332 - 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), θ_m = diffraction angle for order m
λ = LED effective wavelength

ii) Background on the Variables in the lab.

Independent variables (we change):
→ Pinhole diameter (aperture stop) ↳ Condenser lense 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, $\lambda = 525$ nm ↳ Room light Blocked
↳ lense choices

(5)

8. Detailed Procedure.

8.1) Initial placement of LED + Collimator lense.

1:51pm Established the far end of the rail as the one near door to limit light from outdoors into the setup

Placed LED + Collimator lense on far end of rail (≈ 20 cm from end of rail). Measured using Scale on railing

Set Height of the LED Source as 21.5 ± 0.05 cm (take scale to account for end of railing scale).

Quickcheck: Ensured LED Source sits right over the center of the rail. & that the beam propogates approx. on centre of line. ✓

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 ~5 m away wall it looks as sharp as we can. without a clear waist focus along the rail.

Check: No waist 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, Read-Camera-Line-Profile v2.vi on the PC desktop.
It shows two panels
Use Exposure 900 µs, 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 see 28.5 & 31.5 on either Side

⑥

Quic Check: Make Sure CCD face is exposed by removing the lense Tube. ✓

Rotate the Source after Putting a post collar & adjust height of Camera post 21.5 ± 0.05 cm
↳ Used a Ruler to measure.

8.3) Alligning magnification lense

Magnification lense 30 cm in front of Camera (Between Camera & Source). The lense is of 300 m = f. Use 4" post

Move curved part of magnification lens toward the Source.
The ∞ symbol on ~~lens~~ is away from camera. After marking the Position of LED with empty Saddle & Remove LED post.
We moved the magnification lense until the image is sharp on a white card at ≈ 71.5 ± 0.05 cm on rail.

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

(7)

9. Post lab1 Reflections:

*We found it very diffcult to focus the light through a mirror & onto 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 lense was found (iii). But iv) the uncertainty we lost time and could only explore uncertainty of the optic's rail. Must find more uncertainty next lab.

b) Long Term goals: Seems like we were a bit ambicious. It 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, lense, camera were well alligned ✓
vi) Limited Thoughts on Lab2, focus remains on lab1
vii) Reviewed Fraunhofer Diffraction but is only relevant for prelabs
viii) Understood CMOS Cameras, features & exposure time ✓

To do next lab :

Complet goals incomplete in last page
Move to the next part of lab Setup 1, specifically add objective lense, image grating object, place pin hole and as inspected by the lab script while all the elements are co linear and square to the rail.

Lab Session 2: Spatial Filtering (Finishing Set up 1)
Date: Thursday, 8-Jan-2026. Lab Partner: Nathan

Table of Content:

1. Goals: i) Complet lab Setup 1 following the post lab Reflections on (page 7-8) of lab note book.
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 lense, pin hole
v) Image the grating object & Resolve a grating > 10 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.
1:57PM Focused on a new object & verified the distance of the focal length as recommended by lab Script pg 30.

Objective lense at 60.5 ±0.05 cm from Start of rail.

Open the Dual_Camera_line_Profile_v2.vi on NI Vision Accusation Software. This is the default software file on the Desktop.
↳ Set Gamma = 1
↳ Disabled Auto Gain, Set gain as 18
↳ Disabled Exposure Auto,
*To do this open Block Diagrams in NI Vision, click on Vision Accusation 1. Change the Value of Auto Gain & Auto Exposure as off.
Adjust and Best Sharpness & Contrast
Final: Exposure Time : 12000 μs
Gamma: 1 Gain is 18. (no need to change)

(10)

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

3.2 Place Objective lense

Place a new f = 150 mm lense, at 45 cm from magnification lense to Right. Centre-to-centre
↳ ie place new lens at 45 cm + 60.5 cm on the Rail marking = 105.5 ± 0.05 cm
↳ Lift Height of lense to make Rays go through center of lense. Centre Horizontally & Vertically.
↳ Note: The 150 mm lense must be having a fine zoom controls Silver colour on the lense.
↳ Tip, look at the shadow with LED on, ie. The camera must be co-centric to the lense appeture

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 metalic coating on the grating. Saddle of 3".

(Test object)
The grating had a Thor lab text on it, we try to focus on that.

The postion of grating at best focus is 123.5 ± 0.05 cm
Exposure time 300 μs, Gama = 1 & Gain 18

(11)

Now, adjust the vertical & Horizontal fine course dial until you see > 10 Lp/mm.

Success: ↳ We were able to resolve 12.5 Lp/mm. ✓

3.4 Place Condensor lense

Placeing Condensor lense f ≈ 100 mm, at 100 mm or 10 cm from the grating. ie on rail at 134 ± 0.05 cm
Centre the lense by ensuring the illuminated part of the object remains centred in the camera image. lense Focus the object.

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

3.5 Place pin hole & Allign with mirror

The 200 μm pin hole is already on the LM1XY translating mount & it is centred.
Place it Right of Condensor lense at 10 ± 0.05 cm away from lense on the Source Side.
↳ Ensure pin hole shadow is centred on Condenser lense using the X, Y Knobs.
Tip place a white card after the Condensor lens & observe the image to Centre it

Place the Blue coated on one side mirror, 10 ± 0.05 cm from the condensor. lense & auto collimate, ie, observe the back reflection onto the pinhole. Make dots co-centric.

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

Insert $f = 50mm$, Condensor lense to image LED source onto pinhole (focus it).
" LED image focused onto aperture stop. (pinhole)

↳ Remove pinhole by unscrewing it from the mount But keeping the saddle, ie, 144 ± 0.05 cm on rail.

↳ Adjust field lense height to keep Beam centered at object & objective.
⇒ Recall field lense is 50mm = f, plano convex lense.

Replace pinhole & confirm LED image is focused onto pinhole

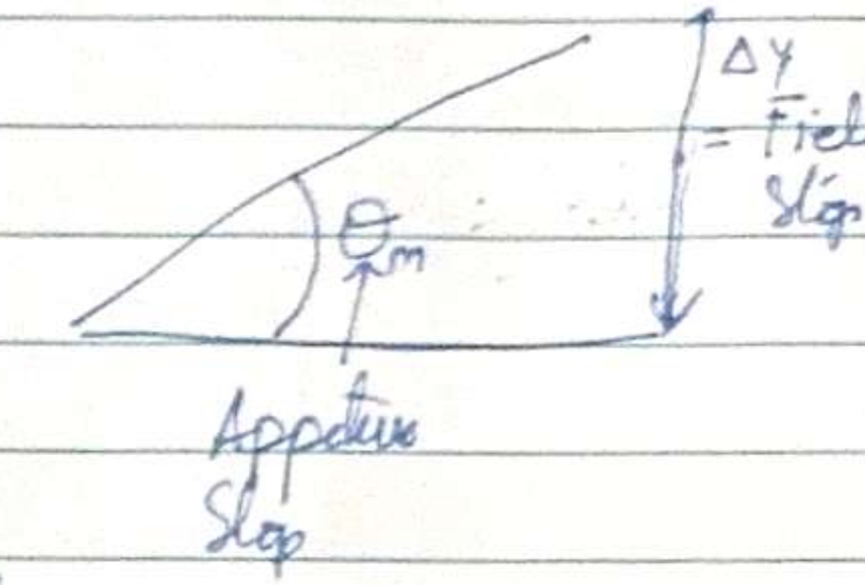
3.6 Place field Stop Iris

3:35PM – Placed 0.5" iris (field stop) (ID 12, small diameter) as adjustable field stop.
⇒ Centre 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 50mm lens ø" "field lense" we could get to.

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

Reduce the iris to get ~ 5mm illuminated field at the grating.
use a White plastic card to see this field of view.
N

∴ Explaining Theory for our Observation : (Note)
Note: Field stop controls illuminated area on the object, aperture stop controls the effective size of the extended source.
So controls illumination angular extent.



3.7 Final elements to Block stray light

To improve Accuracy : Finally Add a large mounted iris in on the Source side of the field iris to reduce stray LED light Beams.

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

Quick Check. 4.) Error Identification for Uniform illumination

ISSUE!
4:00 PM When Iris is reduced to ~ 5mm 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 nope even with dark door it remained.

4:15 PM Proffessor 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.

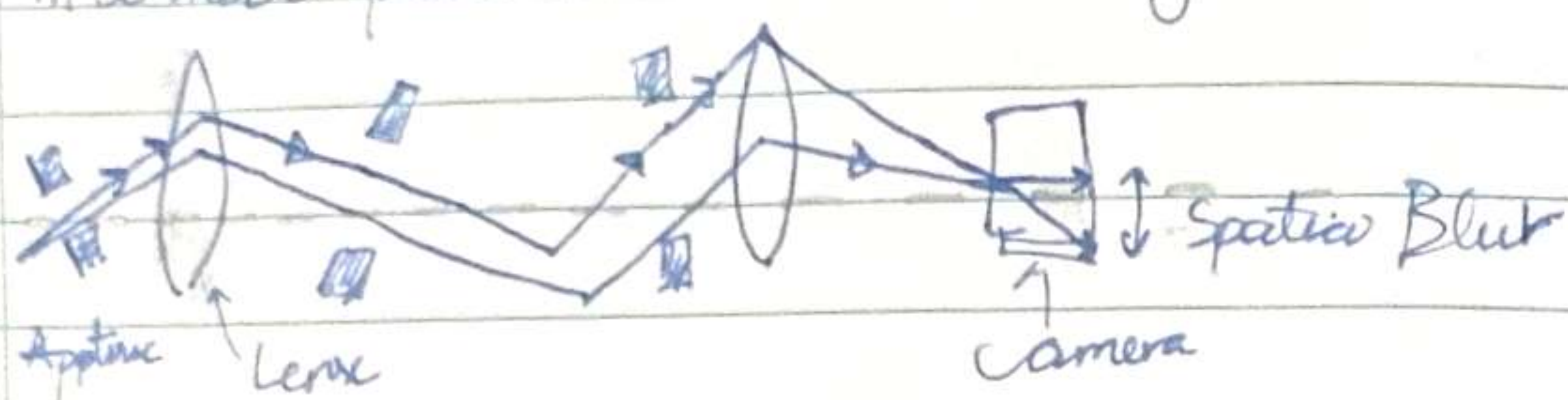
Errors : ↳ So, L5 & L4 were pointing the wrong direction
↳ Because one lense was rotated too much, each element after that tried to correct it But this caused more & more errors.
" Curious why this Makes non uniform illumination" !! Sketch Behind →

(14)

4.2 Some Theory & Explanations of our Errors.

In Correct placement Sketch (Rough & Inaccurate)

fig 2:



Observe How mis places lenses & appertures 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 alligned & Co encentric

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 un screw the element (like lense) from its holder mount while the post & saddle are in place.
So unscrew element by element towards the source until the illumination on a card is uniform.

4.4 Probable Source of errors:

Lense focus points
Railing, it is really straight?
Im proper lense positions
Camera Accuracy.

(15)

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 allignment of Saddle.

DO! We also noted that next lab, we should have a better sketch for the experiment. One that has Both the aparent relative distance of component But also the direction they point in.

The main issue was that we had one apperture rotated off centre & that caused all following lenses & appertures to be rotated. But!! We learnt cool tricks to just remove the lense (un screw it) from its holder & Hence go Back to an earlier stage of the experiment. Super Cool! I am impressed by How modular the optics lab is! ᵕ̈.

To clarify

ASK → Clarify the distance on the grating before next lab.

Ask → How to speed up experiment?

Ask → Documentation for the Rail Train

Ask → I think I want the lense manufacturing documentation to find the errors in the lense. ???

Find → lab View & Camera Accuracy.

(16)

6. Goal Evaluation & what to do next lab

i) We Completed the Lab Set up But we found errors. Next lab we must redo this setup strategically to correct this.

ii) Yes we found & thought of the sources of errors but not Quantitatively. Try to do this next lab

iii) We roughly explored the equipments needed for Pre Lab 2 like Ronchi Ruling,

iv) Explored Real Spacing with full set up

v) Was not able to do the Testing, Next Lab after doing Corrections we will do this

vi) Added objective lense & pinhole elements ✓

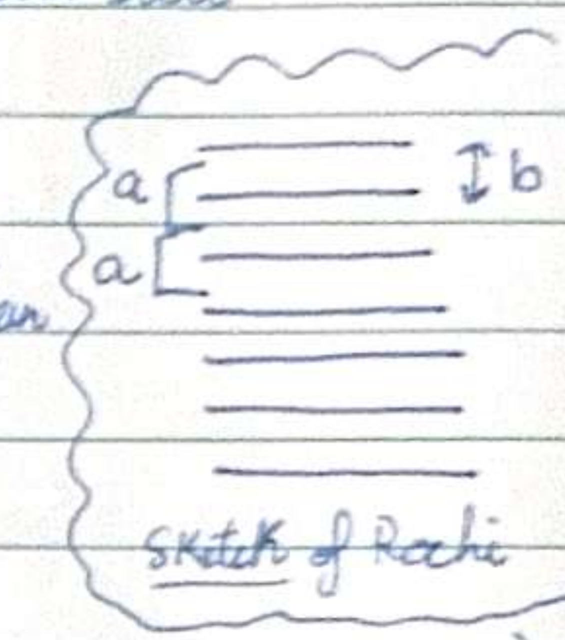
v) We imaged 12 lp/mm ✓ (more than the 10 lp/mm). We almost went to the 15 lp/mm but it was a littlet too Blur

(17)

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

0. Pre lab Question 2

* Ronchi 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



a) ⇒ Eq.:(32): $I(\theta) = I_0 \left(\frac{\sin\beta}{\beta}\right)^2 \left(\frac{\sin N\alpha}{N\sin\alpha}\right)^2$

where $\alpha = \frac{Ka}{2}\sin\theta$, $\beta = \frac{Kb}{2}\sin\theta$, $K = \frac{2\pi}{\lambda}$ (Source lab Script pg 11)

↳ Starting from the lab Script's eq 30; in 1D Fraunhofer field at angle θ, 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 $a(x')$, Lipson uses $f(x)$ while I like $\Pi(x)$"

∴ Eq 30: $E(u) \propto \int_{-\infty}^{\infty} a(x')\, e^{iux'}\, dx'$

or using $u \equiv K\theta_x$; $E(\theta) \propto \int_{-\infty}^{\infty} a(x')\, e^{iK\theta_x x'}\, dx'$

