(i)

lab 1 Session 1: SF

0. Prelab Q 1:

a) Given a 5 mm 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, $M_{\text{field stop} \to \text{object}} = f_{condenser} / f_{field} = 100mm / 50mm = \boxed{2}$

→ 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

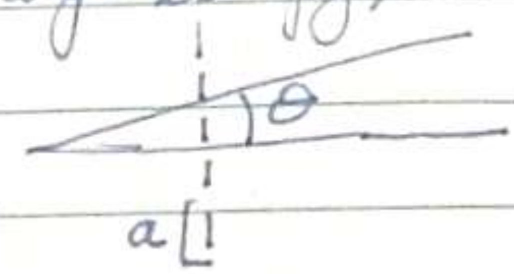
Then fine tune while watching object illumination

(ii)

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

⇒ For a grating of period a, the diffraction 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: $f_4 = 150\,mm = 0.15\,m$, $\lambda = 525\,nm = 525\times10^{-9}\,m$

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

$\therefore \Delta x = \frac{0.15\times525\times10^{-9}}{1\times10^{-4}} = 7.875\times10^{-4}\,m = 0.7875\,mm$

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: $FWHM_x \approx 1.03 \frac{\lambda f}{D_{pin\,hole}}$

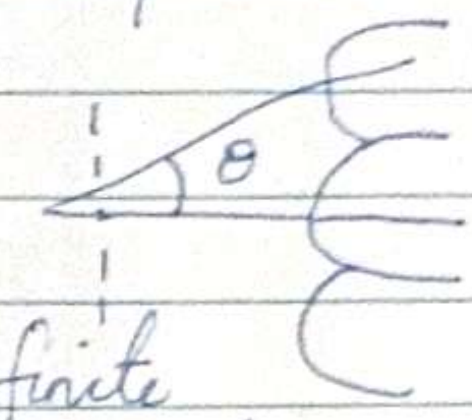
D_p

(iii)

c) Spectral Broadening of grating order

For a Ronchi ruling (transmission grating) with period d

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



If illumination is not monochromatic but has a finite spectral width FWHM $\Delta\lambda$ around central λ_0, then the same diffraction order m 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: $d\cos\theta_m \times \frac{\partial\theta_m}{\partial\lambda} = m$

$\therefore \frac{\partial\theta_m}{\partial\lambda} = \frac{m}{d\cos\theta_m}$ 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. Its 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. $\Delta\theta_0 \approx 1.03 \cdot \frac{\lambda_0}{a}$

from airy disk formula for circular aperture FWHM.

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

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

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

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

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

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

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

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

$$m = 1.78 \times \frac{525\times10^{-9} \times 200\times10^{-9}}{100\times10^{-9} \times 30\times10^{-9}} = 62.3$$

but should be more like 6.2 (extra zero) so 7the 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 lense for sharpings.
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 line exposure time, gain, –

2. Apparatus

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

Sources & Cameras:
↳ LED Source ($\lambda = 525$nm) (Bandwidth 25nm) 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

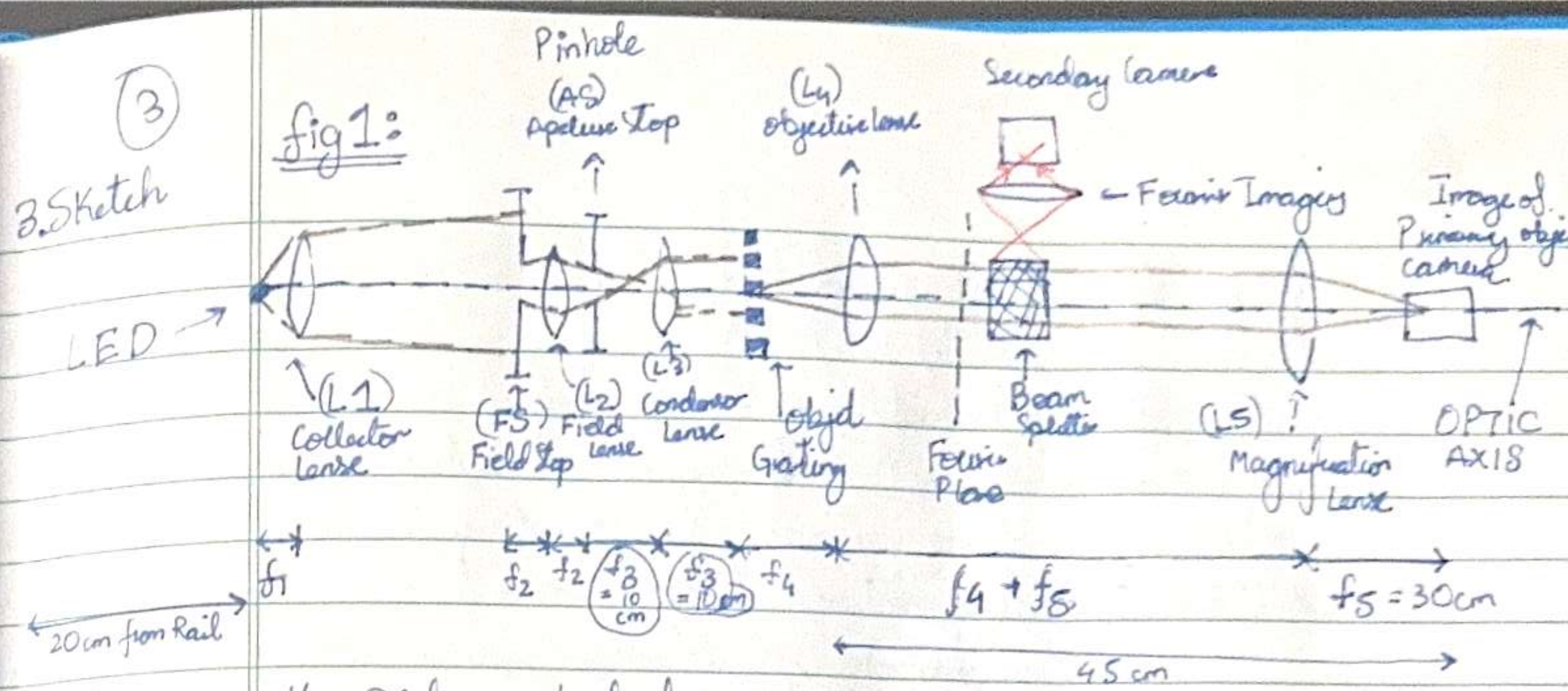
Test Object:
↳ Variable line grating (Thorlabs)!! Dont touch with Bare Hands!!

