625 Czerny-Turner Grating Spectrometer Experiment

MAT

March 19, 1998

1 Basic Idea

In order to avoid chromatic aberrations or limitation of spectral range by absorption of glass lenses, the Czerny-Turner system uses a spherical converging mirror to collimate light into a blazed, reflective, plane grating, and another to refocus the dispersed spectral lines onto the exit slit, as in Fig. 1. The spectrum is scanned by rotating the grating; everything else stays fixed. It differs from the Ebert Fastie in having two small independent curved mirrors instead of one large spherical mirror serving the same role. This of course provides an additional degree of freedom for minimizing aberration.

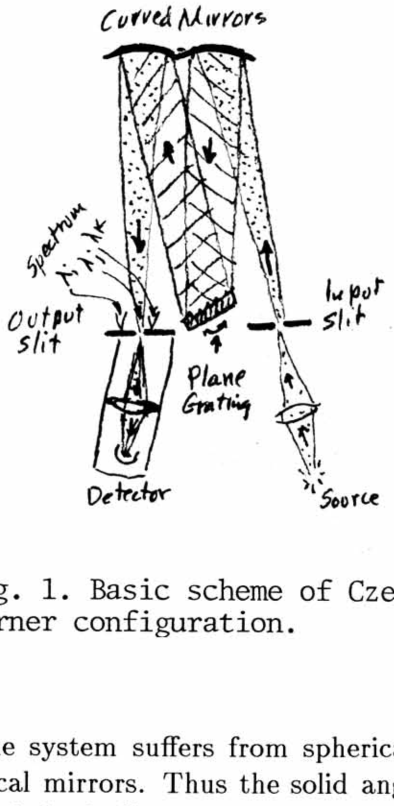


Fig. 1. Basic scheme of Czerny-Turner configuration.

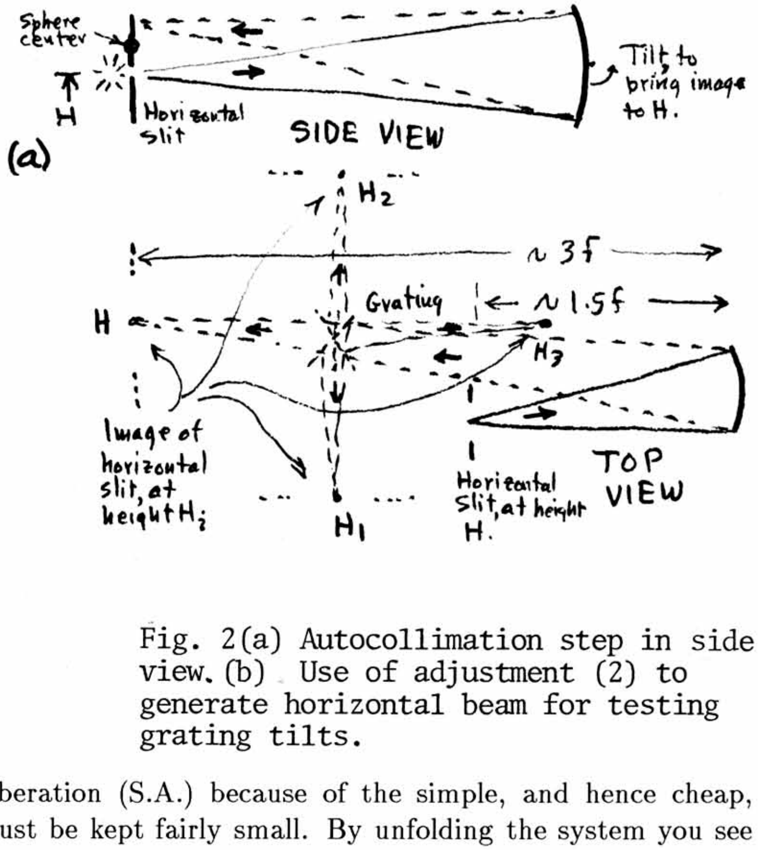


Fig. 2(a) Autocollimation step in side view. (b) Use of adjustment (2) to generate horizontal beam for testing grating tilts.