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

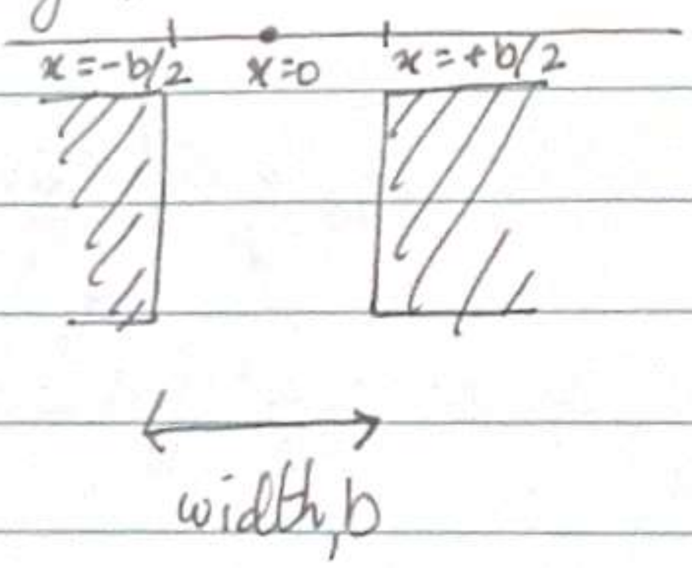
∴ $E(\theta) \propto \int_{-\infty}^{\infty} a(x')\, e^{iKx'\sin\theta}\, dx'$

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

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

Do not panick! all this says is, if your light beam is positioned between the slit (ie it is not Blocked by the slit, it passes through) other wise 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 dirac comb we can just later on use properties of F.T (fourier Transform) to multiply. Convolution in one K space is Multiplication in the fourier space ☺

$$\underset{\text{one slit}}{E_1(\theta)} \propto \int_{-\infty}^{\infty} \Pi(x')\, e^{-i k x' \sin\theta}\, dx' = \int_{-\frac{b}{2}}^{+\frac{b}{2}} e^{-i k x' \sin\theta}\, dx'$$

$$= \left[\frac{e^{-i k x \sin\theta}}{-i k \sin\theta}\right]_{-b/2}^{+b/2} = \frac{e^{-ik(+b/2)\sin\theta} - e^{+ik(+b/2)\sin\theta}}{(-i k \sin\theta)}$$

Note: $\frac{e^{-i\theta} - e^{+i\theta}}{-i} = 2\sin\theta$ use →

$$= \frac{2\sin(Kb/2 \sin\theta)}{K\sin\theta}, \quad \text{now let } \beta = \frac{Kb}{2}\sin\theta$$

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

This is the envelope function

Quoting Lipson (pg: 245-247)

A diffraction grating is given by

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

Single Apptr Mask — Dirac Comb of slits — a, line spacing (period) N, Total nos of slit

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

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

$$\mathcal{F}\{f(x)\} = E_1(\theta) \times \sum_{n=0}^{N-1} e^{-iuna} \quad (8.45) \quad u = \frac{2\pi}{\lambda}(\sin\theta - \sin\theta_0)$$

Note $\sum_{n=0}^{N-1} e^{-iuna}$, as $N \to \infty$, the sum is, $\sum_{m=-\infty}^{\infty} \delta\left(u - \frac{2\pi m}{a}\right)$

The index m is called order of diffraction. When realistic, N is finit The geometric sum Becomes, $= \frac{1 - e^{-iuNa}}{1 - e^{-iua}}$ (8.47 lipson)

The intensity, $\underset{\text{Array or Comb}}{I(u,v)} = \left|\frac{1 - e^{-iuNa}}{1 - e^{-iua}}\right|^2 = \frac{\sin^2(uNa/2)}{\sin^2(ua/2)}$

Now again $\alpha = \frac{Ka}{2}\sin\theta = \frac{ua}{2}$ is how we define in this lab (Look at Lab Script pg____)

$\therefore$ The total Amplitude Becomes: $E(\theta) \propto \underbrace{\frac{\sin\beta}{\beta}}_{\text{Single Slit}} \underbrace{\frac{\sin(N\alpha)}{\sin(\alpha)}}_{\text{Repeating Slits}}$

Total Intensity $I(\theta) \propto |E(\theta)|^2 \propto \left(\frac{\sin\beta}{\beta}\right)^2 \left(\frac{\sin(N\alpha)}{\sin(\alpha)}\right)^2$

$$\boxed{I(\theta) = I_0 \underbrace{\left(\frac{\sin\beta}{\beta}\right)^2}_{\text{Single slit Envelope (Diffraction)}} \underbrace{\left(\frac{\sin(N\alpha)}{\sin\alpha}\right)^2}_{\text{N Array, (Interference)}}}$$

If you let N=2 You get Young double slit eqn. ☺

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:

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

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
```

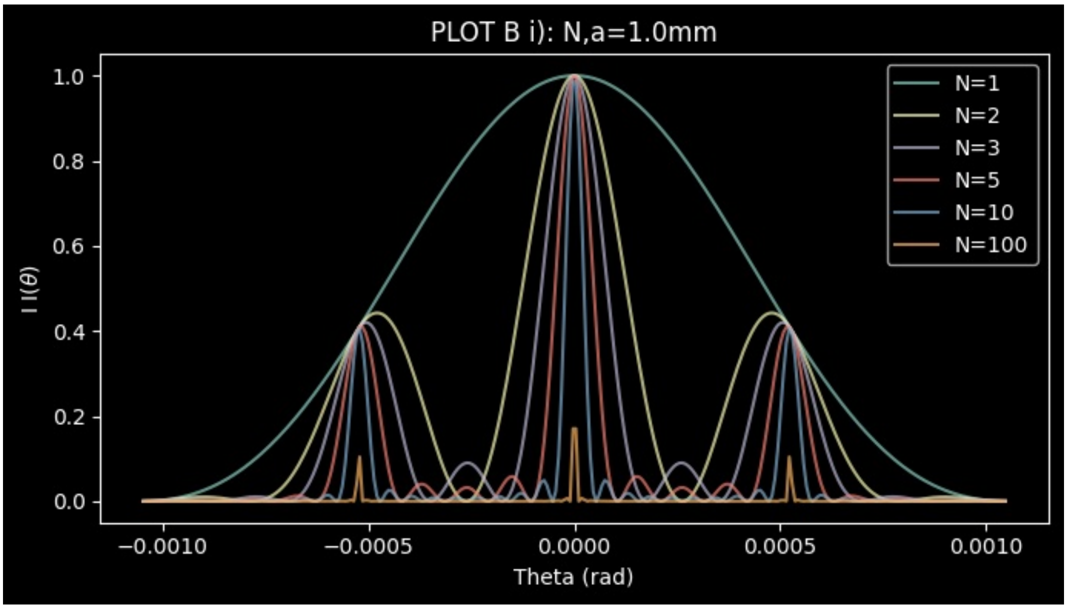
Note:

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

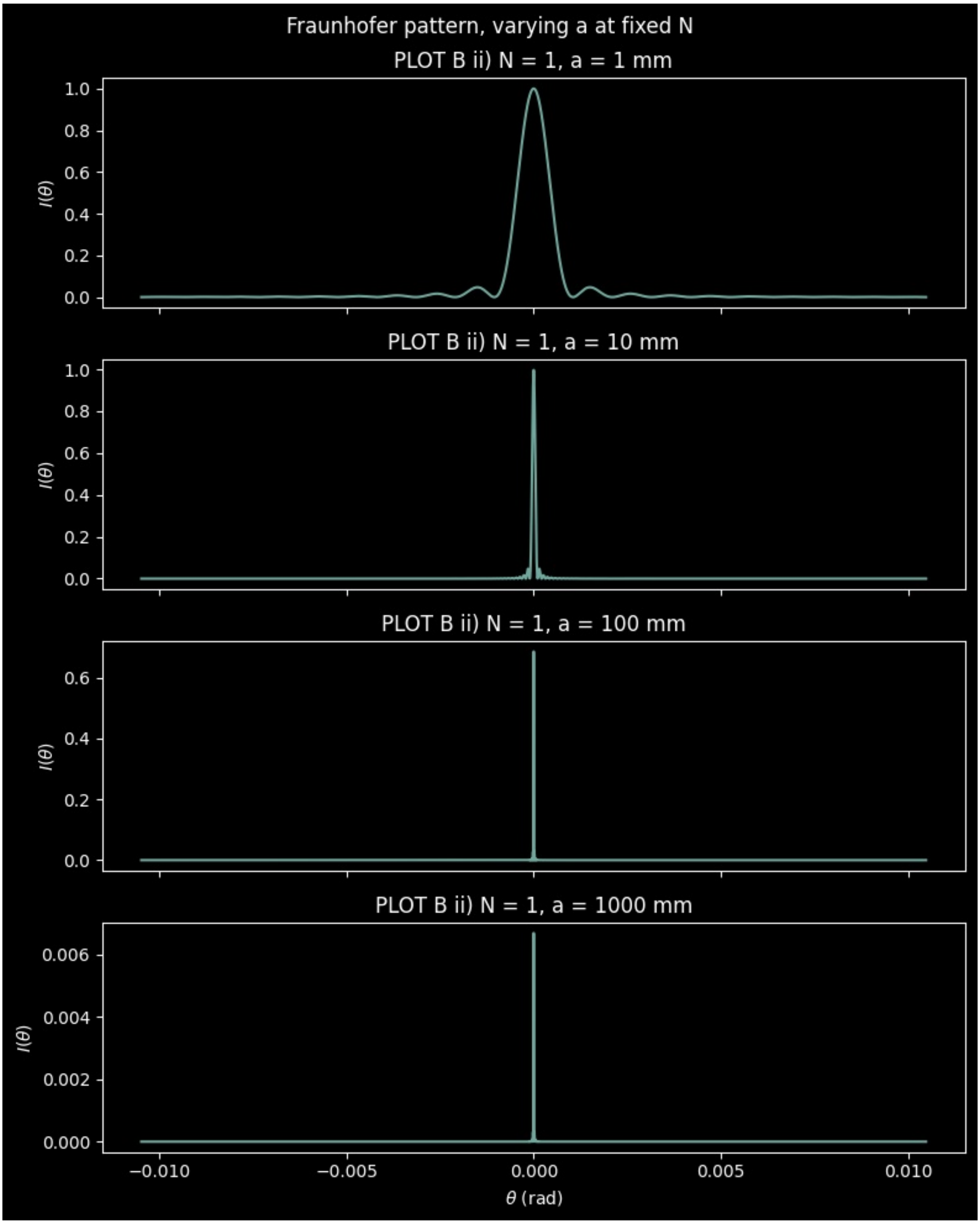
In [11]:
```
theta = np.linspace(-np.pi/3000,np.pi/3000,300)
N_lst = [1,2,3,5,10,100] # different numbers of slits
a_lst = [1,10,100,1000] # mm

# 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()
```

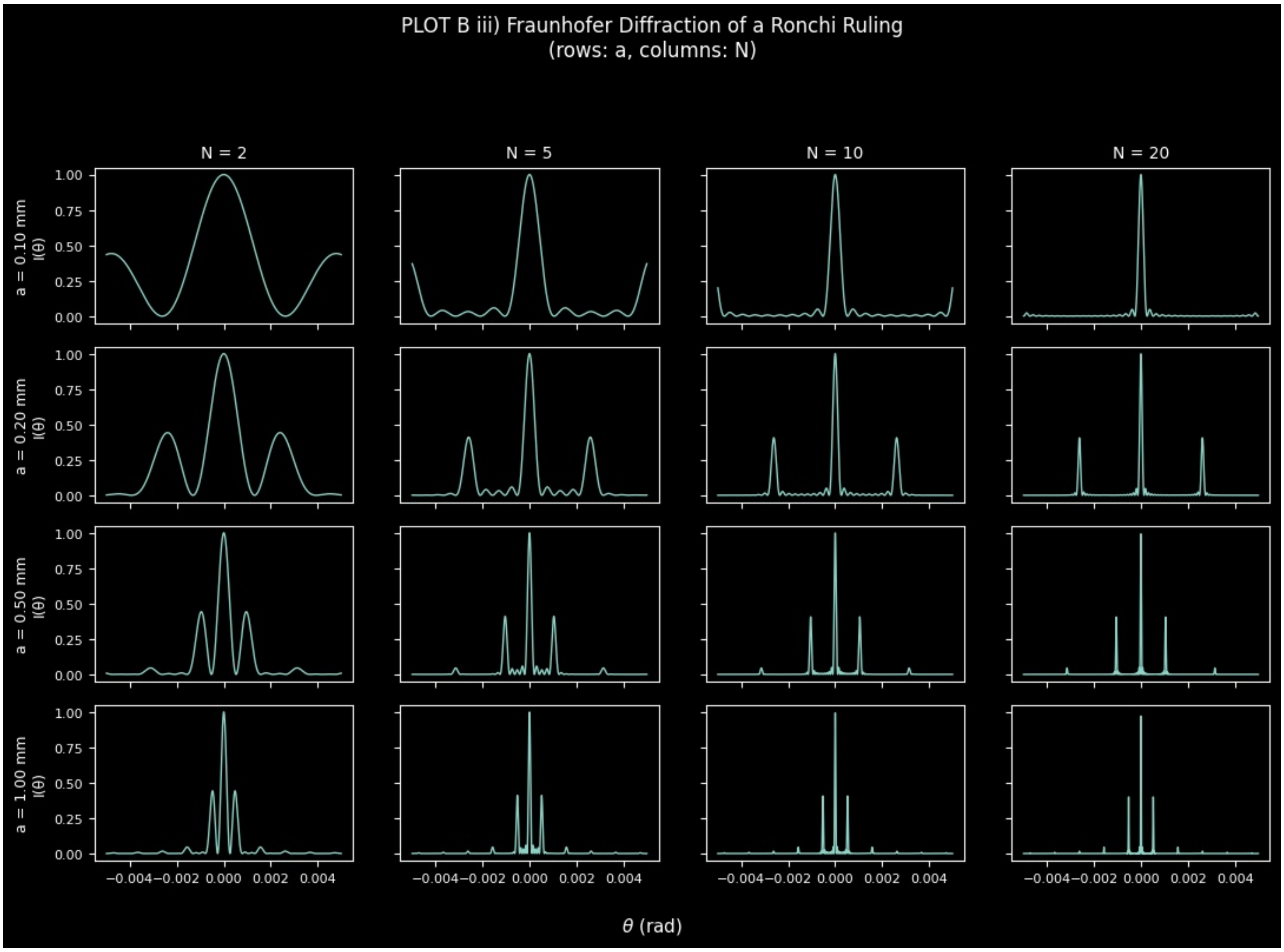
```
<Figure size 1600x800 with 0 Axes>
```



iii) Grid