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. Find more

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

6. References:

* LabScript: PHYS 832 - Spatial filtering 2026, Jan 8 Edition

(4)

7. i) Some Useful Background Theory

* Kohler illumination Brief:
  ⇒ Field stop Controls illuminated area at object
  ⇒ Pinhole (Apperture Stop) controls angular extent / coherance 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 wave length

ii) Background on the Variables in the lab.

Independent variables (we change):
→ Pinhole diameter (aperture Stop) ↳ Condensor 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.

1.51 pm — Established the far end of the rail as the one near door to limit light from out doors 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 care to account for end of railing scale).

Quickcheck: Ensure 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 (Betwen Camera & Source). The lense is of 300m = f. Use 4" post

Move Curved part of magnification lens toward the Source.

The ∞ symbol on ~~lense~~ is away from camera. After making 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 ✓

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 Lab 2, focus remains on lab 1

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

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 inscripted 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.
1:57 PM 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, & The camera must be co-centric to the lense apperture

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 position of grating at best focus is 123.5 ± 0.05 cm
Exposure time 300 μs, Gamma = 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 Condensor lense using the X,Y Knobs.
Tip place a white card after the Condensor lens to 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 concentric.

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 centred at object & objective.
⇒ Recall field lense is 50mm = f, plano convex lense.

Replace pinhole & confirm LED image is focused onto pinhole

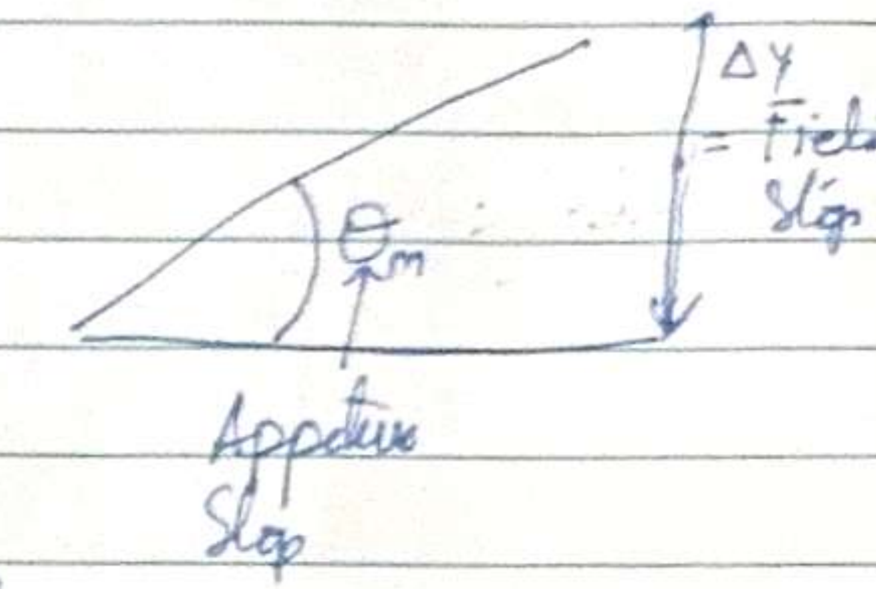
3.6 Place field Stop Iris

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 centred 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! When Iris is reduced to ~ 5mm illumination on the grating.
4:00 PM 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 repeated with dark room it remained.

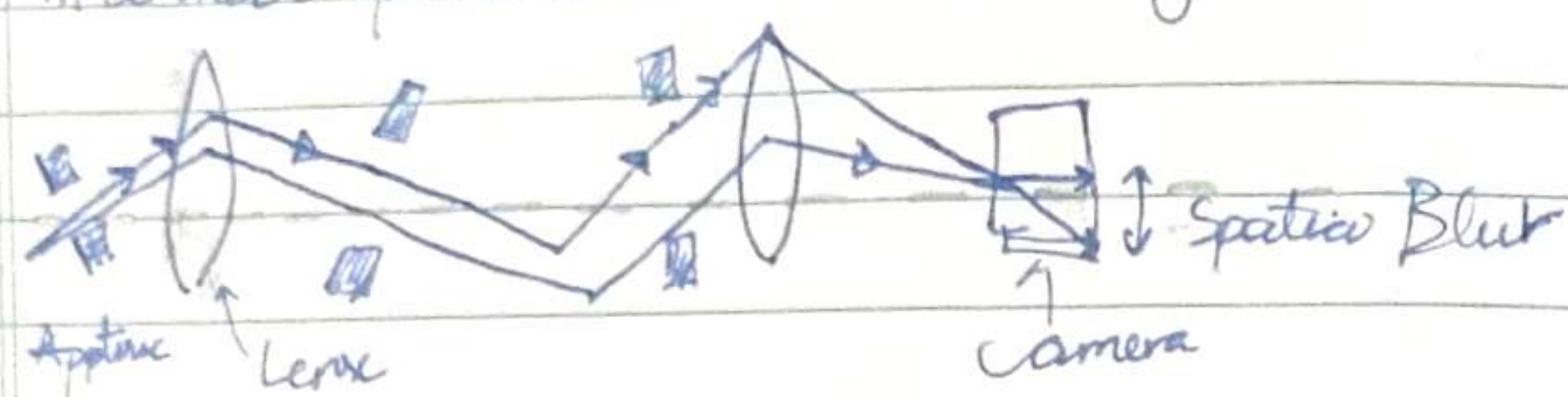
4:15 PM Proffessor Paul assisted us,
↳ We observed that even if we placed a white card after each element. We could see exactly where the non uniform illumination started.