The system suffers from spherical abberation (S.A.) because of the simple, and hence cheap, spherical mirrors. Thus the solid angle must be kept fairly small. By unfolding the system you see that it is basically symmetric; remember from the camera discussion that this eliminates coma. The effect of astigmatism can be wiped out (for most applications) by placing both slits in the tangential focal surfaces. In other words, the tangential focal lines being parallel to the slit jaws, loss of resolution by astigmatism is avoided in this fashion.

You task for this afternoon will be to start right from scratch and proceed systematically to line up the whole system properly.

2 Systematic Approach

2.1 Basic Philosophy

Some of the adjustments are sensitive - first order effects - while others are not so sensitive - second order effects. Generally our strategy will be to line up the second order adjustments first - by straightforward measurement - then proceed to the more critical adjustments using more sensitive tests for these adjustments.

2.2 All in a plane

Some optical systems fall on a single optical axis and are best set up in a straight line on an optical bench. Obviously this is not such a system. The next simplest thing to a straight line is a flat plane surface. In practice a flat surface of magnetic material permits the use of modern magnetic clamps for anchoring the components solidly, once they are in place. Our plate is a magnetic alloy of stainless steel, avoiding rust. (Most stainless steel is not magnetic.)

The first thing to do is establish your actual optical plan, a constant distance, H, above this plate, simply by measuring upward from the magnetic table, the same distance to the center of every component. Start with the grating, of course, since it is not easily adjustable in height above the table; set your heights gauge to establish H as the heights of the center of the square grating. (Be very careful not to touch the ruled surface of the grating at any time with anything at all!) Now, using this height - gauge setting, set both slit centers and both mirror centers all to this same height H.

The remaining adjustments having to do with the reference plane involve angular adjustments by tilting things: (1) Since the curved mirrors are quite a bit oversize, their height can be set very carelessly, but not the height of the sphere-center point for each; this is adjusted by rotation about a horizontal axis that is tangent to the mirror surface. (2) Wavelengths are scanned by rotating the grating about a vertical axis that is tiltable by two base-screws, and this axis must be made pretty accurately vertical. (3) The normal to the grating face must be set perpendicular to the axis of (2), i.e. so that it lies in the optical plane.

1. Height of cuirved mirrors. First we one of the slits 90^o until it is horizontal, not vertical, and we recheck it to height H, rather carefully. Now we fill it with light and illuminate one of the mirrors, adjusting the mirror to autocollimate an image of this slit back onto the screen, as shown in the side view by Fig. 2 (a). Tilt the curved mirror as shown to bring the slit image into coincidence with the slit, both at height H. Repeat for the other mirror. In both cases measure the sphere-radius R, not particularly carefully. This completes step (1).
2. Now we use step (1) as a tool in step (2) and (3). By bringing the mirror in to about 3/4 R (i.e. 1.5 times f) we get a magnification of about 2 and a real image of the slit at about 3f or 3/2 R. To see it, you have to have the mirror enough off the axis that the return beam misses the slit housing as shown from above in Fig. 2 (b). Now we can inject this beam into the grating face turned first $+45^o$ later -45^o from the beam and measure the sharply-focused slit images at some heights H1 and H2. If $H1 \neq H2$, tilt the rotation axis of the grating until $H1 = H2$. The turn the grating face to about $0\ ^o$ and find the slit image at $H3 \neq (H1 = H2)$; tip the rotation axis

in the other tip direction until finally you get H1 = H2 = H3 all around. This means the axis of rotation is normal to the reference plane, and step (2) is completed.

3. If now (H1 = H2 = H3) $\neq$ H, it is because the grating-face-normal is not perpendicular to the axis of rotation. Use the screws behind the grating to make (H1 = H2 = H3) = H and step (3) is completed.

Now all the optical-plane adjustments are done, and we can slide the components around on the plane without disturbing the plane adjustments. (We hope.)