```
# 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]
```

```python
# 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(θ)", 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()
```



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 $\boldsymbol{a}$ (in mm), and columns correspond to different numbers of illuminated slits $\boldsymbol{N}$. 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:

- $\alpha = \frac{1}{2}ka\sin\theta$
- $\beta = \frac{1}{2}kb\sin\theta$
- $k = 2\pi/\lambda$
- $\lambda = 525$ 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: $[\sin(N\alpha)/(N\sin\alpha)]^2$.
- **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.

(20)

b)

Plotting logic, Pseudo code

Array $N=[1,2,3,5,10,100]$, $a=[1,10,100,1000]$

For i in range list N : mm

- plt. subplot (2, len (N), i)
- plt. plot (theta, I(argument)) include i & a[0]

generated from np.linspace)

- plt. Titel (f" N {i}

Illy for a do with j.

Geometry	**Scalar & 1D**: Polarization, finite slit height, and 2D structures are ignored.
Light Source	**Perfectly Coherent**: Single wavelength $\lambda = 525$ nm with no spectral bandwidth.
Optics	**Idealized**: No lens aberrations, misalignment, detector noise, or finite pixel size.
Normalization	**Per-subplot**: 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)

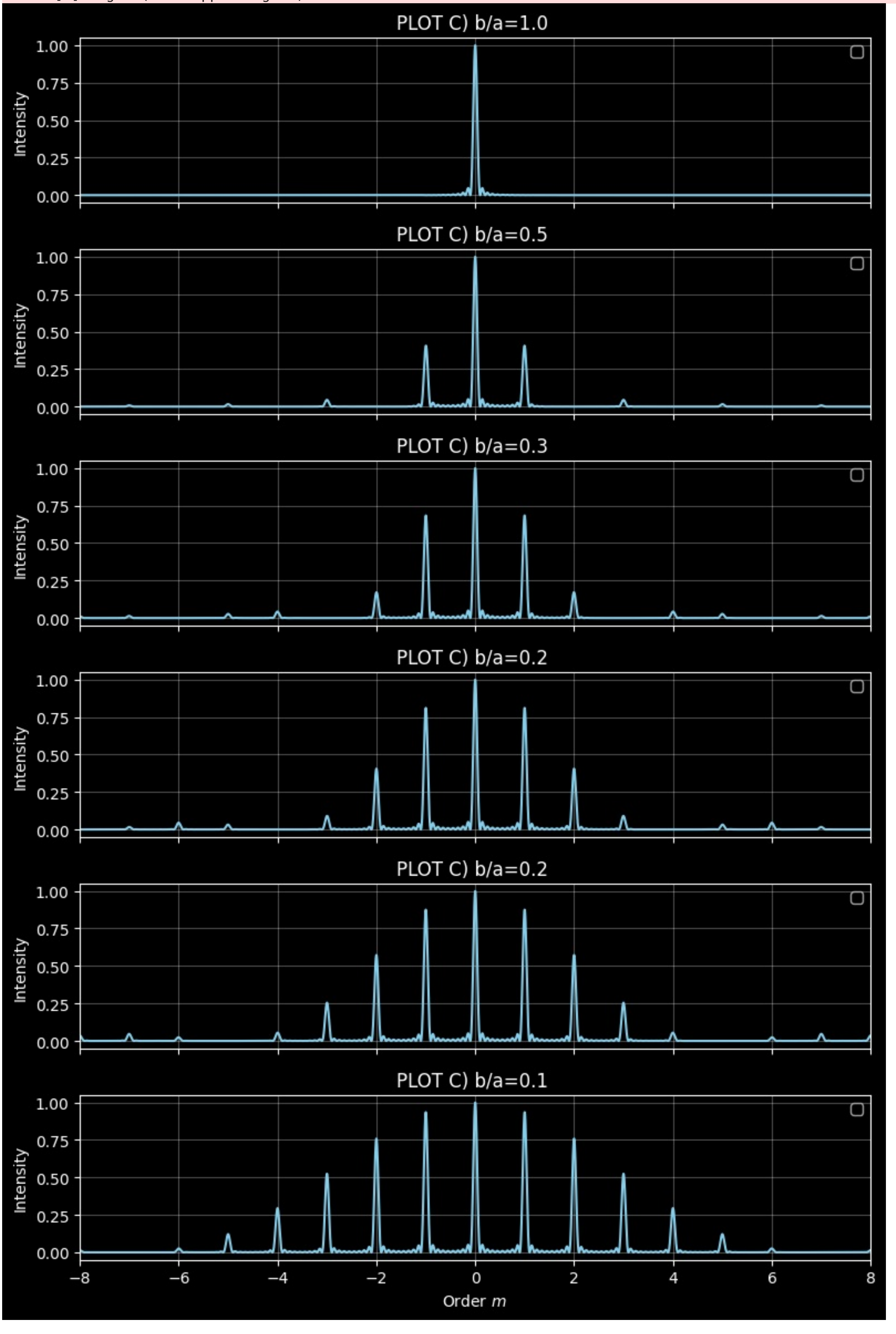
Effect of varying the duty cycle b/a. How it affects the relative intensity of diffraction orders (including which orders may be suppressed).

I will be Fixing the N at 5 and a=0.20mm

and Vary the duty, b/a

In [14]:
```python
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"PLOT 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.
  axs[i].legend(loc='upper right')
```



21

Qualitative Explanations.

Spacing Between Orders:
As a increases, the diffraction order closer together
N has no effect

Width of Diffraction Peak
As N increases, diffraction peaks become narrow & sharp.

Overall Envelope
⇒ As b gets smaller, produces wider envelope, more diffraction orders are visible.

(22)

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

⇒ Note the suppressed diffraction orders.

⇒ 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 ± 1 diffraction orders increases.
When $b/a > 1$, it is actually not even existant.
for $b/a = 0.5$ to $1/100$ do increase

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 ie, more higher order retain intensity. More power is concentrated in higher order m's.

⇒ Suppressing orders.

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

(23)

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

∴ at $\frac{mb}{a} = n$ //

for the Ronchi ruling, $b/a = 1/2$ even

$$\frac{I_m}{I_0} \propto \left[\frac{\sin(\pi m/2)}{\pi m/2}\right]^2$$

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

⇒ $\pm 2\pi = n\pi$, $\pm 4\pi = n\pi$, $\pm 6\pi = n\pi \ldots$

So these Become Zeros. and hence are suppressed. While odd Powers Remain

Ily for Ronchi ruling, $b/a = 1/3$

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

d) In experiments, diffraction orders will not be sharp & may broaden.
The reasons boil down to what the physical reality is.

1) Finit 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 finit angular extent. So the grating is illuminated by a smaller range of incident angles θ_0.
For each incident angle, the grating equation $a(\sin\theta - \sin\theta_0) = m\lambda$ gives slightly different output angles θ for the same m.

⇒ Measured intensity has a superposition (Convolution) of many slightly shifted pattern. This leads to Broader diffraction patterns of each order. Rather than being delta functions we have Sinc functions.
↳ Its won't be sharp as the contrast decreases.

2) Finite spectral Bandwidth.
↳ Now Eq. 32 assumes an mono chromatic illumination λ. But although we have a largely mono chromatic source that is indistinguishable by eye, it still has a bandwidth of 25 nm for a central wavelength of $\lambda_0 = 525$ nm (Refer to lap Script Appendix: pg 22).
⇒ For a given order m, different wavelengths satisfy $a\sin\theta_m\lambda = m\lambda$.
So we see slightly displaced peaks, and angular broadening & more blurring for high orders.

lab Session 3 : SF
Date : Thursday 15-Jan-2026, lab Partner : Nathan

Table of Content

Note : Since my lab partner isnt going to be here for a while, I've decided to work on some preparation & sketches & 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) Move & Complete lab Setup 2. v) locate fourier plane using viewing 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 from a real-space image of the grating &
viii) Identify major limitation in illumination uniformity & document one check & verification

2. Apparatus, Referens

Refere once again to Same as (pg 2-3)

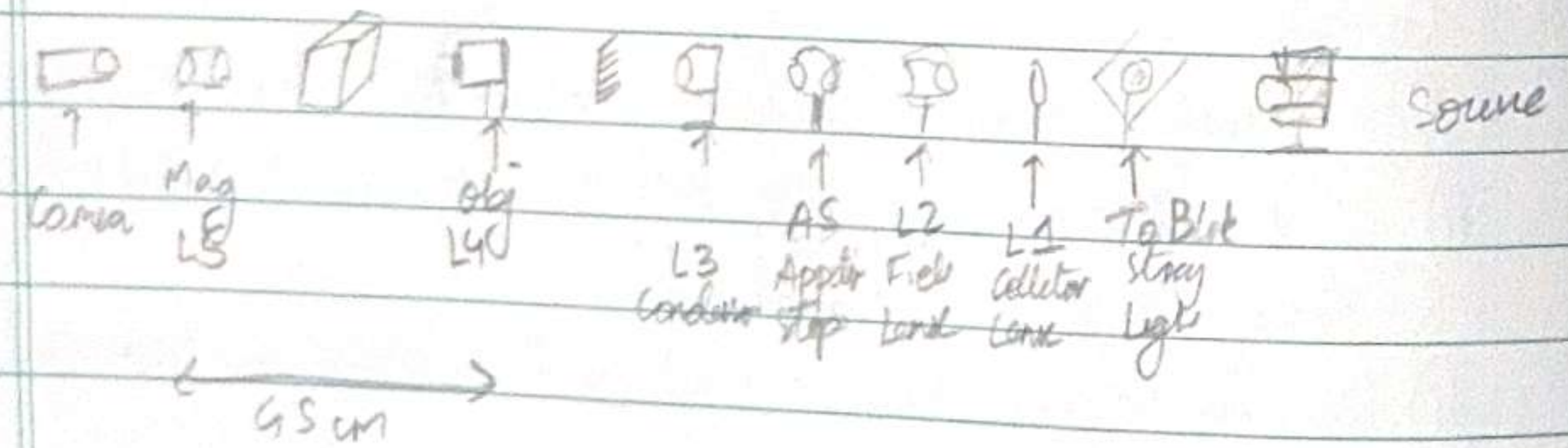
i) Additional Apparatus to meet lab 3 :

* Ronchi Ruling * Camera: BFS-U3-16S2M-CS
* Adjustable iris (field stop) & pinhole at aperture stop (200 µm)
* Paper to wedge the saddle & correct the pin hole stage

ii) Additional Referens

* Hect, Eugine, Textbook Optics (Library)
* Lipsion, Modern Optic, 4th edition (library)

3. Updated sketch. (Appendix Sketch to show lens Orentation)



4. Procedure

4.1 Corrective measures :

Based on the figure we adjusted the direction the lense face in the sketch. Allign all of the lenses square to the rail

Nathan Joined the lab

1:45PM 4.2 Alligning Lense Allignment By making Backward Attempt 1

we trying to work Backward, removed the L4.

Then trying to decrease the pin hole size at

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

2:15PM 4.3) Restarting Configuration after Magnifying lens (Attempt 2)

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

Trying to Reset configuration after the magnification step

Placed objective lense 45 (150mm) ± 0.05cm from magnification lense

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

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

We moved the mount on the condenser lense by unscrewing it.

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

(28)

Attempt to wedge printer paper for pinhole saddle to allign 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

* Placed a white card after Each element (starting from Source & towards camera Side)
* Confirmed the beam stayed centered
* Observed largely uniform light! Yay!

Success!

5. Testing the setup

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

Using the Vertical 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.

(29)

Testing

Using the line tool on the Image Panel, we make a line over the diffraction pattern over a length of 1mm. Covering pixel 255 to 1328 on x axis.
Camera has a pixel of 1440 × 1080 (Given on the Software itself (cross checked by seeing the Bottom Right Corner)

BFS-U3-16S2M-CS documentation on canvas for the camera says each pixel is 3.45 μm

∴ image size is, (1328 − 225) pixel × 3.45

The grating we used was 10 lines per 1 mm.
∴ we observed 24 lines.
The object distance is: $10 : 1\,mm$
$24 : x$

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

2.4 mm on object gives. $(1328 - 225) = 1103$ pixel
∴ $1103 \times 3.45\,\mu m = 1103 \times 0.00345\,mm$

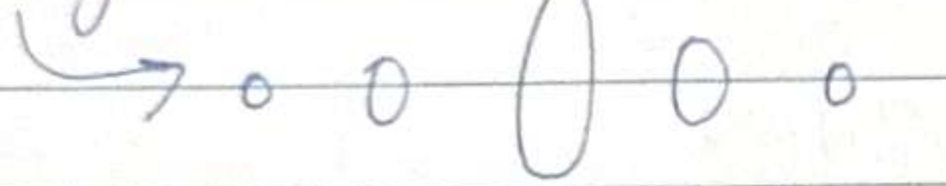
$M = \frac{i}{o} = \frac{1103 \times 0.00345}{2.4} = 1.585$ magnification

We are below it, we needed a magnification of 2 (Prelab 2) only ≈ 1.6.
This is from the 4-f relay: $M = \frac{f_{imaging\ lens}}{f_{objective}} = \frac{300}{150} = \underline{\underline{2}}$

Adjusted the field stop iris such that we see only about 15 lines in well 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 ≈ 94 ± 0.05 cm (along rail)



Place a camera on this plane. & fine adjusted the base. This spot was on camera side after the L_4 lense.
at 93.5 ± 0.05 mm.

Taking measurements of the diffraction pattern on labView
Exposure: 1500 μs; Gain: 1, Gamma: 1.5. Auto exposure off.

Data: 390 674 953 : Pixel

284 279

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

Again 281.5 pixels × 0.00345 mm
= 0.971175 ± 0.05 mm

This is distance between the central & the first maxima.

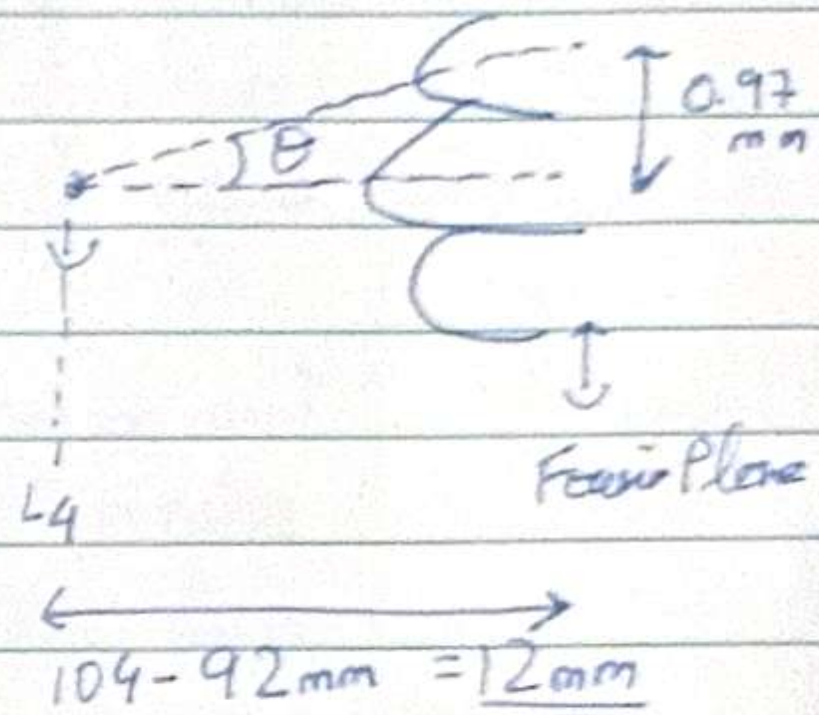
Errors, Hot spots on the camera formed a strong central dot.

6. Analysis

To find the angle

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

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



The labscript also suggests:

$\sin\theta_1 = \frac{\lambda}{d} = \frac{528}{12\,mm}$

Figure Saved

We took an image of the fourier image using the "Save fourier" button on the panel.
↳ Saved it to Canvas on: "Ahilan & Nathan Group/Lab 1-Spatial filtering/Session3/2026-01-15_SES3_FourierImaging_01.tiff"

7. Major Issues:

ISSUE 1) Observed Very Bright spots especially in the centre. Made it harder to see exactly where the Centre is (Refer to Image in Canvas, look in last page)

ISSUE 2) Fine allignment of Rail & Saddle but this was easily mitigated with different Saddle, Keep this in mind for future labs.

8. Uncertainty notes:

⇒ Pixel measurement: ±1-2 pixels, Because each pixel is 3.45 μm size, we have an uncertainty of ±(3.45-6.9) μm to the spacing on diffraction pattern. Hence to the θ angle as well.

* ⇒ In future lab, we should find this value!

9. Goal Evaluation

1) locate Fourier plane ✓ 2) Camera at fourier plane + recorded spacing ✓
3) Magnification measurement + Comparison ✓ 4) Noted limitations ✓

10. Reflections & Plan for next lab.

1) After Comming home & looking at the fourier diffraction patter Image, I realized it might not be camera hot spot! When we 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 save it too.

4) Explore the use of Git hub for file sharing. (TA Zach said to format better)

34

Ahilan Kumaresan

Lab $\boxed{1}$ Session $\boxed{4}$ SF

Prelab Question 3.

1. Let the grating be perodic in x with period d. Over one period, model its amplitude transmittance as a rectangular pulse:

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

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

Fourier Series form:

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

& fourier coeffients: $C_n = \frac{1}{d}\int_0^d t(x) e^{-i2\pi n x/d} dx$

$$= \frac{1}{d}\int_0^\omega e^{-i2\pi n x/d} dx$$

DC offset term, $c_0 = f$

for $n \neq 0$

$$C_n = \frac{1}{d}\left[\frac{e^{-i2\pi n x/d}}{-i2\pi n/d}\right]_0^\omega = \frac{-1}{i2\pi n}\left(e^{-i2\pi n f} - 1\right)$$

$$C_n = \frac{\sin(\pi n f)}{\pi n} e^{i\pi n f} \qquad (n \neq 0)$$

2) In a 4f imaging System, fourier plane contains discrete diffraction orders n 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:

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

As usual, $I = |E(x)|^2 = E(x)\, E^*(x)$

← Complex Conjugate

<u>Code Below:</u>

36

Pre-lab Question 3

January 20, 2026

Ahilan Kumaresan

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

[15]:
```python
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
```

37