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 →

4.2 Some Theory & Explanations of our Errors.

InCorrect placement Sketch (Rough & Inaccurate)

fig2:



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 Sources of errors:

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

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 apparent 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.

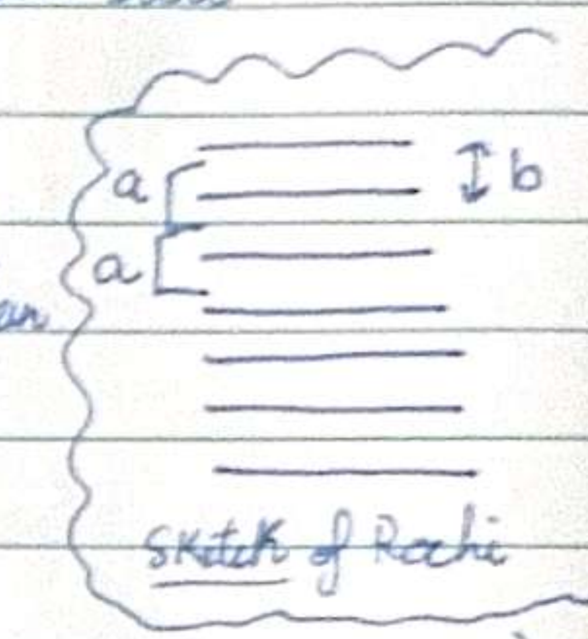
6. Goal Evaluation & what to do next lab

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

For logistical Reasons, the next lab would be the "Lab Period 2" even though 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 quite far away from the mask) $\theta_x \approx \sin\theta$ & $u = K\theta_x \approx K\sin\theta$

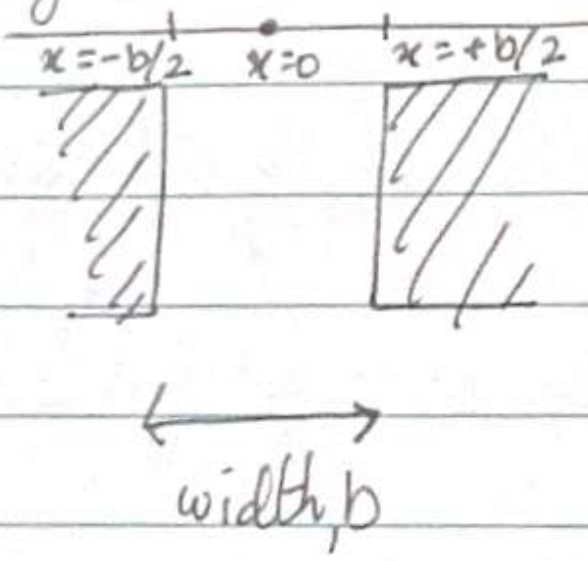
∴ $E(\theta) \propto \int_{-\infty}^{\infty} a(x')\, e^{iKx'\sin\theta}\, dx'$

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. ᵕ̈ 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 ᵕ̈

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

$$= \left[\frac{e^{-iKx\sin\theta}}{-iK\sin\theta}\right]_{-b/2}^{+b/2} = \frac{e^{-iK(+b/2)\sin\theta} - e^{+iK(+b/2)\sin\theta}}{(-iK\sin\theta)}$$

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

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

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

The Intensity or the Diffraction Pattern 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 finite The geometric sum Becomes, $= \frac{1 - e^{-iuNa}}{1 - e^{-iua}}$ (8.47 lipson)

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

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: $E(\theta) \propto \underset{\text{Single Slit}}{\frac{\sin\beta}{\beta}}\ \underset{\text{Repeating Slits}}{\frac{\sin(N\alpha)}{\sin(\alpha)}}$