2.3 General arrangements on the plane

Look at Fig. 1 and think, what should we be trying to do now? Well, we should maintain a symmetry of input/output sides, pretty much; we should be seeking to squeeze the slits in close to the grating to minimize the off-axis angle at the mirrors, and we should also be trying to put the two mirrors close together to bring the grating into closer correspondence with a pure Littrow configuration. However, if we carry this at an extreme, light from slit S1 will go direct to both mirrors then to slit S2 without going to the grating. To control these unwanted light paths it is necessary to separate M1 from M2 by a comfortable amount - say about 25 mm or more between the brass collars, and to insert a black shield between them as in Fig. 3. Furthermore there is a problem with light leaks direct from source to detector without going through the spectrometer, and this is helped by widening the space between slits a bit more than the minimum - make the (ϵs about 20 mm and you should be better off. It will give space for a large black screen from source to detector, as well as short shields on the inside of the slits, as shown. Adjust the latter so the intended mirror is clear and the unintended mirror is completely shaded. In a practical spectrometer, the slits will be on the outside with the grating lying cozily protected inside; this dictates putting the slits just clear of and beyond the grating. The slit-mount tubes should point away from the curved mirrors; also see to it the slit-width adjusting knobs are faced away from the grating for finger access. I would draw a line of symmetry right on the magnetic sheet and put the center of rotation of the grating on this line. I would then draw a cross line at right angles close beyond the grating mount and put slits there, equally spaced. This is shown in Fig. 3. Put everything where you want it, pretty much, measuring off f = R/2 by ruler to position the mirrors approximately.

2.4 Focusing mirrors by autocollimation onto grating face

In this subsection, we focus the mirrors, nearly right, by using autocollimation onto the grating face.

Now you are ready to autocollimate the first mirror (via the grating in order zero) focusing the mirror back and forth to make the beam parallel at the grating, as in Fig. 4. This is not terribly critical but should be done reasonably well. The first practical step in this process is to get the slit that was set horizontally turned back to the vertical; (I would use a cardboard square set on the table top, sighting past the edge of the cardboard to the slit in order to set the slit reasonably near to being perpendicular to the table.) Then move the mirror forward or back (maintaining (1 in Fig. 3 constant) until the slit image is returned onto the slit jaws is sharp. Rotate the grating as needed to bring the image in close to the slit, and also rotate the curved mirror as needed to bring the cone of

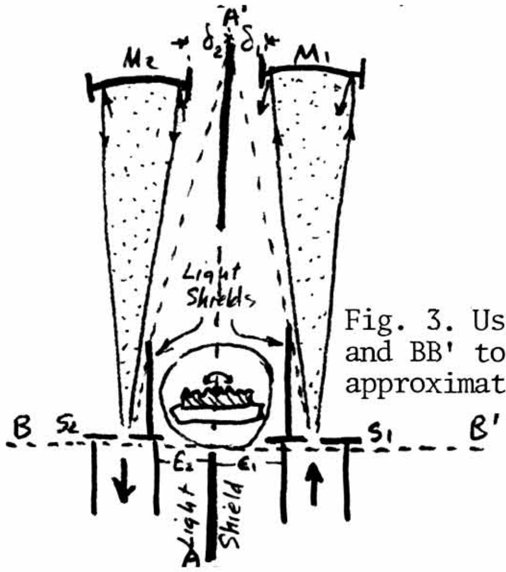


Fig. 3. Use of cross-lines AA' and BB' to symmetrize the layout approximately to begin with.

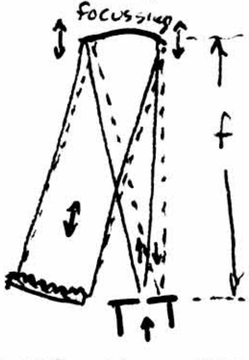


Fig. 4. Collimating.slit mirrors are focussed by autocollimation using grating as mirror and slit jaw as "screen".

light from the mirror roughly centered on the grating. A white card will help you check this centering. Recheck the focus, etc., until you are satisfied with everything at the same time.

Now inject light into the other slit and turn the grating a little to repeat the whole autocollimation process for another mirror. At this point everything should, in principle, be all adjusted ready to go. But you can do better. Before doing so however adjust all the unwanted light shields of Fig. 3 so they are doing their jobs effectively.