```
        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
```

```python
# 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()
```

39

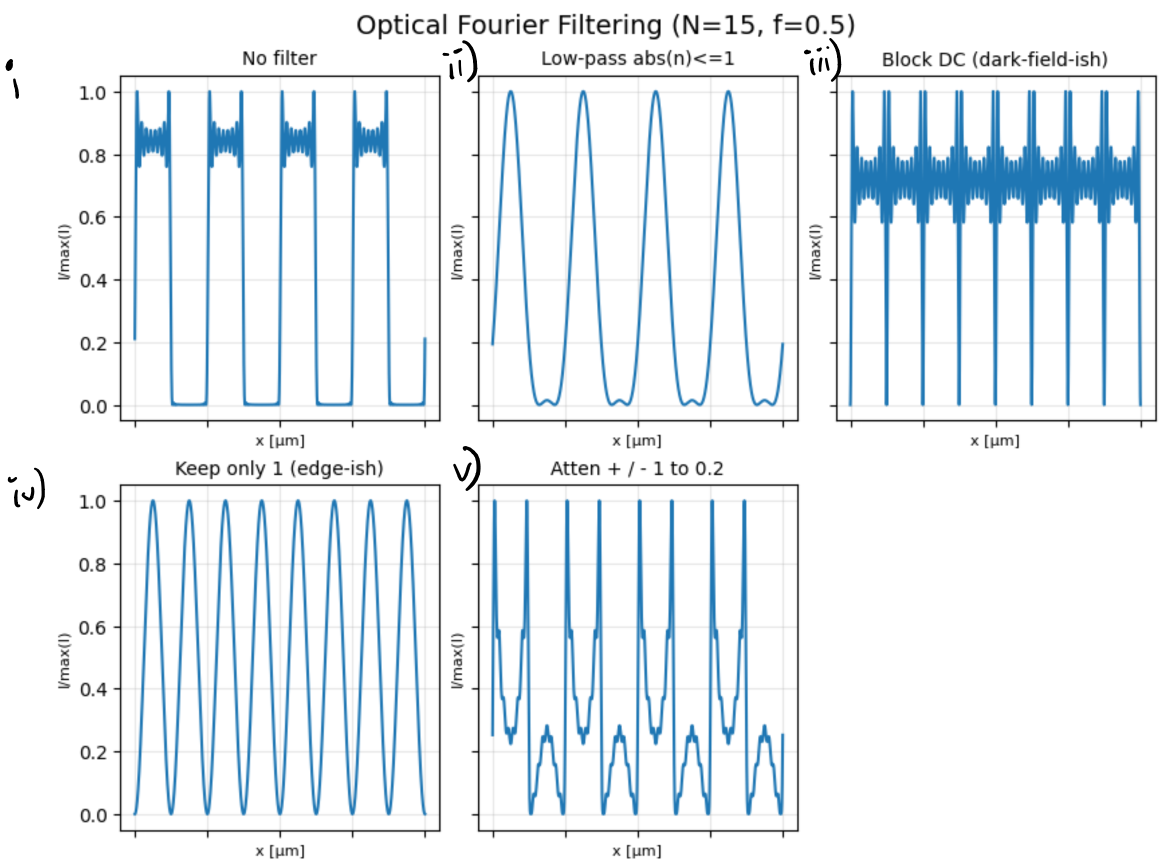

Optical Fourier Filtering (N=15, f=0.5)
i
No filter
ii)
Low-pass abs(n)<=1
iii)
Block DC (dark-field-ish)
iv)
Keep only 1 (edge-ish)
v)
Atten + / - 1 to 0.2
I/max(I)
x [μm]
1.0
0.8
0.6
0.4
0.2
0.0

Figure i - v)

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

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 th real plane.
- Complete Lab Set up 1 and Testing

2. Apparatus

Optics / mounts

- Beam splitter
- 90° short optical rail + feet (leveled)
- 2 irises/apertures for alignment on 90° 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

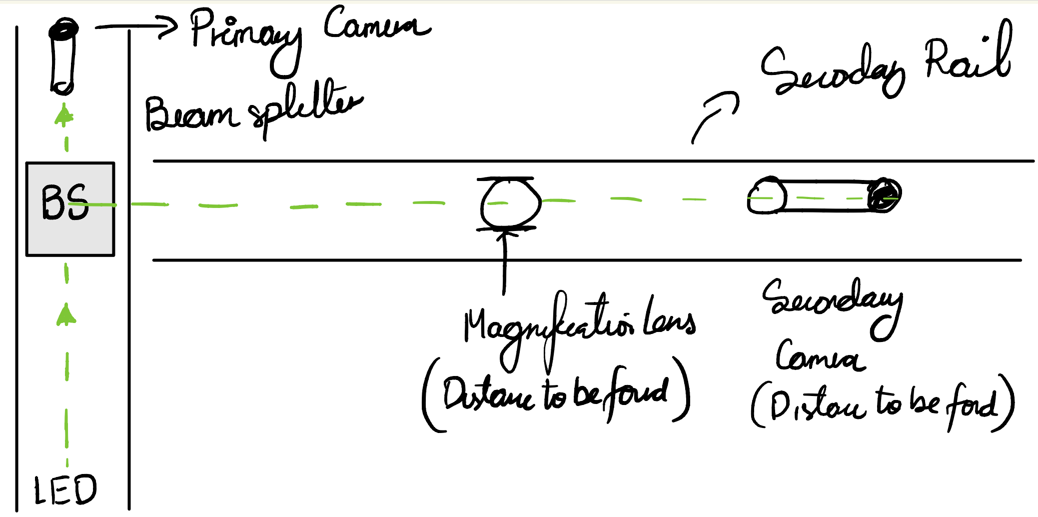
Tools

- 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 & Elements Setup

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) VerifiedBeam 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:

Issue:

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

45

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

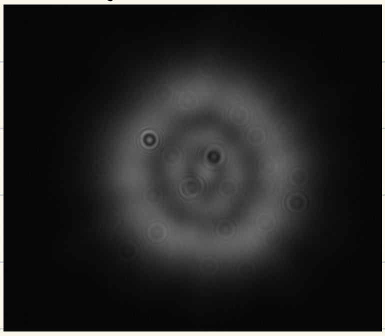


Image 1: Fourier Image Through a pin hole.

Check 2:20

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 foureir camera is on the trnaslational stage and added a Lense tube in front to block stray light from the room.

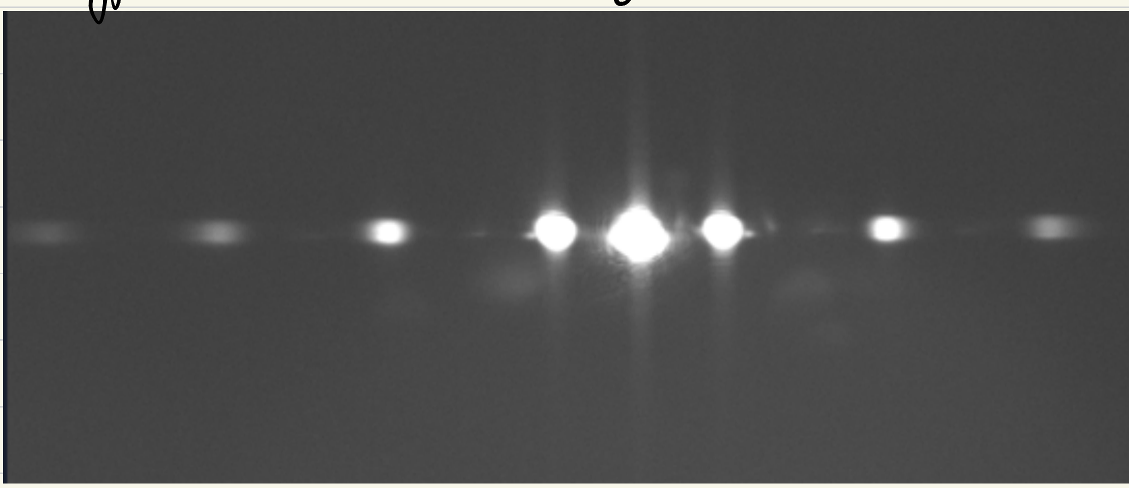
Imagine the Fourier plane onto the Fourier camera so that up to the 7th diffraction orders fit on the CCD for a 10 Lp/mm grating on the test object. ()

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: Diffation Pattern fron seconday rail Camera



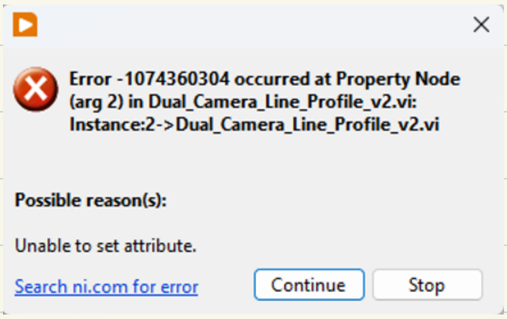
Issue: Can only see 4 diffraction orders, Thereis probably more as when we adjust the mirror horizontally, we can see more but. How do I make all of them visible?

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

Image 3: Screenshot of Error Message.



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.

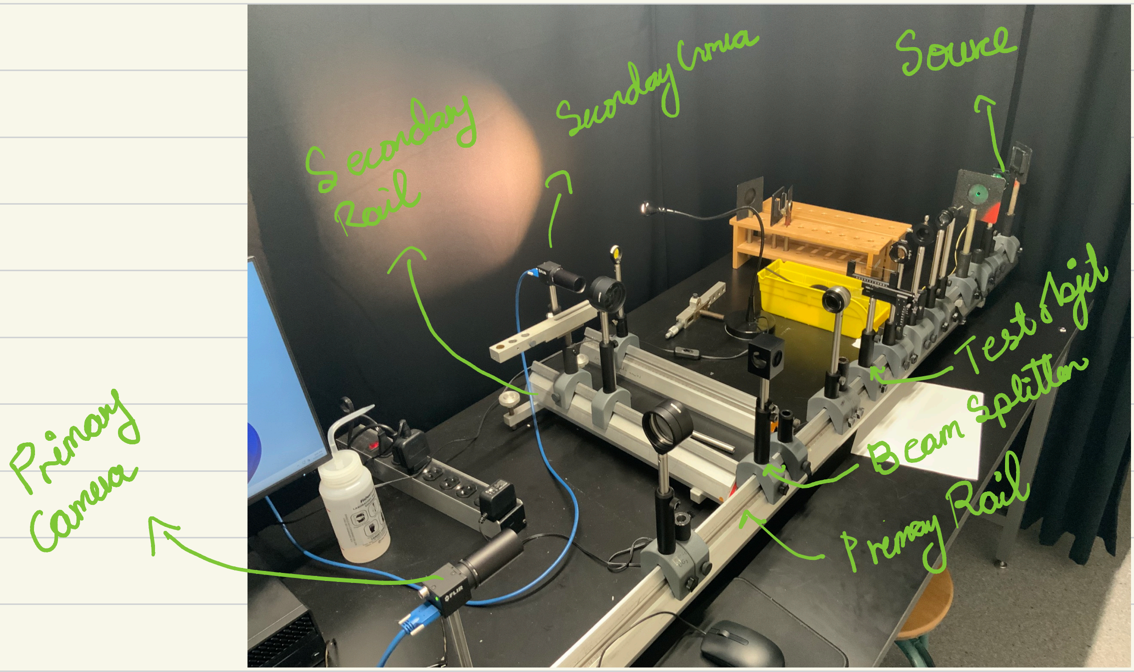


Image 4, Our Optics Setup

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-Setup-Screenshot.png"

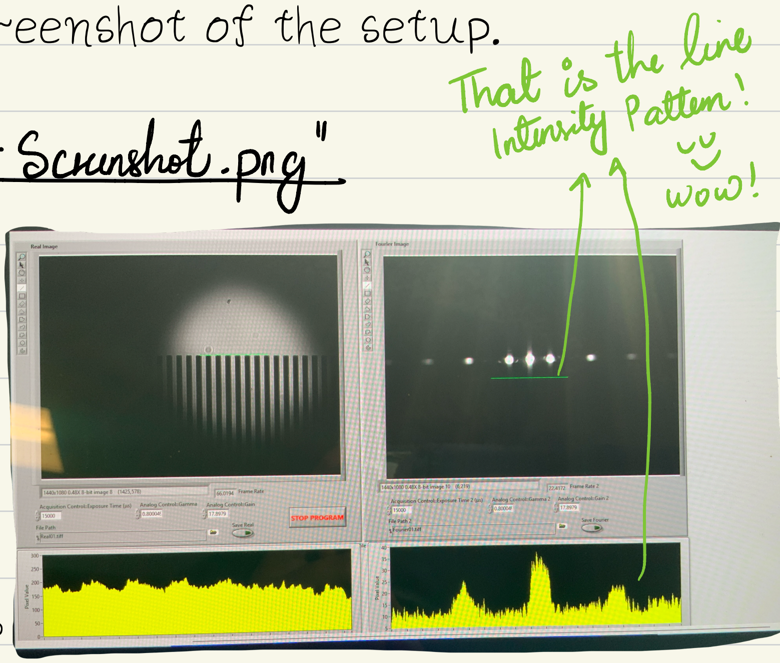


Image 5, Our LabView Setup

49

7. Testing

i) Test 1

New Approach to Note Taking:
Zach, our TA recomended only refering procedures from our sources (like lab Script) and writing only that is new and our personal notes:

This changes everything!
Ahilan kumaresan

Observe 3 things simultaneosly

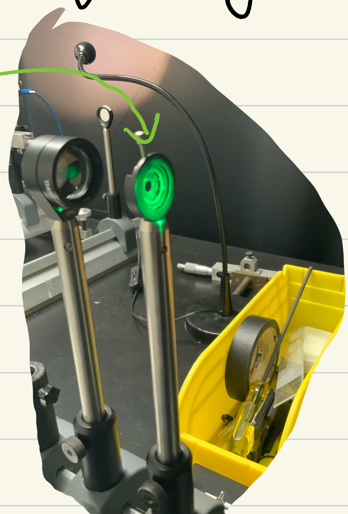
1. The fourier Camera image
2. The real-space image
3. With a card, the illuminated region on object

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

image6: Field Iris



Stored images in Session 4/Notes

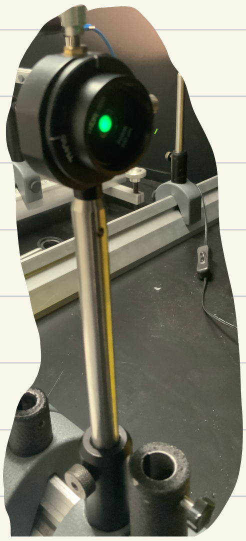
Saved 3 images of 3 different heurstic puplil size.

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

ii) Test 2

Test 2 procedure on (pg 36) of lab Script

Varying Aperture Stop using an iris at Aperture stop plane.



Appeture Stop (Pin hole)

Image 7:

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

↳ Marked the Zeroth order with a line

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

As usual make sure it is square & using a up stream pin hole it is centred.

4:06PM Facing an error because the new iris is not fully on the centre of the Screen.

Looking at the light travel, looks like the problem might be down stream too: Using a white card & another pinhole.

Trying to fix light travel, making it alligned to optical rail.

Put Back the pinhole & trouble shooting.

Resolved:

4:21PM Finally!! The issue was on (L3) Condensor lense

Adjusting Secondary Rail elements for centred line.

new centre (709, 620) pixel.

51

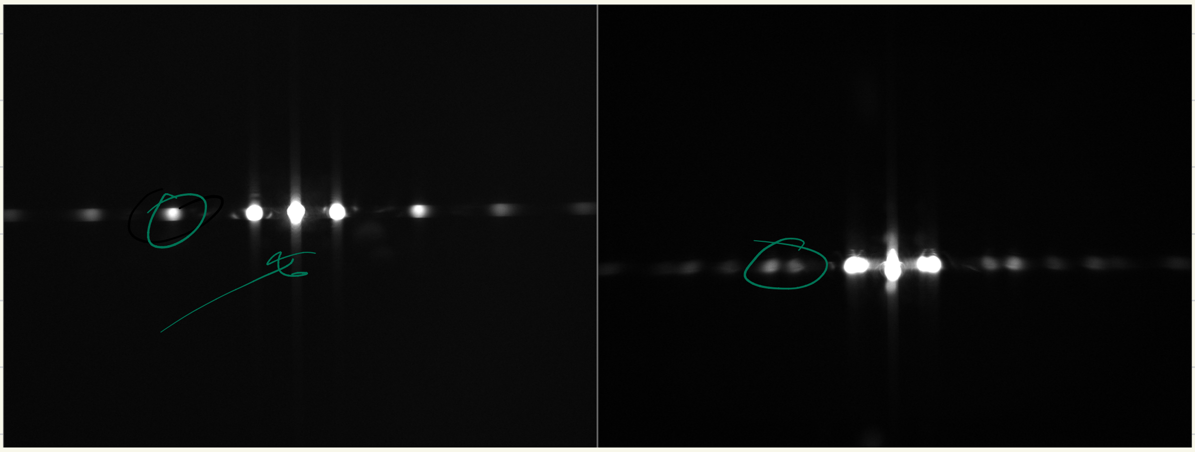
How ever something changed, its more tear drop shaped
Saved image in Session 4/ Notes

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 LabView Exposure Settings

How ever Some new errors popped up :



old diffraction pattern

New diffraction pattern

Probably this shows some unclean lens??

52

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 uplode it. Yes Done.

Goal4: 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 settng
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 & Improving diffraction Image Resolution)

Date: 22-Jan-2026 Lab Partner: Nathan Unhu