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

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

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

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
```

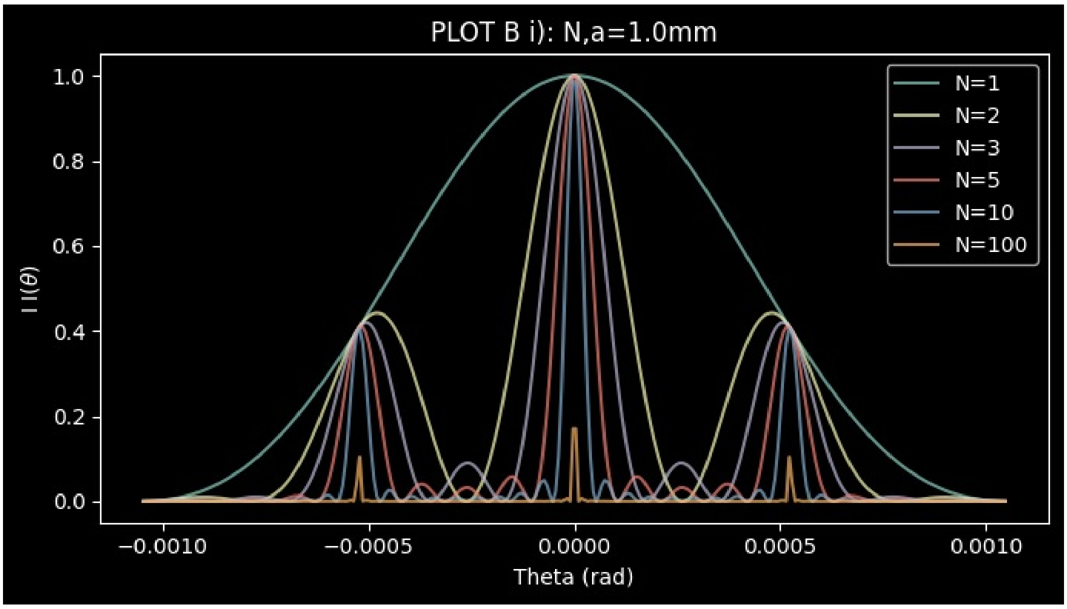
Note:

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

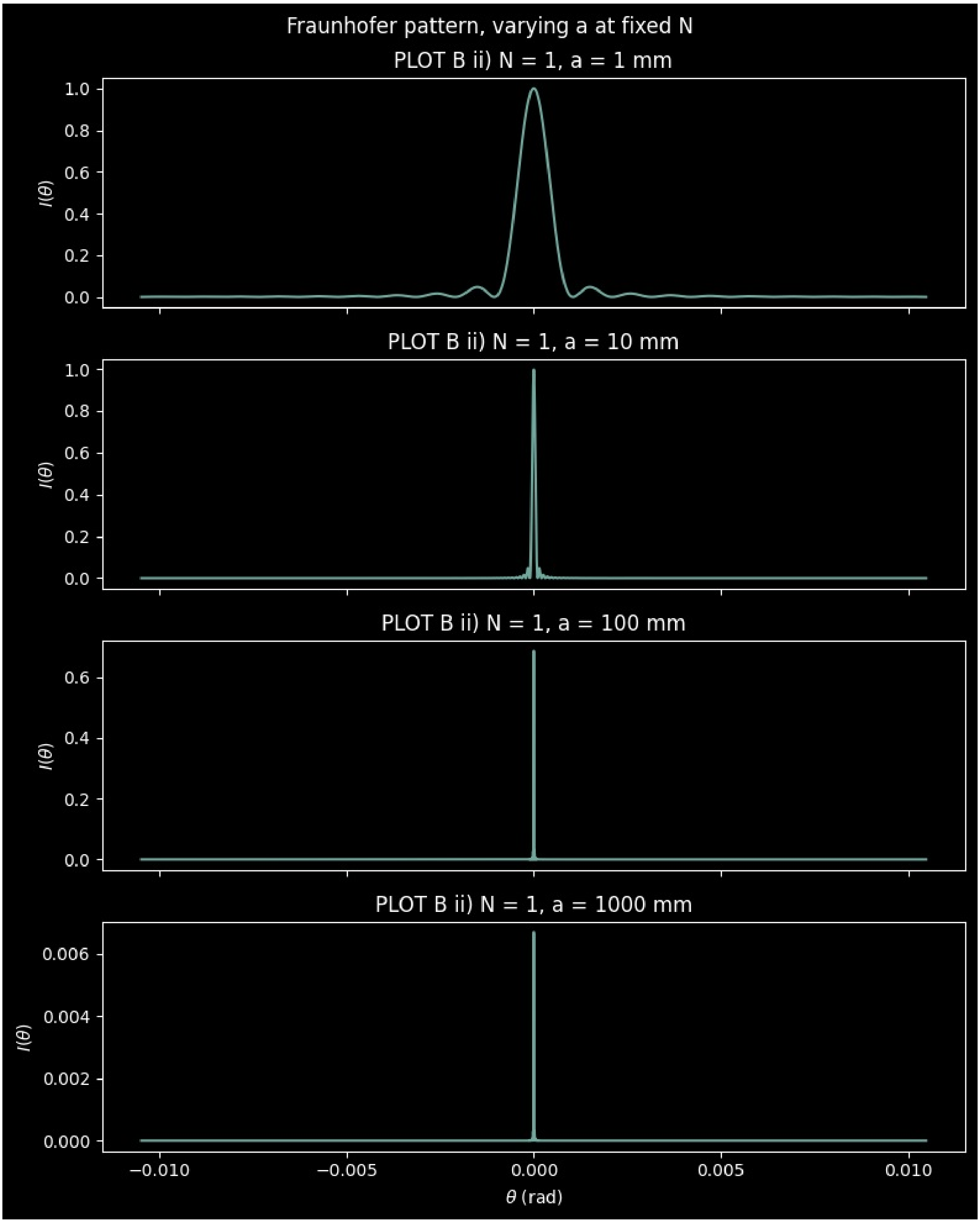
In [11]:
```
theta = np.linspace(-np.pi/3000,np.pi/3000,300)
N_lst = [1,2,3,5,10,100] # different numbers of slits
a_lst = [1,10,100,1000] # mm