2.5 Critical Alignment and Final Focusing

In this, we use critical Alignment and Final Focusing of the Slit Image onto the Output Slit.

Just looking at the autocollimated slit images does not provide the most critical focusing operation you know how to perform. Remember the Schlieren experiment? We can use the same basic method here very easily.

First, though, you want to make the exit slide exactly parallel with the entrance-slit image. To do this, you rotate the grating to reflect the light from one slit/mirror onto the other; just like Fig. 1, except in zero order, the grating serving as a plane mirror. It doesnt matter which slit serves as entrance or exit. Then set the entrance slit very narrow and the exit slide wide. When you rotate the grating with the fine adjustment screw (the motorized wheel...relieve the spring pressure gently with thumb so it turns easily with your index finger.) The entrance slit image will be abruptly cut off by one jaw of the exit slit. Back up and so it again placing a translucent bit of plastic over the exit slit tube to display the light for clear viewing. If the exit slit jaw is not quite parallel to the entrance slit image, the cut-off is neither from the top nor from the bottom.

Now for the final focus. Watch whether the cut-off of the defocused blob on the diffusing plastic goes from left to right or from right to left; this tells you which way your focus is in error, remember? Focus the slit now, not the mirror, until the cut-off is uniform, neither from left nor right, and you are ready to go...except one final point.

2.6 Are the Gratings Rulings Perpendicular to the Optical Plane?

We dont have an adjustment for this, and it is not very critical. You can check it by watching whether the input-slit image seen on the exit slit moves up or down as you progress from order +2 to +1 to 0 to -1 to -2, using some bright monochromatic source such as Na or Hg green. It should not move either way of course.

2.7 Aligning external source/condenser

This is the usual business of filling the system with light efficiently. Get a condenser lens set up and figure roughly where you want it and the source to be for focus. But then remove the condenser and set the source so that the pinhole image of the source formed on the collimating mirror (by the slit serving as pinhole) is centered both ways on the mirror. Raise/lower and right/left the source to achieve this. Now when you put in the lens and focus a centered image of the source onto the slit, you are guaranteed that the mirror is filled with light as well as being centered. If not, try changing the conjugate relations of the source/mirror and repeating the alignment process.

2.8 Aligning the sensor/condenser

You would expect to use a lens to image the grating onto the sensor, minifying as necessary to try to get all the emerging light onto the active sensor given suitable lenses. (Why not image the slit instead of the grating, in this case?) Probably instead you will find a little light-tight box containing both lens and sensor, as a unit, which you can just place up against the slit barrel to minimize light leaks. For best results on light leakage you may also cover the whole system with a black box.

3 Check out with various slit size arrangements

Connect a recorder to the sensor output.

1. Compare the strengths of the different orders with the blazed order on the recorder.
2. Wide slits: Triangular/trapezoidal/rectangular line shapes. Suppose you open both slits wide, and equally, and scan a spectral line. What line shape do you expect? Try it.

   No close the entrance slit to 2/3, or 1/2, or 1/3 of the exit slit width and repeat.

   Next close the entrance slit very nearly shut and try again.
3. Narrow slit/resolution. Close both slits as much as you can while still getting light through the sensor, and scan a line.

   Scan the Na doublet. Can you resolve it?

   What seems to be limiting your perceived resolution, ultimately, with this combination of components, from source thru recorder? (Dont jump to conclusions; think about the whole system.)

4 Measuring angles

We will use a convention of measuring all angles in the same sense as the grating mounting, namely angles increase clockwise as seen from above. Three angles of the Grating's Mounting can be measured, G_a, G_r and $G_{diffration,m}$ to the usual normal to the grating surface (shown as dotted) with an arbitary "zero angle" shown as dashed. Our results will, of course, depend only upon differences so the actual "zero angle" does not matter.

For each angle measurement use the vernier and a magnifying glass. Notice that the angles are in degrees and minutes dividing the circle into $\frac{1}{360\times60} = \frac{1}{21{,}600}$ of a turn. It does NOT divide the circle into decimal parts of a degree or decimal parts of a turn! (A more modern, automatic and expensive angle measurement may use units such as $\frac{1}{32{,}768}$ of a turn or $\frac{1}{1{,}048{,}576}$ of a turn. Why?)