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 forrier 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;

iii) Slit intuition (classic example)

- A wide slit ;(smooth spatial variation) $\longrightarrow$ narrow diffraction pattern
- A narrow slit ;(sharp spatial confinement) $\longrightarrow$ wide diffraction pattern

This is the same reason:

- Fine details $\longrightarrow$ large angles
- Coarse features $\longrightarrow$ 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 foe 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 oarts of the elemtns.

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

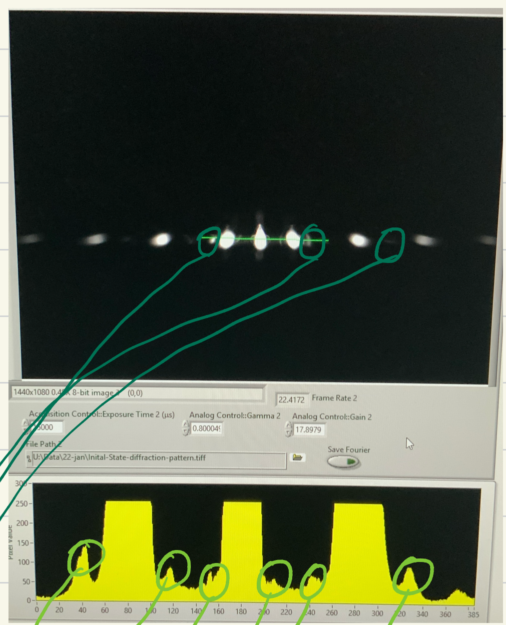
Looking at the current state, maybe this issue isnt too bad. The internsity patterm definetly show multiple values. But Maybe this isnt too bad ???

Saved as initial-state - diffraction pattern.tiff

Observation

I can say that because there is both more dots on the fourier image but also, the intensity pattern reveal multiple smaller peaks.
These are not diffraction orders.

Image 1: Initial State Screenshot



Clearly There are multiple reflections

1:42PM

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 labscript (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.

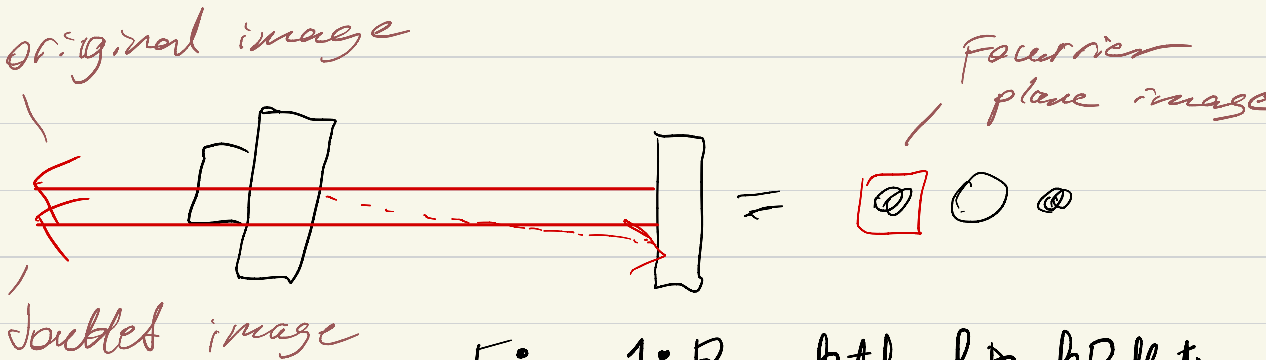


Figure 1: Ray sketch of Back Reflection

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 Session5/Notes

Observation

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

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

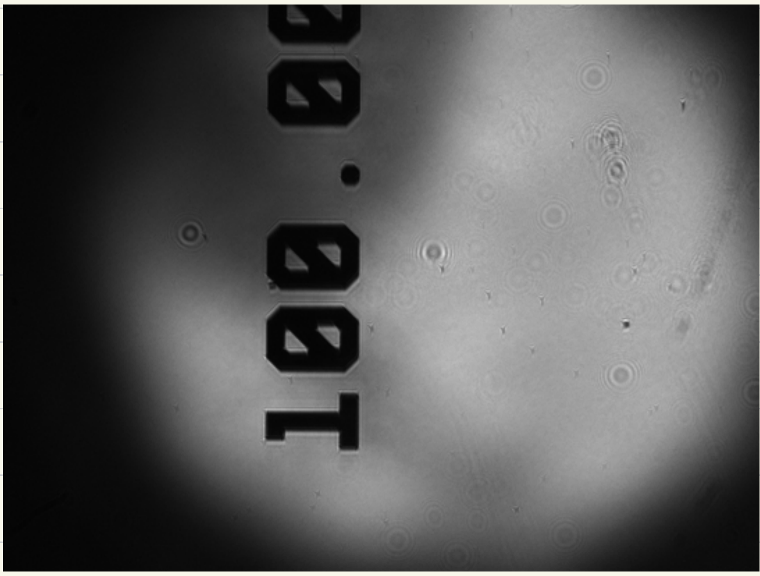


Image 2 : Fresnel Frindges on Image

Tip

When trying to focus & eleminate fresnel frindges try to focus on a small defect on the test object & make it sharp.

iii) Continuing with Test 2 again

- added the aperature stop before the forrier plane splitter, closing the aperature 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 aperature in its place. This changed the brightness of the image without changing the illumination area much.
- Moved the small iris back towar da the LED source and make the image edges sharper
- Saved Image: Correct-iris-position.tiff

Image3:
· Corrected sharp real Image after correcting iris

Compared to our previous images the edges are way sharper!

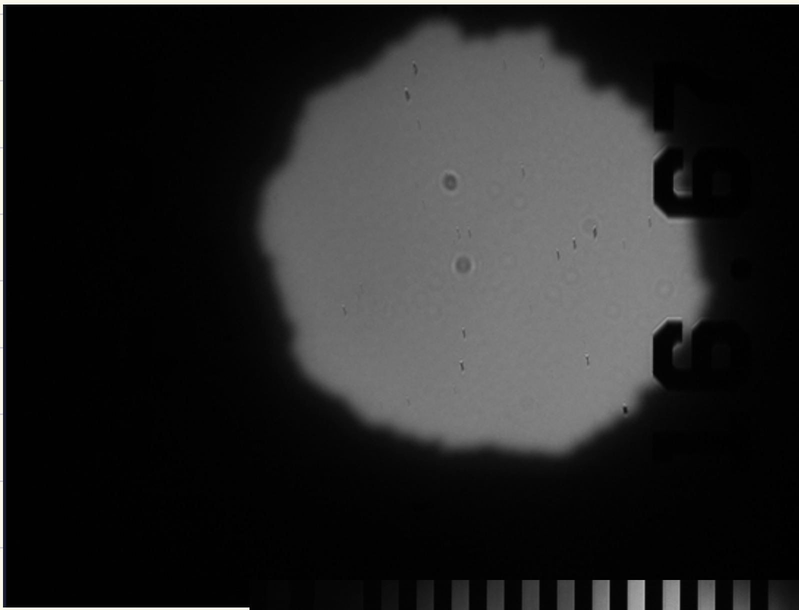


Image4: Showing an example of a defect on grating we focused on

- 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 +-35nm)
Recorded images of 12 and 16.67 l/mm. Spacing between 16 (0th -> 1st order) is 202 pixels. Spacing for 12 is 132 pixels
(space below for calculation of magnification level)

$$\theta_1 = \sin^{-1}\left(\frac{\lambda}{d}\right) = \left(\frac{525 \cdot 10^{-9}}{\frac{1}{16.67 \cdot 1000}}\right)$$

$$= 0.501^\circ$$

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

$$f_{eff} = \frac{\Delta x}{\theta_1} = \frac{202\,\text{pxl} \cdot 3.45\,\mu m/\text{pxl}}{0.501^\circ}$$

$$= 139\,\mu m$$

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)

63

Second order ↑ 1st order Zeroth order ↑ first order

Image 5 :
26 lp/mm

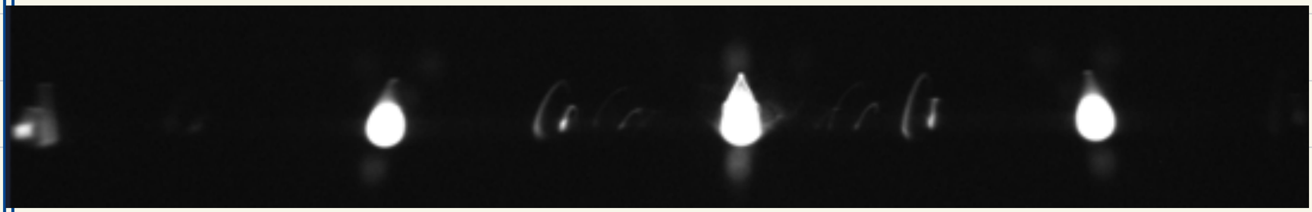


Image 6 :
50 lp/mm

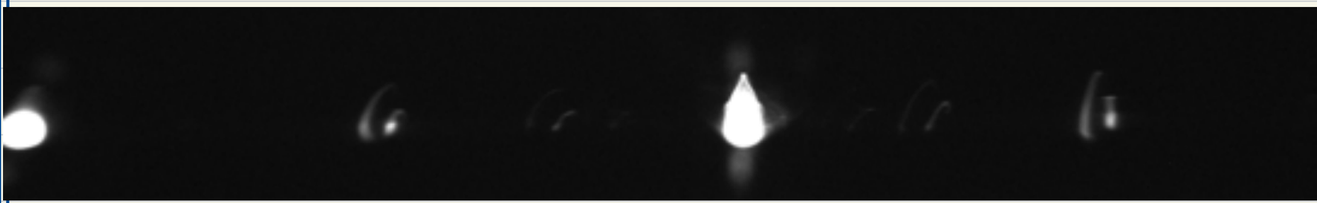
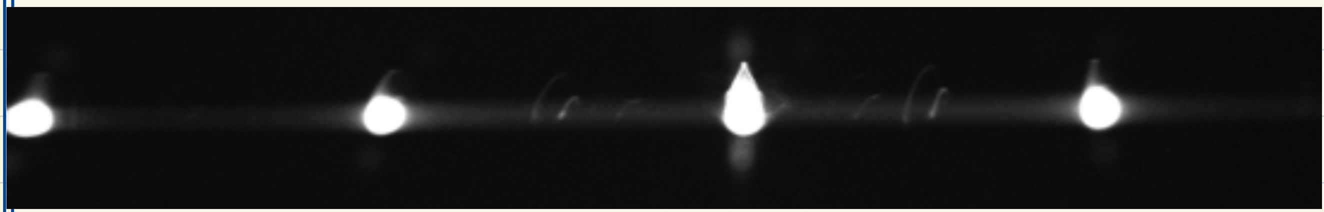


Image 7 :
26 and 50 lp/mm



All files Saved under Session 5/Notes

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

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 birght while the first order is relatively dim.

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

Success! : confirmed overlap between forrier 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.

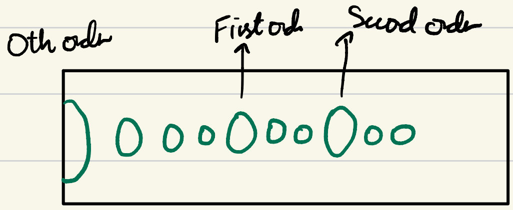


Figure 2: Fourier Image Idea

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

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.

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
θ_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).

65

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

~~Date: 27 January 2026~~
~~Lab Partner: Nathan Unrhu~~

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, ±1, ±2, ...) λ = wavelength = 525 nm d = grating period = 100 μm (for 10 lp/mm).
θ_1 = first order angle Δp_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

Observation: 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: 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.

Calibiate the Real image:

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