# 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()
```

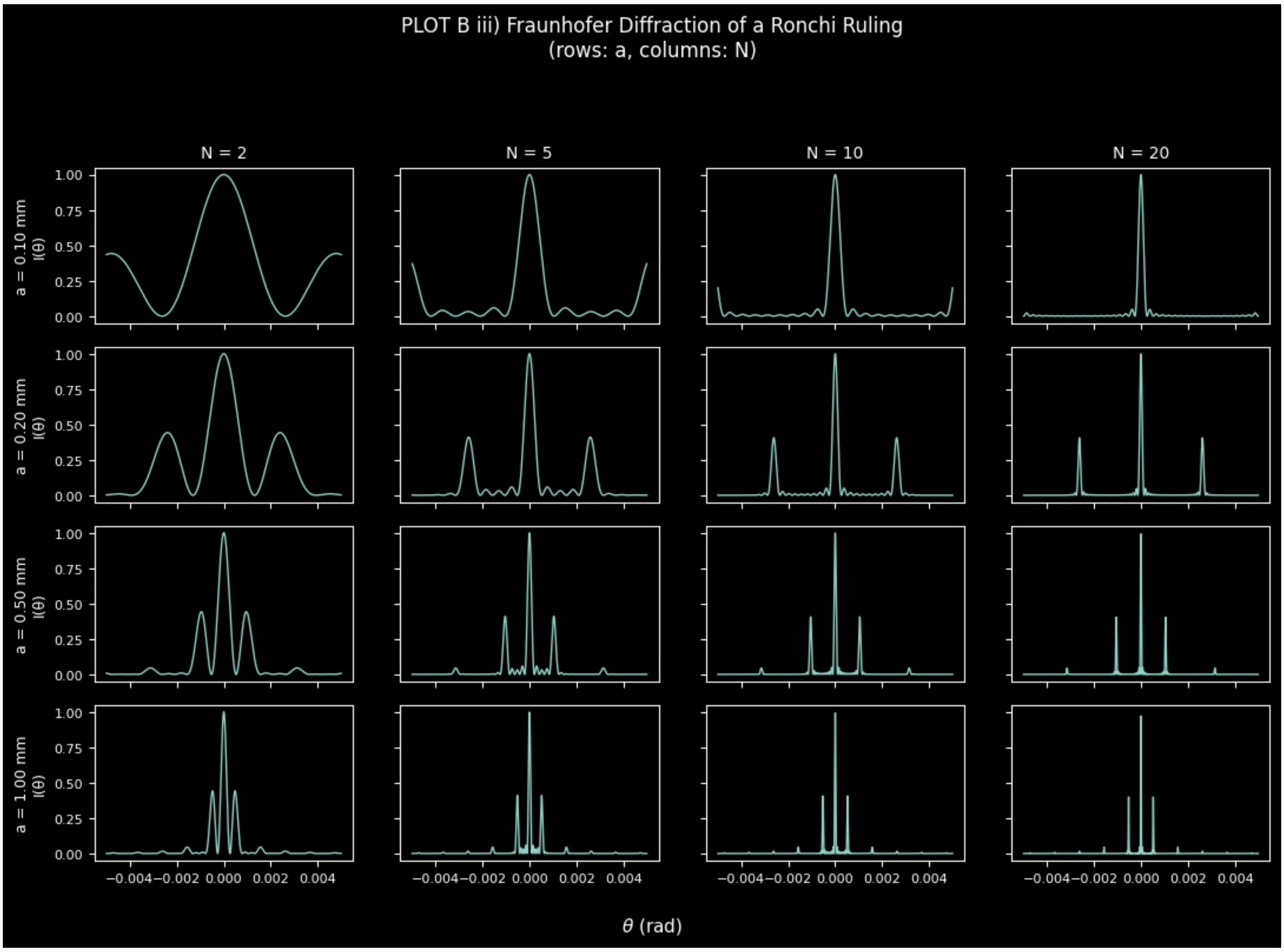
```
<Figure size 1600x800 with 0 Axes>
```



iii) Grid

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

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

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

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

Variables Defined:

- $\alpha = \frac{1}{2} ka \sin\theta$
- $\beta = \frac{1}{2} kb \sin\theta$