If you are unsure how to use a vernier, ask your instructor.

1. Use the grating to cause autocollimation of the light back via the first curved mirror to the first slit.

   * Measure the angle G_a of this grating position.

2. Use the grating to cause a simple reflection of the beam from the first mirror onto the second mirror and onto the second slit.

   *Measure the angle G_r of this grating position.
   Define the difference $\phi = G_a - G_r$ so that the angle between the incident light beam from the first spherical mirror and the refracted or reflacted light beam to the second spherical mirror is 2ϕ.

3. Notice how when a light beam strikes the grating, several diffracted beams (m= -2, -1, +1 and +2) are created along with the "reflected" or m=0 beam.

   Now notice that one of the diffracted beams is brighter than the others. This bright beam is due to the grating having "blazed" rulings. Rotate the grating to cause the strongest diffractive beam (probably m=+1) to be delivered to the second mirror and thence to the second slit.

   *Measure the angle $G_{diffration,m}$ of this grating position.

   $G_{diffration,m}$ depends upon the wavelength λ. (The previous G_a and G_r depended on the geometry of your setup and did not depend upon the wavelength.)

5 Calculating the wavelength λ

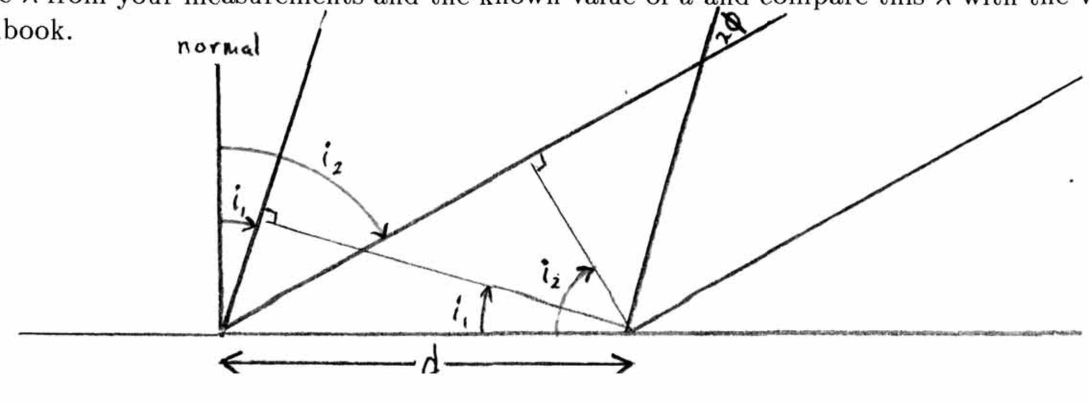
With angles as shown for order m as on the next page, with i_1 and i_2 being, as usual, the angles to the normal of the incoming and outgoing beams, the path difference for adjacent grating rulings or grooves is an integer number of wavelengths.