Pixel span $1150 - 602 = 548$ pixel for 10 period

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

With the Real space camea hang a pixel size $\Delta_{Pixel} = 3.45\,\mu m$.

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

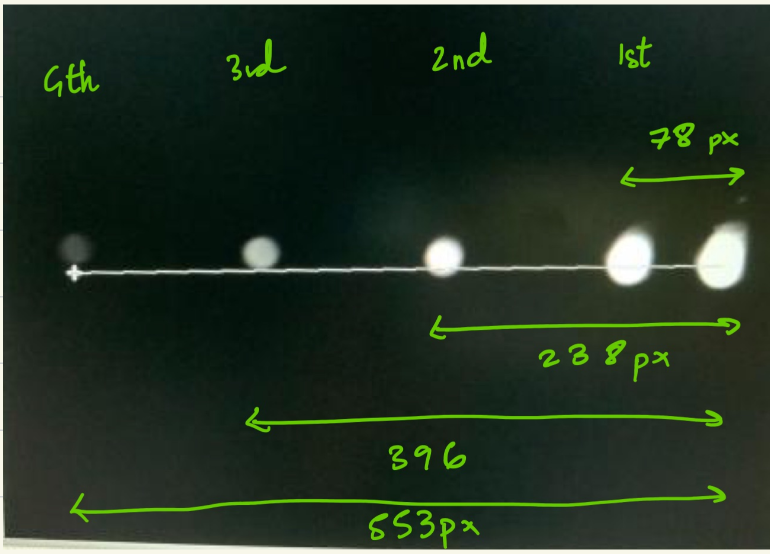
$$\text{Expected magnification} = \frac{f_5}{f_4} = \frac{300}{150} = 2.0\times$$

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

Calibration for fourier Image:

66 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 ($m = 2,4,6\ldots$) are suppressed becase :

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

Fourier Camera Callibration:

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

$$K_{cal} = \frac{\theta_1}{\Delta P_1} = \frac{5.25\,m}{78\,px} = 0.0673 \text{ mrad/pixel}$$

(For variable Definations go to Section 5

Order m	Measured (px)	Theory: m × 78 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 (~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 μm

⇒ Extracting Grating Period

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

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

$$a = \frac{\lambda f_{obj}}{\Delta x} = \frac{\lambda}{\theta_1} = \frac{525\,\text{nm}}{5.25\,\text{mrad}} = 100\,\mu\text{m}$$

B. Spatial Filtering

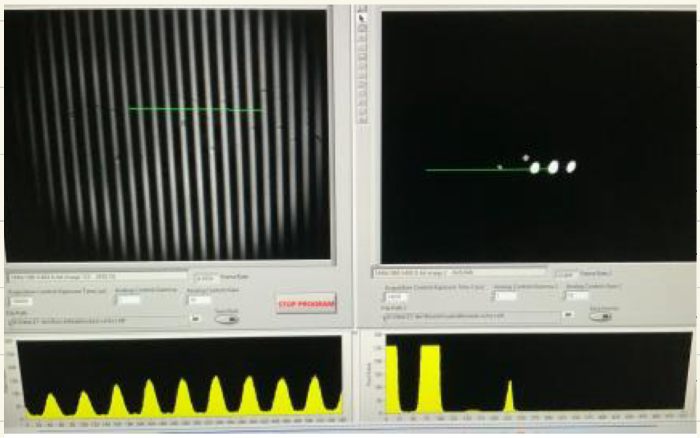
Following procedure on Lab Script pg. 41—43

- 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: Defualt-and-blocked-ve1to1.tiff

Images below.

a) Default - blocked half



b) Normal

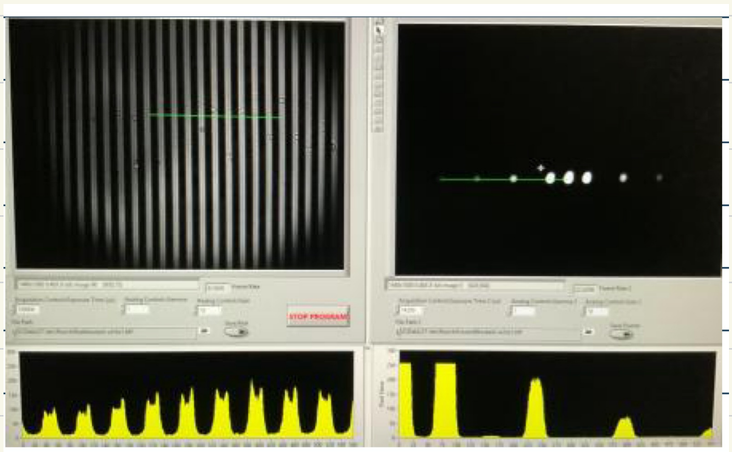


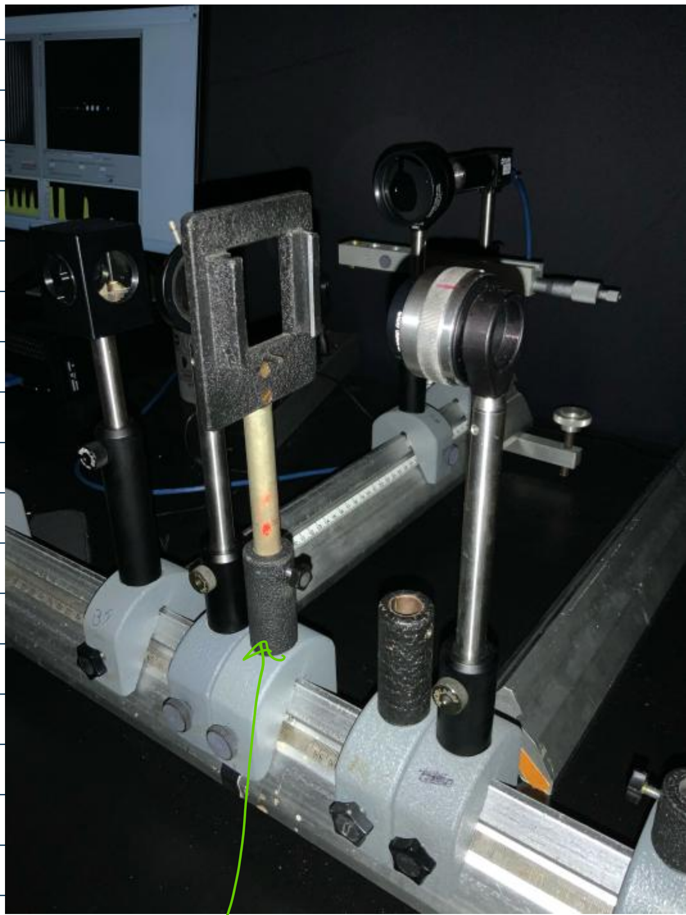
Figure 6.2: LabViewScreenshots_ a & b

At (

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 fourier Mask



Placing the fourier mask after the condenser lense. at the fourier plane

Case (a) All orders (reference case)

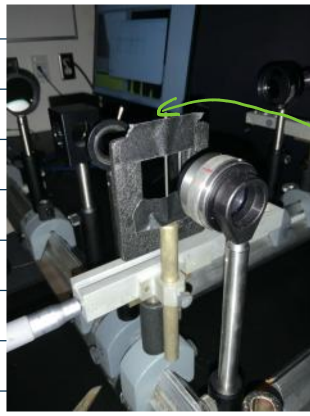


Fig6.4a): Allen Key mask

Saved Images as "RonchiReal-A.tiff"
"RonchiFourier-A.tiff"
Default image. Looks bright and the real image is all well illuminated

We accidently increased the Iris so new images as

Saved Images as "RonchiReal-A2.tiff"
"RonchiFourier-A2.tiff"

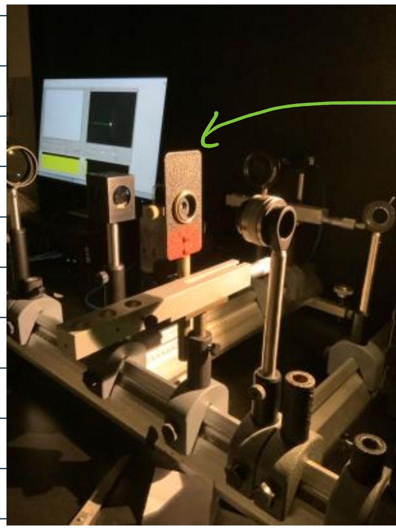


Fig 6.4 b) Iris Mask

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.

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:

$$E(x) = C_0 + C_1 e^{ik_0 x} = \frac{1}{2} + \frac{1}{\pi} e^{ik_0 x}$$

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 mmax
With symmetric ± 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 ± 1:

$$E(x) = \frac{1}{\pi}\left(e^{iK_0 x} + e^{-iK_0 x}\right) = \frac{2}{\pi} \cos(K_0 x$$

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

The intensity varies at frequency 2k0, 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/= 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:

$$I(x) = \left| \sum_{m=0} C_m e^{imK_0 x} \right|^2 = \left| f(x) - C_0 \right|^2$$

For a square wave, this enhances edges while suppressing uniform regions. However, for a wellfocused
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 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 = ±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	$a/2$	**Frequency doubling** — 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

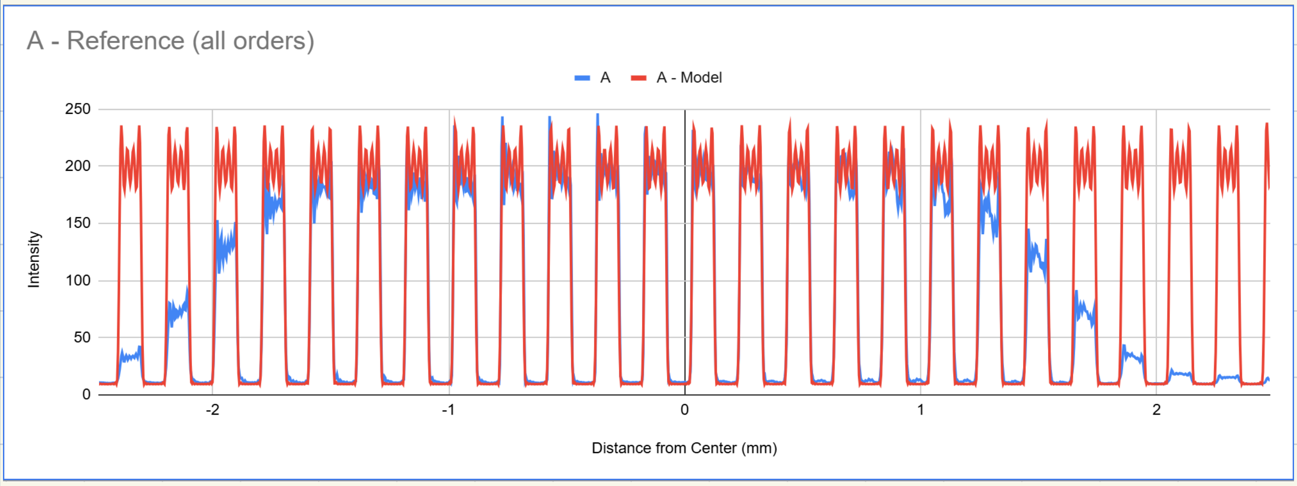


Figure A.1: Case (a) — All Orders (Reference)

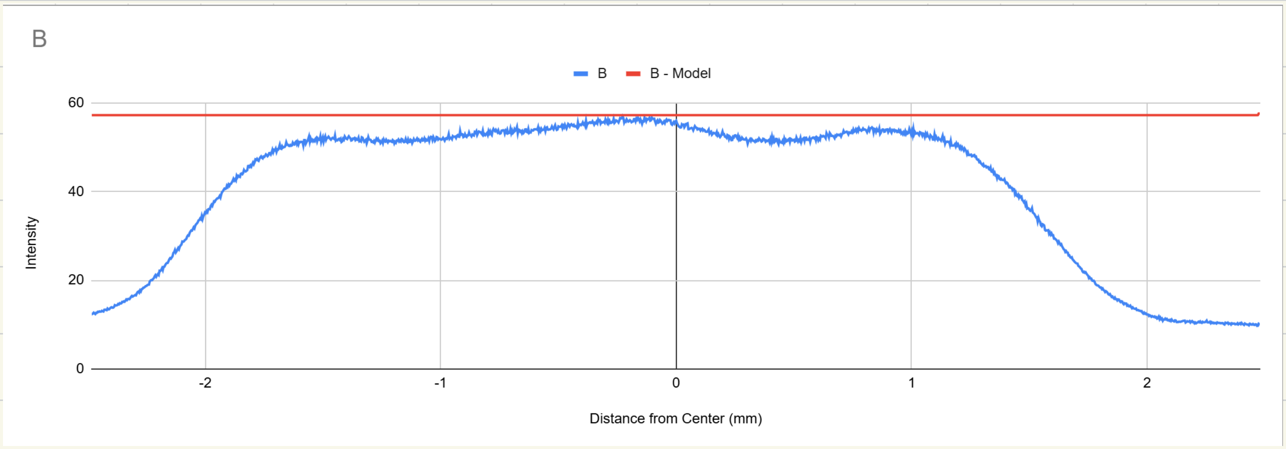


Figure A.2: Case (b) — Zero Order Only

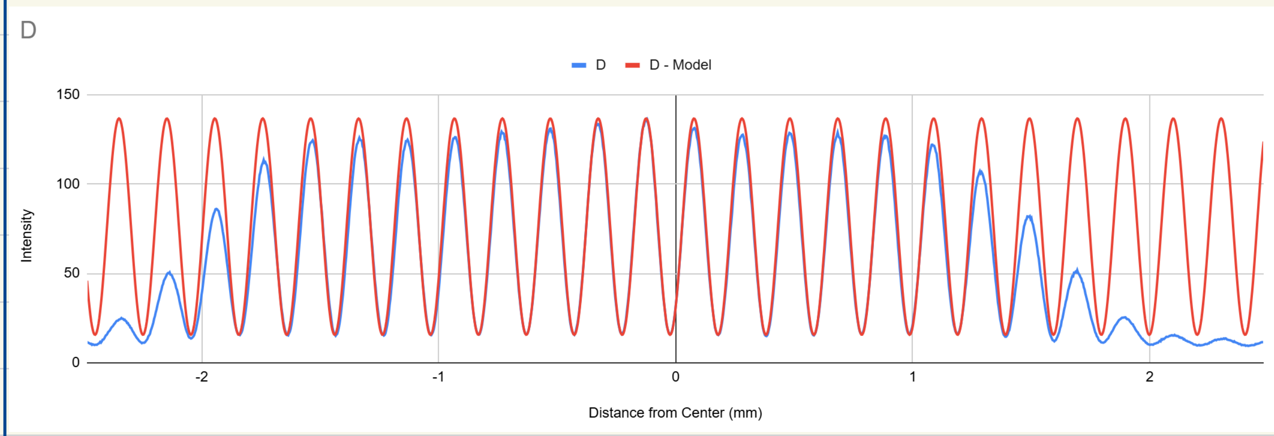


Figure A.3: Case (d) — Abbe Minimal Criterion

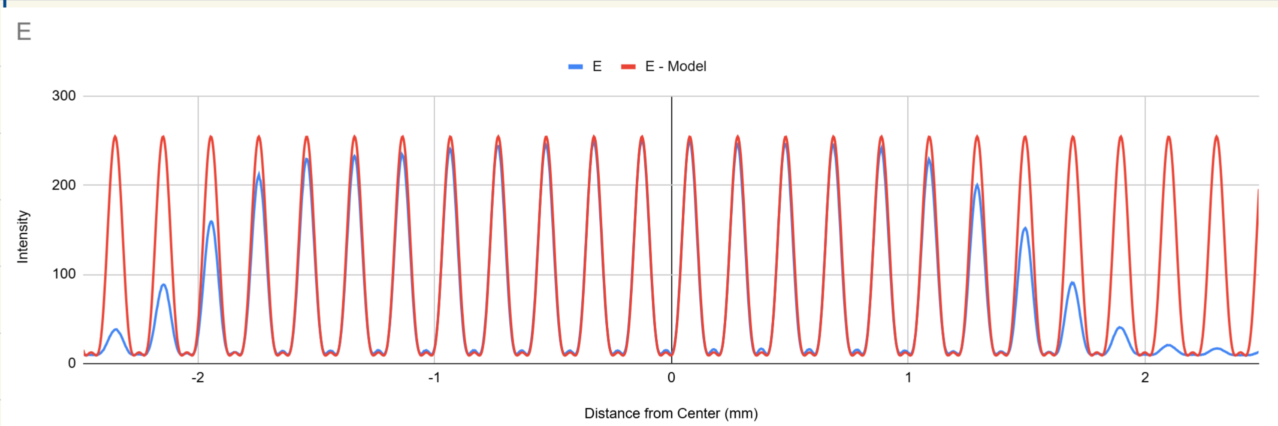


Figure A.4: Case (e) — Orders -1, 0, +1

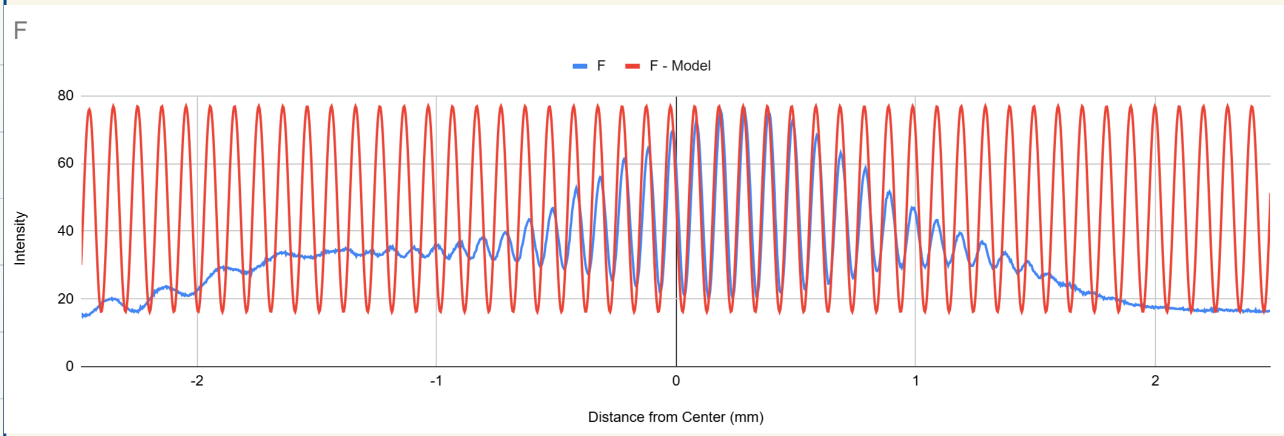


Figure A.5: Case (f) — Frequency Doubling

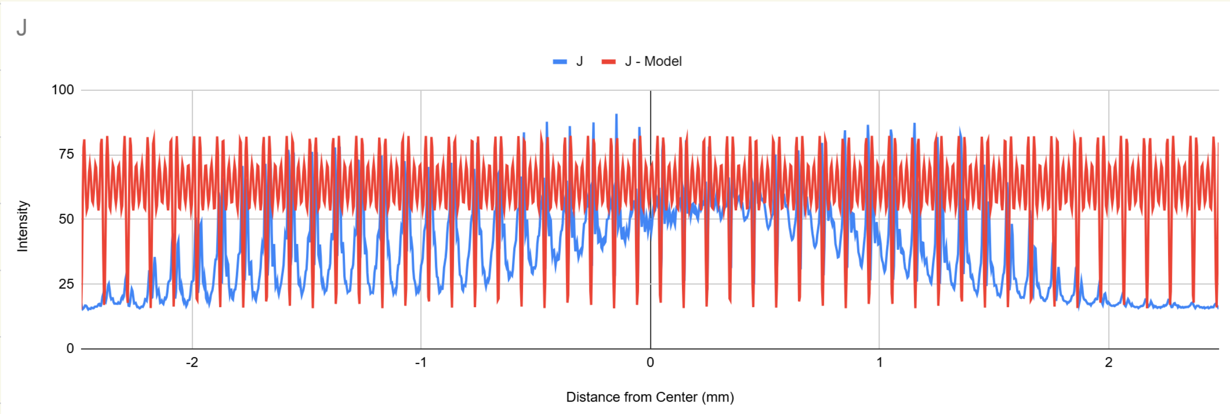


Figure A.6: Case (j) — Dark Field

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

77

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 ±1 required to resolve periodicity

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

7. Discussion

i) Abbe Minimal Criterion

Case (d) demonstrates that transmitting orders 0 and +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 ±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 → 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 ±1 produces apparent frequency doubling. This occurs because:

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

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 ± 35 nm	Systematic
Bandpass filter	515 ± 5 nm	Systematic
Pixel position	±2 px	Random
Grating period	100 ± 3 μm	Combined

Table 6.5 Uncertinity Sources for Calibration

The Dominant Uncertainty is probably the Pixel Position measurement (±2 px) contributes:

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

EFFECTIVE FOCAL LENGTH (from model fit): f = 202.2 ± 0.1 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

Uncertinity Propogation : from Calibration (pg. 67)

$\Delta p = 78.9$ px/order

$\theta_1 = 5.25$ mrad

$K_{cal} = 0.0673$ mrad/pixel

& $a = \frac{\lambda}{\theta_1} = \frac{525\,nm}{5.25\,mrad} = 100\,\mu m$

Propogation:

$$\frac{\sigma_\lambda}{\lambda} = \frac{5}{525} = 0.95\%$$

$$\frac{\sigma_{\Delta p}}{\Delta p} = \frac{2}{78.9} = 2.5\%$$

$$\frac{\sigma_a}{a} = \sqrt{0.0095^2 + 0.025^2} = 2.7\%$$

So $a = 100 \pm 3\,\mu m$ (1 sigma), Agrees with nominal value with uncertainty

Dominant uncertinity : Pixel position (±2 px) - Random

9. Reflection

1. Goals Status

✓ Compared diffraction pattern to theory — excellent agreement (2% discrepancy)

✓ Calibrated Ronchi ruling: $a = 100$ µm, $b/a = 0.5$ (confirmed by absent even orders)

✓ Established quantitative baseline: scale = 1.82 µm/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 ± 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 requirment of this lab (Collect Data and Analysie it), it makes sence to focus on a quantitive Project, I will proritize Project 4. Extended Source. Here we will investgate: 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 practacal, 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_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_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_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 $\lambda = 525$ nm grating period a = 100 µm, 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″ × 1″ on thick glass substrate)
a Birefringent Resolution Target (2″ × 2″ slide, Thorlabs R2L2S1B)

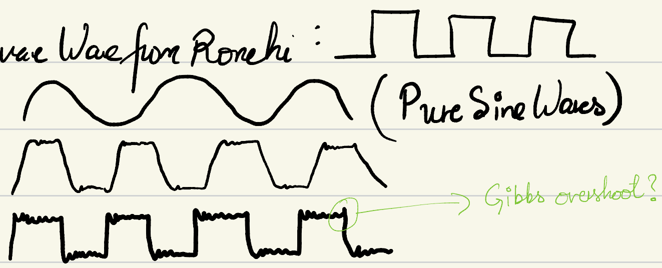
5. Additional Infromation

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. $m\_max = 1$ (ie, $-1, 0, 1$ Transmit) is just the fundamentals DC + low spatial frequency. $m\_max = 3$ (ie, $-3, -1, 0, 1, +3$) is fundamental & some mid or higher spatial frequency.

Original Square Wave from Ronchi :
m_max = 1 :
m_max = 3 :
m_max = 7 :



(No matter how many orders we add, some overshoot wont go)

Gibbs Phenomenon

When a Fourier series is truncated at finite m_max, the reconstructed function exhibits:

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

As m_max increases:

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

6.Bacground 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 μm, 200 μm, 300 μm (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 μm (small) -Most coherent, sharpest diffraction peaks, best resolution
200 μm -Intermediate
300 μm (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

87

Useful formulas

$$A_{c\text{-}th} \simeq \left(\frac{\lambda z}{d_{source}} \right)^2$$

distance to source

Source diameter

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

Angular width $\Delta\theta \simeq \dfrac{d_{source}}{f_{condenser}}$

Focal len

In pixel, $\Delta p \simeq \dfrac{d_{source} \cdot f_{Fourier}}{f_{condenser} \cdot \Delta\,\text{pixel}}$

Reyleigh Crit. $\delta x_{min} = \dfrac{0.61\,\lambda}{NA}$

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" × 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 μm or 200 μm pinhole (not 300 μm)

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)/ ObserveAsymmetric 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 ϕ: $\mathrm{Square}(x) = \Pi(x)$

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

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 μm (from Session 6 calibration):
m_max - Expected Ringing Period Λ_ring = a/m_max
1 -100 μm
3- 33.3 μm
5- 20 μm
7-14.3 μm

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, ±1, ±3, ±5, ±7...	23.4%	–
5	0, ±1, ±3, ±5	10.4%	P/10 ≈ 5.9px
3	0, ±1, ±3	11.7%	P/6 ≈ 9.6px

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 → 9% as mmax → ∞ (Gibbs phenomenon)
- Ringing period: Λ_ring ≈ P / (2·mmax)

KEY RESULT:
Overshoot persists at ALL finite mmax values. This is fundamental
to truncated Fourier series, not an experimental artifact.

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

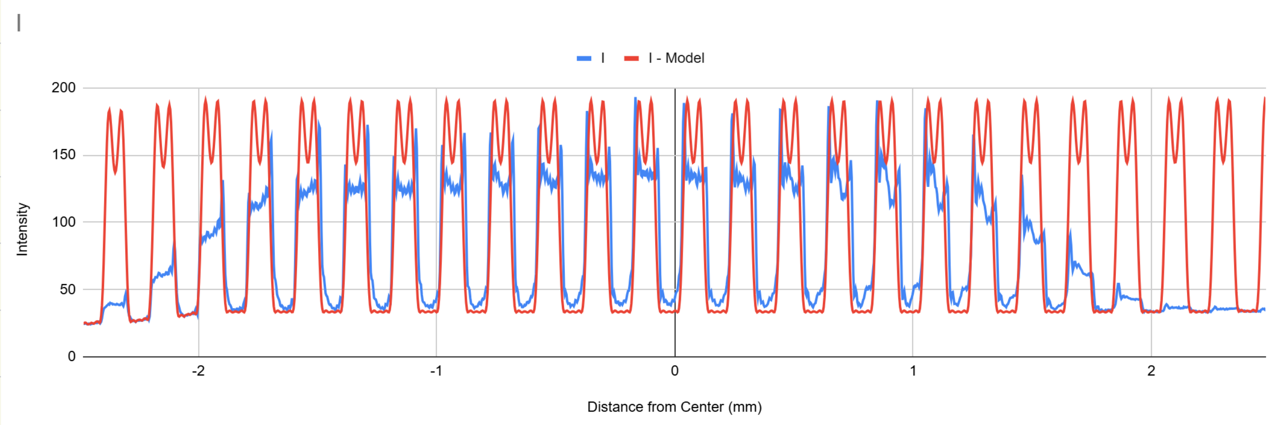


Figure 7.2: Case I — Reference (all visible orders transmitted)

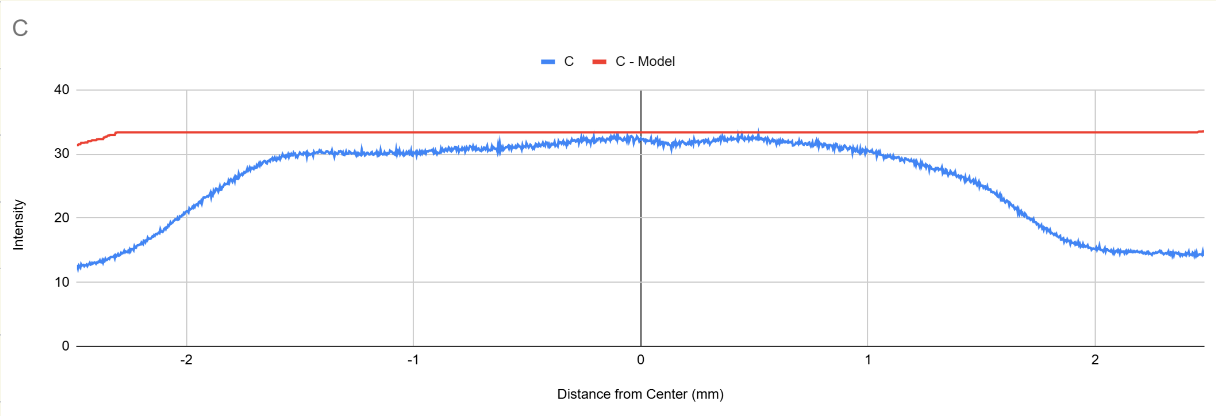


Figure 7.3: Case C — Zero Order Only (m = 0)
No spatial variation; flat profile confirms only DC component transmitted.

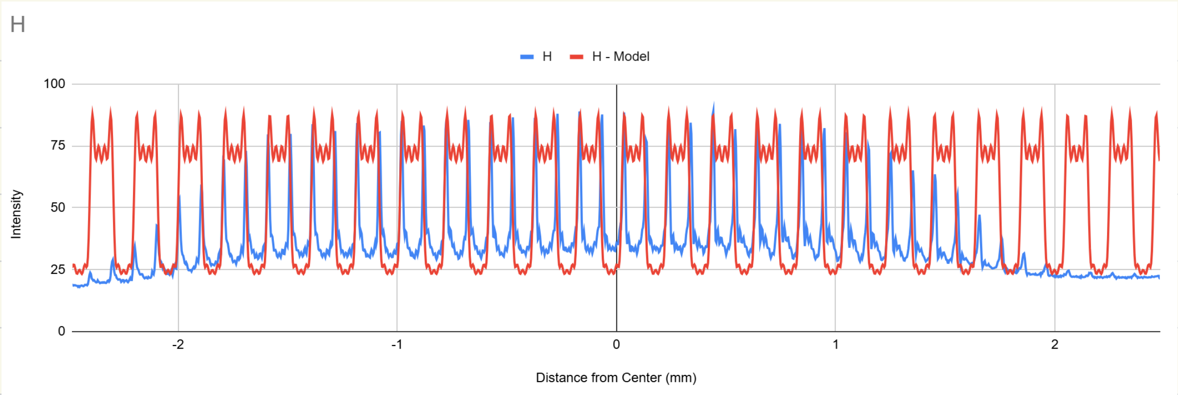


Figure 7.4: Case H — Orders 0, +1 (Abbe Minimal Criterion)
Sinusoidal modulation at fundamental frequency. Demonstrates minimum

93

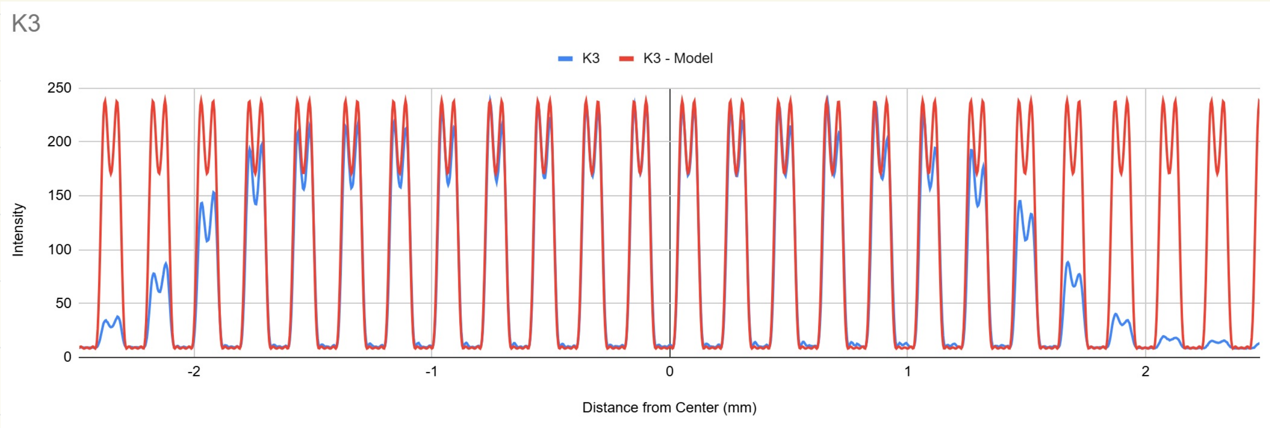


Figure 7.4: Case K-m3 (m_max = 3, orders 0, ±1, ±3)

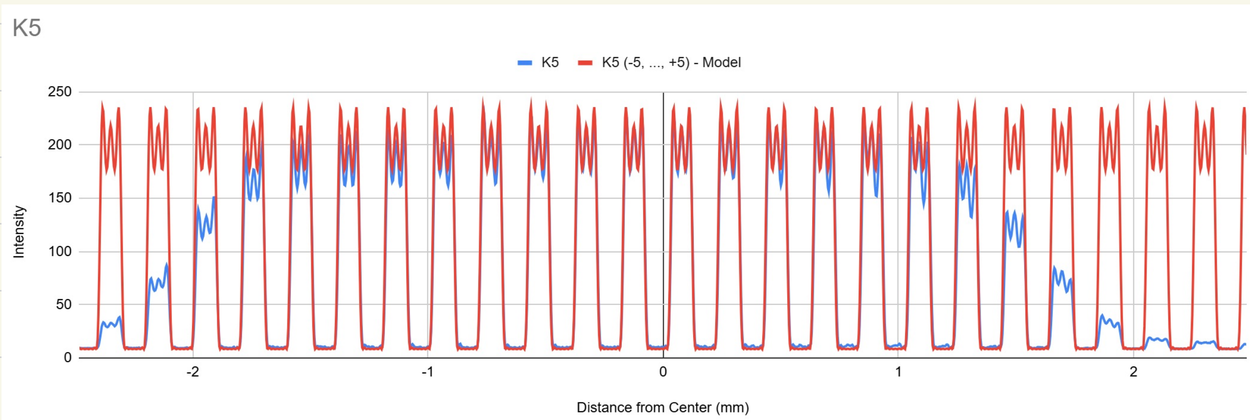


Figure 7.5: Case K-m5 (m_max = 5, orders 0, ±1, ±3,

m_max	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 ~9% (Gibbs phenomenon).

PHYSICAL INTERPRETATION

Gibbs Phenomenon:

- Truncating Fourier series at finite m_max causes overshoot near discontinuities (edges)
- Overshoot amplitude ≈ 9% regardless of m_max
- Ringing period $\Lambda\_ring = a/m\_max$ (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 $\Lambda\_ring = a/m\_max$
- Overshoot (~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″ × 1″ on thick glass substrate), or;
- a Birefringent Resolution Target (2″ × 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 lpmm 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;

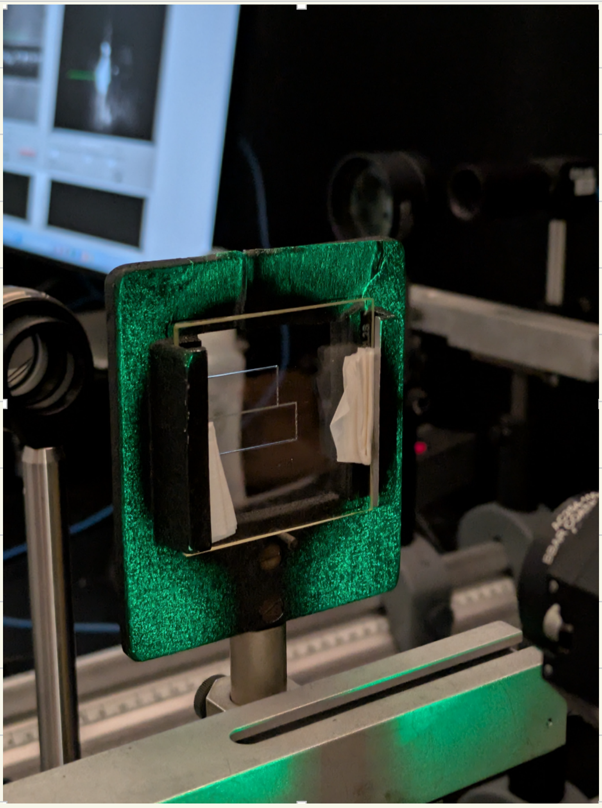


Figure 7.1: Thorlabs Target Birefringent.

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

Detailed Procedure

- For the first image, the settings for brightfield-A-Real/Fourier are:

Instructions (labs

i

- 3000, gamma 1, gain 18 (Fourier)
- 110000, gamma 1, gain 18 (Real)
- Files: BrightField-a-Real.tiff, BrightField-a-Fourier.tiff

Use the camera to observe the image formed

ei

- 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: Unchaned 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

Interpretation

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: $m = 0, +1, +2, +3, \ldots$
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 ($d\phi/dx$) 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	Asymmetric 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	λ/4 plate shifts zero order by 90°, converting phase → 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 → 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 ~1 period of data (~58.6 pixels)
- Region selected for best illumination uniformity
- Single-period approach justified by non-uniform illumination across full image

χ^2 INTERPRETATION:
- χ^2/DoF $\approx$ 1: Good fit
- χ^2/DoF $\gg$ 1: Poor fit or underestimated uncertainties
- χ^2/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

Main Figures

Main Tables

Boxed Conclusions

Session	Result	Page
1	Köhler illumination: $M_{\text{field}} = 2$, $D_{\text{FS}} = 2.5$ mm for 5 mm FOV	i
1	Sharp focus achieved with equipment square to optic axis	6
2	Resolved 12.5 lp/mm grating (exceeded 10 lp/mm goal)	11
2	Non-uniform illumination caused by L4/L5 lens orientation errors	14
3	Uniform illumination achieved after corrections	28
3	Measured magnification $M \approx 1.585$ (expected $M = 2$)	29
4	Dual-camera Fourier plane system operational	48
4	BS placed at 82 ± 0.05 cm; FL at 29 cm on secondary rail	44, 46
5	Image doubling resolved via condenser lens realignment	58
5	Effective focal length $f_{\text{eff}} = 139$ mm measured	61
5	Confirmed overlap of 26+50 lp/mm diffraction orders	63
6	Grating calibration: $a = 100 \pm 3\,\mu$m (10 lp/mm confirmed)	76
6	50% duty cycle confirmed (even orders suppressed)	67
6	Frequency doubling observed in Case (f): $m = \pm 1$ only	72
7	B3 Gibbs ringing: $\Lambda_{\text{ring}} = a/m_{\text{max}}$, overshoot $\sim$9%	89
7	Phase contrast BEST technique for imaging phase objects	94

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 $f_{\text{eff}} = 139$ 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 ($a = 100 \pm 3\,\mu$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,

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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6	Abbe criterion: Case D (126.6 units) vs Case B (47.2 units)	76
7	B3 Gibbs overshoot: 23.4%, 10.4±6%, 11.7±6% for $m_{\max} = 7, 5, 3$	91
7	Phase object: dark-field contrast = 0.84 (best technique)	101
7	χ^2/DoF: Case A = 1.533; Cases B/C ≈ 0.02 (model fits)	102
7	Fitted parameters: $\lambda = 525 \pm 86$ nm, $f = 202.2 \pm 0.1$ mm	79

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