- $k = 2\pi/\lambda$
- $\lambda = 525$ 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

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

For i in range list N:

- plt.subplot(2, len(N), i)
- plt.plot(theta, I(argument)) include i & a[0]
  generat. form np.linspace)
- plt.Titel(f" N {i}

Ily 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).

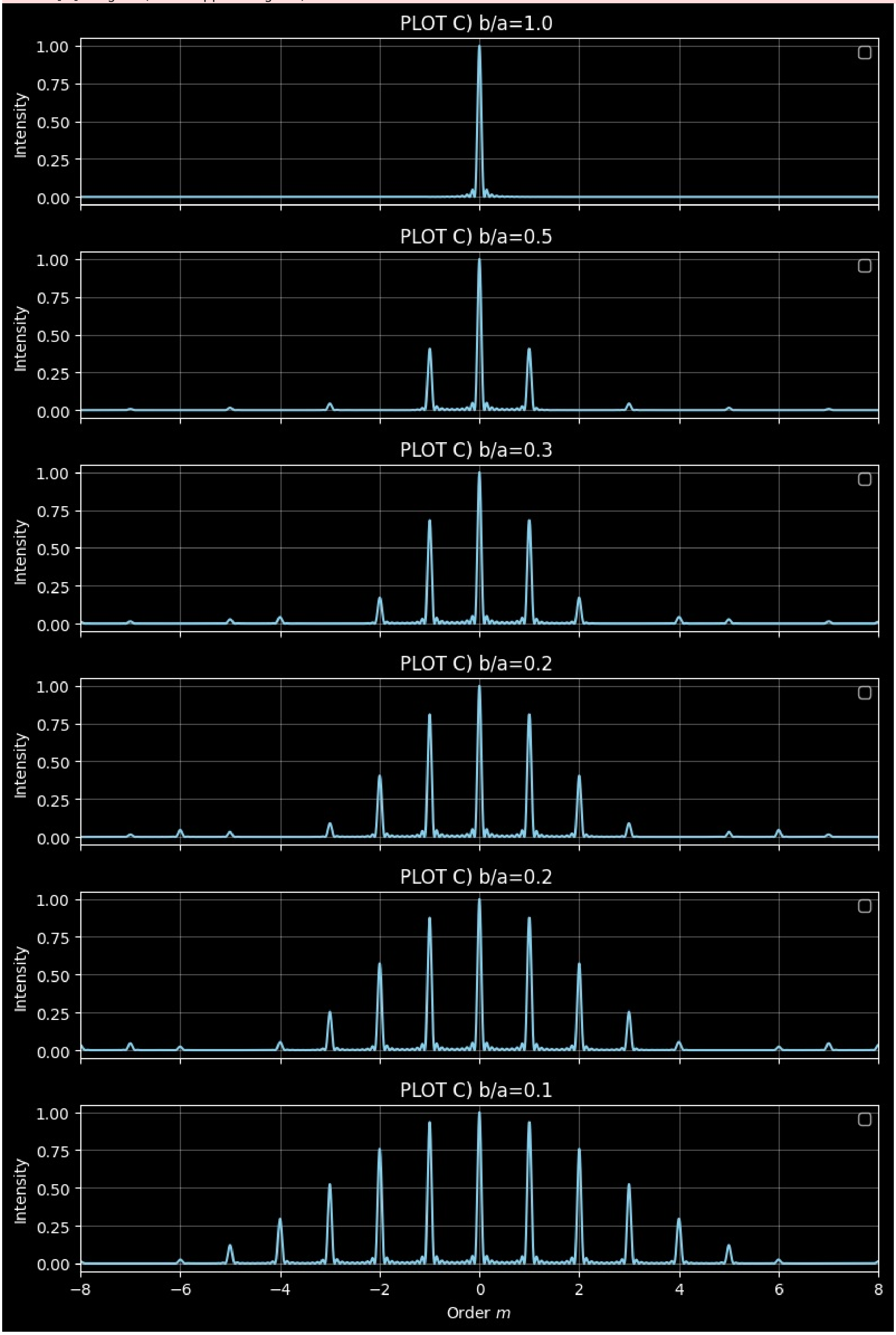
I will be Fixing the N at 5 and a=0.20mm

and Vary the duty, b/a

In [14]:

```
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')
```



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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.

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 in concentrated in higher order m's.

⇒ Suppressing orders.

When ever the numerator goes to Zero, the intensity of the order is suppressed.

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

$\therefore$ at $\frac{mb}{a} = n$ //

for the verification, $b/a = 1/2$ even

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

when even m's, ±2, ±4, ±6...

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

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

lly for verification, $b/a = 1/3$

when m's, ±3, ±6, ±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 indistinguable by eye, it still has a bandwidth of 25nm 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 broading & 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 isn't 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 configurations (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 10 lp/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, References

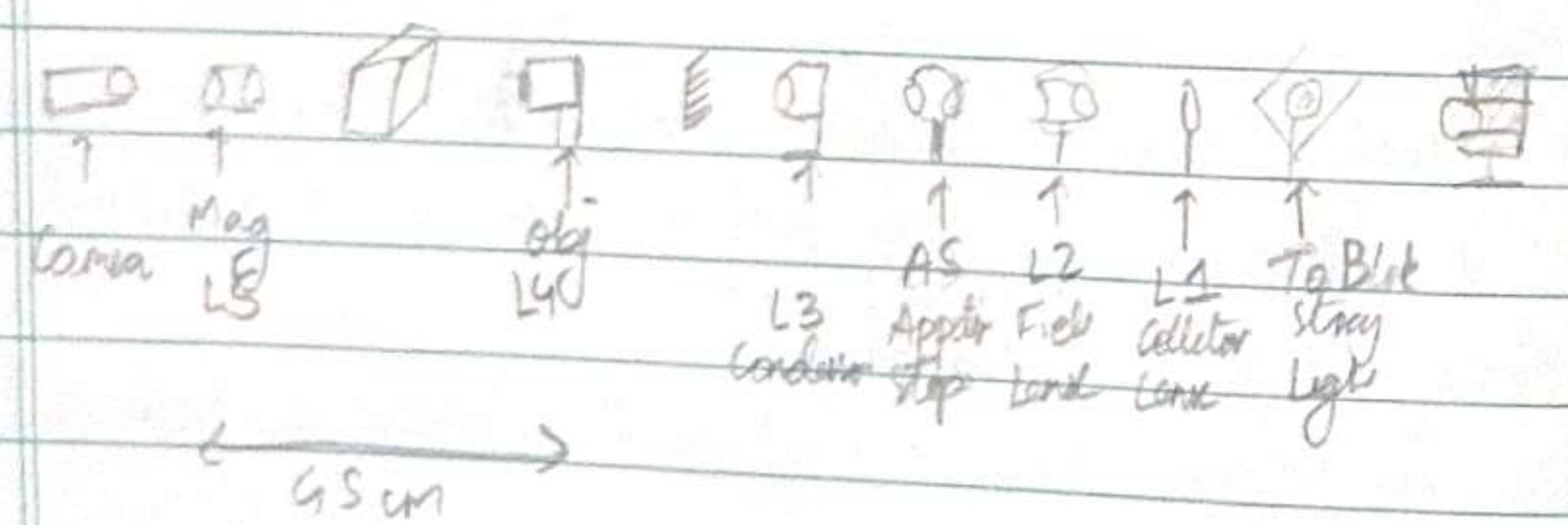
Refer once again to same as (pg 2-3)

i) Additional Apparatus to meet lab 3 :
* Ronchi Ruling * Camera: BFS-U3-16S2M-CS
* Adjustable iris (field stop) & pinhole at aperture stop (200 pm)
* Paper to wedge the saddle & correct the pin hole stage

ii) Additional References

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

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



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 working 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 or the condenser lense by unscrewing it.

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

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Allempt 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!

S. Testing the set up

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 and illuminate.

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Testing

Using the line tool on the Image Panel, we make a line over the diffraction pattern over a length of 1mm. 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 : $10 : 1\,mm$, $24 : x$

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

2.4 mm on object gis. (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: $M = \frac{f_{magnifier}}{f_{objective}} = \frac{300}{150} = 2$

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 $\approx 94 \pm 0.05$ cm (along rail)

Place a camera on this plane, & fine adjusted the base. This spot was on camera side after the L_4 lens 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

$\underbrace{390 \quad 674}_{284} \underbrace{\quad 953}_{279}$

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

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

This is distance between the central & the first maxima.

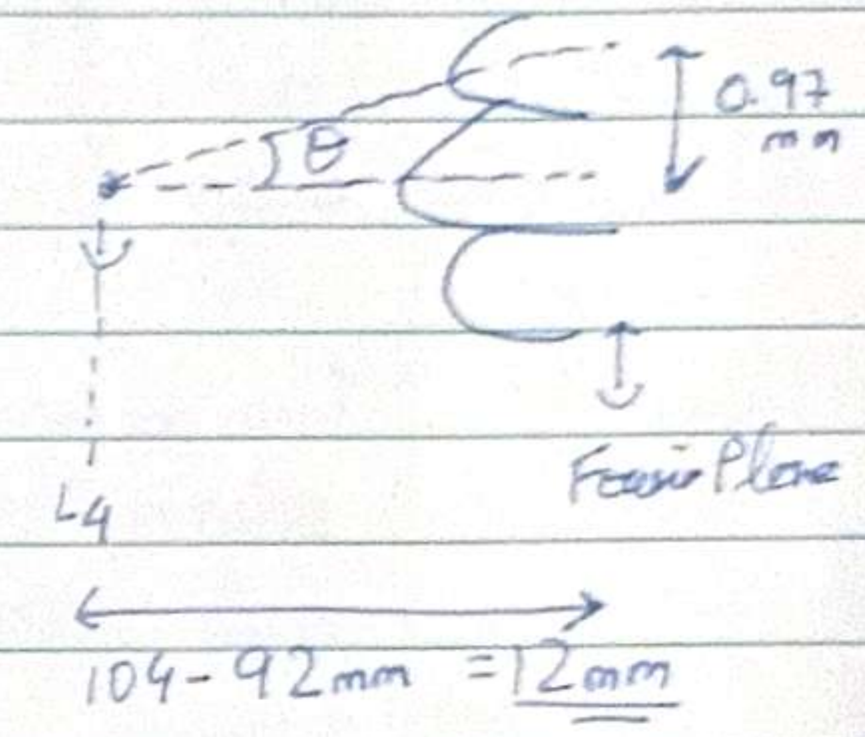
Errors, Hot spots on the camera formed a strong central dot.

6. Analysis

To find the angle

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

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



The labscript also suggests:

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

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

Figure Saved

↳ Saved it to Canvas on: "Ahilan & Nathan Group/Lab1-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. Uncertainity 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. Good Evaluation

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

10. Reflections & Plan for next lab.

1) After Coming home & looking at the fourier diffraction pattern Image, I realized it might not be camera hot spot! 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.

Required Submission Summary (Page-Ordered, Entire Notebook)

1. **Köhler illumination: field-stop sizing for a 5 mm illuminated FOV (calculation + tuning note)**
   Computed field-stop iris diameter for 5 mm object FOV using 4-f relay magnification ($M = f_{\text{cond}}/f_{\text{field}}$), and noted final fine-tuning while watching object illumination. **pp. 1–2**.

2. **Core background theory + experimental variables map (what controls what)**
   Short Köhler illumination roles (field stop vs aperture stop vs field lens), grating equation reminder, and explicit independent/dependent/control variables list (including LED wavelength / room-light control). **p. 2**.

3. **Camera + rail alignment checks and measured geometry (first quantitative measurements)**
   CCD exposure check, camera post height measurement (21.5±0.05 cm), and initial placement/position measurements used throughout setup. **p. 3**.

4. **Real-space imaging chain alignment: magnification lens focus found and verified (sharp image checkpoint)**
   Magnification lens orientation notes, placement, and achieving sharp focus on card at ∼71.5±0.05 cm with lens centered and optics square to the rail. **p. 3**.

5. **Objective lens placement + test object focusing with acquisition settings recorded**
   Objective lens placement (150 mm lens), centering via shadow/concentricity method, variable line grating placement, best-focus position, and camera settings (exposure, gamma, gain). **pp. 4–5**.

6. **Illumination train build: condenser lens positioning + aperture-stop pinhole alignment procedure**
   Condenser lens placement relative to object, centering criterion (illumination stays centered while focusing), 200 μm pinhole positioning, XY centering method, mirror/autocollimator back-reflection concentricity alignment. **p. 5**.

7. **Imaging LED onto aperture stop: inserting field lens / confirming LED image focus on pinhole**
   Inserted $f = 50$ mm lens to image LED onto pinhole (aperture stop), removed/replaced pinhole to verify focus while preserving saddle position, and maintained beam centering through object/objective. **p. 6**.

8. **Field stop implementation: iris edge imaging + achieving ∼5 mm illuminated field at grating**
   Installed 0.5” iris as field stop, centered on beam, slid to image sharp iris edge on camera, reduced aperture to set ∼5 mm illuminated field using a white card. **p. 6**.

9. **Non-uniform illumination diagnosis: locating the fault + identified lens-orientation error**
   Documented non-uniform illumination upon shrinking field stop, stepwise diagnosis by checking illumination after each element, and identified incorrect lens orientations (L4/L5) + cascading compensation effect; sketch/interpretive note included. **pp. 7–8, 14**.

10. **Session planning + reflective evaluation: what worked, what failed, what to fix next (with goals audit)**
Structured plan for subsequent work, post-lab reflections on alignment bottlenecks and time loss, and explicit goals review (short/long term) including incomplete setup/testing status and identified need for quantitative uncertainty work. **pp. 8–11, 16**.

11. **System-level documentation: apparatus inventory + full optical-layout sketch with key distances**
Complete apparatus list (sources, optics, stages, software) and full hand-drawn system schematic with initial distances (LED-to-rail end, lens separations, pinhole and object distances). **pp. 11–12**.

12. **Measurement uncertainty note for rail readings (least count estimate)**
Documented attempted uncertainty sourcing and practical estimate from rail least count (1 mm $\Rightarrow \pm 0.05$ cm). **p. 12**.

13. **Pre-lab analysis: spectral broadening model + order at which FWHM doubles (with sanity-check note)**
Derived combined width model ($\Delta\theta_m^2 = \Delta\theta_0^2 + \Delta\theta_{\text{spec},m}^2$), solved for order criterion, numerical substitution, and noted factor-of-10 discrepancy to resolve. **pp. 13, 15**.

14. **Pre-lab analysis: Fourier-plane order spacing + pinhole size criterion for peak FWHM $\approx 0.1\Delta x$**
Derived order spacing $\Delta x = f\lambda/a$, computed Δx for 10 lp/mm, set target FWHM, and stated diffraction-limited scaling for a circular aperture (Airy/FWHM form) as the design criterion. **p. 14**.

15. **Error-mechanism explanation + correction strategy (practical alignment workflow)**
Interpreted how misplacement/tilt produces spatial blur / illumination gradients, listed probable sources of error, and recorded the "unscrew optics element-by-element" correction strategy without disturbing posts/saddles. **p. 14–16**.

16. **Ronchi ruling theory build: Eq. (32) derived from single-slit FT + Dirac comb / finite-N sum**
Started from Fraunhofer FT expression, derived single-slit envelope, invoked convolution with a Dirac comb for grating, used finite geometric-series result to obtain $\left(\frac{\sin\beta}{\beta}\right)^2 \left(\frac{\sin N\alpha}{N\sin\alpha}\right)^2$. **pp. 17–19**.

17. **Computational plotting plan + qualitative interpretations from plots (spacing, width, envelope)**
Wrote plotting logic/pseudocode for varying N, a, b and summarized qualitative outcomes: order spacing vs a, peak narrowing vs N, envelope widening vs smaller b. **pp. 20–21**.

18. **Duty-cycle analysis: missing/suppressed orders + condition for suppression (with examples)**
Explained how varying b/a redistributes intensity, identified suppression condition $\sin(\pi mb/a) = 0$, and worked explicit cases ($b/a = 1/2$, $1/3$) for which orders vanish. **pp. 22–23**.

19. **Real-experiment realism: why orders broaden (finite source size + finite LED bandwidth)**
Documented physical broadening mechanisms beyond ideal theory: extended source/finite

angular extent and finite spectral bandwidth, and linked these to convolution/broadened peaks and reduced contrast (esp. at higher orders). **p. 24**.

20. **Rebuild + correction workflow: lens orientation fixed, backward alignment attempts, and saddle/pinhole mechanical fix**
    Updated sketch emphasizing lens orientation, attempted backward alignment approaches, identified saddle/pinhole alignment issue, used a new saddle (after paper wedge attempt), and verified beam centering element-by-element with a white card. **pp. 25–28**.

21. **Uniformity verification checkpoint: "card-after-each-element" test and success criterion recorded**
    Verified the beam stayed centered through the optical train and observed largely uniform illumination after corrections; documented the check procedure and conditions (room lights down, lens tube installed). **p. 28**.

22. **Quantitative test measurement: real-space magnification estimated from pixel calibration and line counting**
    Used NI acquisition + line tool to count pixels across imaged grating region, applied camera pixel size (3.45 μm), converted to image size, computed object size from 10 lp/mm and observed line count, and estimated magnification ($M \approx 1.585$) with comparison to expected $M = 2$ from $f_{\mathrm{mag}}/f_{\mathrm{obj}}$. **p. 29**.