$$m\lambda = d \; sin \; i_1 \; + \; d \; sin \; i_2$$

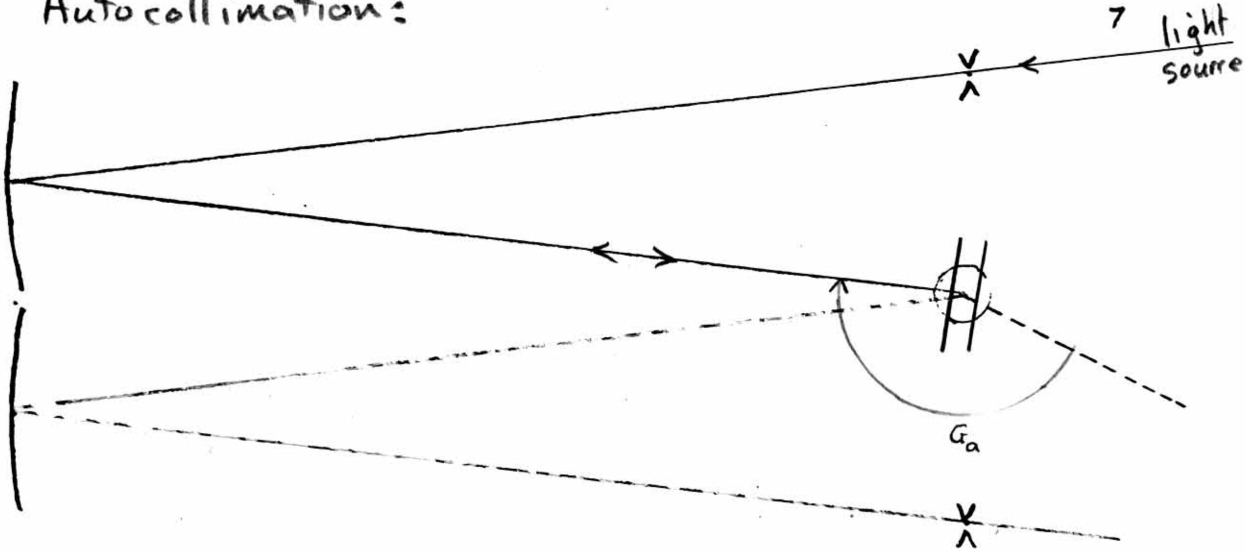
Use $\phi = G_a - G_r$
$i_2 = G_a - G_{diffraction,m}$ and
$i_1 = i_2 - 2\phi$
$i_1 = G_a - G_{diffraction,m} - 2(G_a - G_r)$
$i_1 = -G_a + 2G_r - G_{diffraction,m}$.

Substituting these in the path difference equation, we get;
$$m\lambda = d \; sin \; (-G_a + 2G_r - G_{diffraction,m}) \; + \; d \; sin \; (G_a - G_{diffraction,m})$$

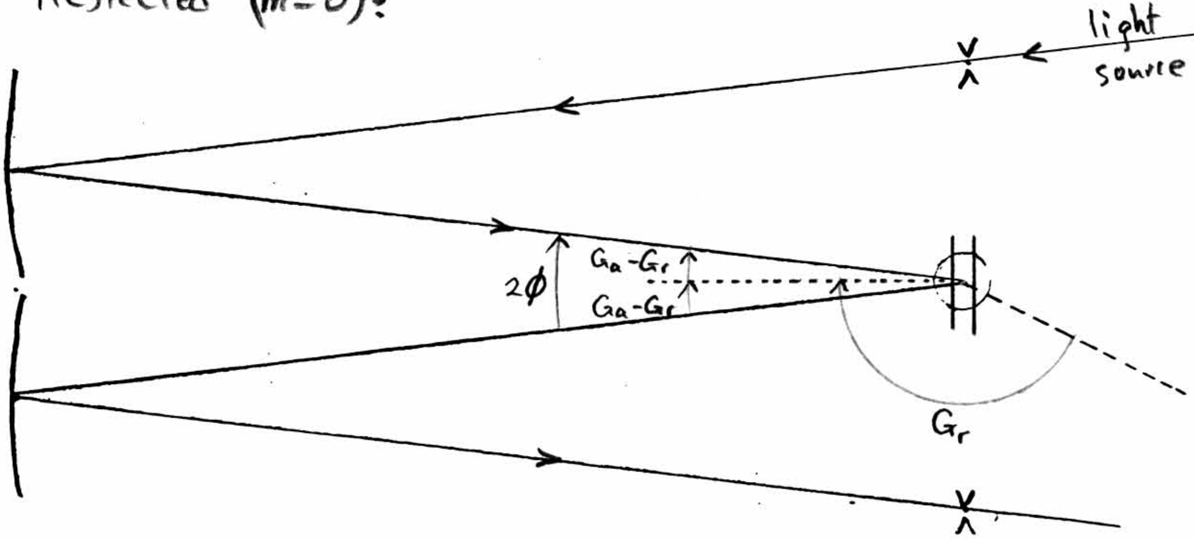
Calculate λ from your measurements and the known value of d and compare this λ with the value from a handbook.



Autocollimation:



Reflected (m=0):



Diffracted m≠0: