Czerny-Turner Spectrometer Experiment

Physics 625 Lab

1-Basic Idea

In order to avoid chromatic aberrations or limitations of spectral range by absorption of glass lenses, the Czerny-Turner system uses a spherical converging mirror to collimate light onto 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.

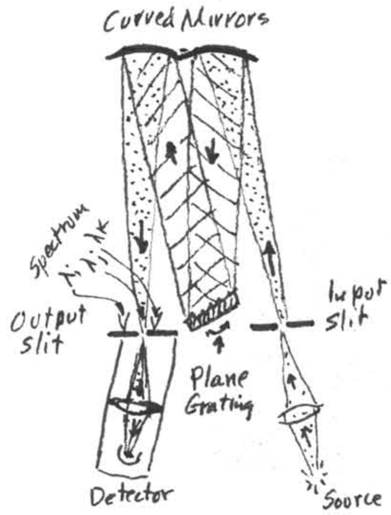

Fig. 1. Basic scheme of Czerny-Turner configuration.

The system suffers from 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 on 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.

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

2-Systematic Approach

A. 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.

B. 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 plane, 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 height gage to establish H as the height 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 - gage 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: (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),(2),(3) are all adjusted by tilting things, as we said.

Number (1) is very easy to do. First we rotate one of the slits 90° 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 slit jaws as a sort of 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.

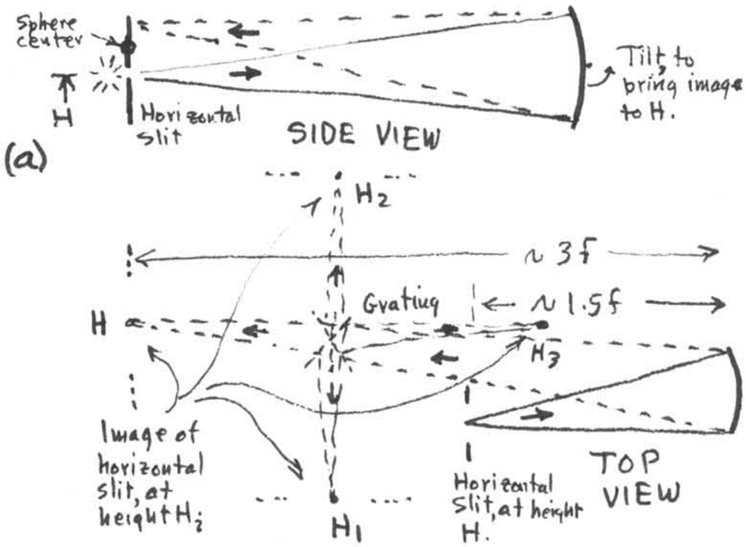

Fig. 2(a) Autocollimation step in side view. (b) Use of adjustment (2) to generate horizontal beam for testing grating tilts.

This completes step (1). Now we use it 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 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° later -45° from the beam and measure the sharply-focussed slit images at some heights H_1 and H_2. If $H_1 \neq H_2$, tilt the rotation axis of the grating until $H_1 = H_2$. Then turn the grating face to about 0° and find the slit image at $H_3 \neq (H_1 = H_2)$; tip the rotation axis in the other tip direction until finally you get $H_1 = H_2 = H_3$ all around. This means the axis of rotation is normal to the reference plane, and step (2) is completed. If now $(H_1 = H_2 = H_3) \neq H$, it is because the grating-face-normal is not perpendicular to the axis of rotation. Use the screws behind the grating to make $(H_1 = H_2 = H_3) = H$ 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.)

C. General arrangement 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 to an extreme, light from slit S_1 will go direct to both mirrors then to slit S_2 without going to the grating. To control these unwanted light paths it is necessary to separate M_1 from M_2 by a comfortable amount - say an inch 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 ϵ's about 3/4" and you should be better off. It will give space for a large black screen between source and 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 the 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.

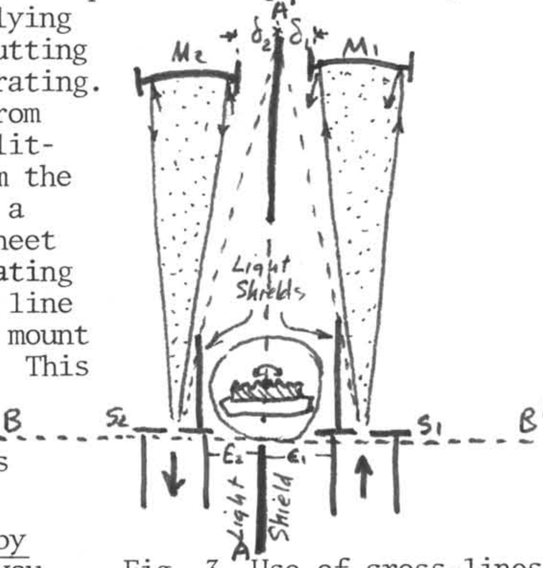

Fig. 3. Use of cross-lines AA' and BB' to symmetrize the layout approximately to begin with.

D. Focussing mirrors nearly right by autocollimation onto grating face. Now you are ready to autocollimate the first mirror (via the grating in order zero) focussing 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 δ_1 in Fig. 3 constant) until the slit image returned onto the slit jaws is sharp. Rotate the grating as needed to bring the image in close to the

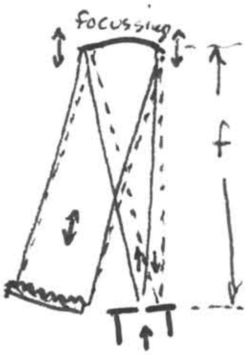

Fig. 4. Collimating-slit mirrors are focussed by autocollimation using grating as mirror and slit jaw as "screen".

slit, and also rotate the curved mirror as needed to bring the cone of 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 the other 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.

E. Critical alignment and final focussing of slit image onto output slit. Just looking at the autocollimated slit images does not provide the most critical focussing 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 slit 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 doesn't matter which slit serves as entrance or exit. Then set the entrance slit very narrow and the exit slit 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 do 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 will squirt up from top to bottom, or vice versa. Rotate one slit or the other very carefully until the cut-off is neither from the top nor from the bottom.

Now for the final focus. Watch whether the cut-off of the defocussed blob on the diffusing plastic goes across 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.

F. Are the grating rulings perpendicular to the optical plane? We don't 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.

G. 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 image bathing the mirror is centered. Why? Check to see if 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.

H. 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.

A. Compare the strengths of the different orders with the blazed order on the recorder.

B. 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.

Now 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.

C. 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.)

Chapter 1

5/5 SPECTROMETER ARRANGEMENTS WITH PRISMS & GRATINGS

1.1 5/5.1 Examples of prism spectrometers

The simplest example of a prism spectrometer is obtained by replacing the dispersing element of our generalized slit spectrometer (Fig. 5/2-1) with a prism, with typically a 60^o prism angle. Figure 5/5-1 shows such a mounting in which the prism is held fixed in a position corresponding to minimum deviation for some wavelength near the middle of the spectral region being studied, and the spectrum is recorded on a photographic plate. Often the plate holder is tilted or bent to conform more exactly to the focal curve of the camera lens, to correct more fully for chromatic aberration and astigmatism than can be achieved by relatively simple lenses. The amount of tilt can become quite large, for example, in the case of a UV-visible spectrograph using a quartz prism and single-element quartz lenses. Generally the spectral range of interest is considerably greater than the range over which it is possible to get good correction for chromatic affects. (This problem arises also in the case of the grating spectrograph.)

A monochromator can be made by putting a slit in the focal plane to isolate the wavelength of interest. A scanning spectrometer can be made by providing means for moving the slit along the focal plane and recording the output with a photodetector-recorder combination.

One serious disadvantage of a monochromator of this type is that the exit beam angle changes with wavelength. For most experimental purposes it is desirable to have a fixed entrance and exit angle. There are several arrangements permitting this feature.

If the prism is used with a mirror, as in Fig. 5/5-2, the light that passes through the prism at minimum deviation (the condition of symmetry about the prism bisector) is reflected from the mirror along the direction of the incident light. The mirror could also be mounted so as to give any desired angle of deviation for the light passing at minimum deviation.

This constant deviation feature is achieved in a single piece of glass in the Pellin-Brocca prism, often called the **constant deviation prism**, shown in Fig. 5/5-3. In essence, the usual triangular prism is split along the bisector of the prism angle, reflected through 90° by total internal reflection, and sent through the second half of the prism. Light at minimum deviation emerges at 90° from the incident beam. This form of the constant deviation prism is very popular in both prism spectrographs and prism monochromators. The prism can be rotated to tune the monochromater to the desired wavelength. The prism-turning mechanism is often supplied with a graduated drum giving the emergent wavelength when the prism is properly aligned. This drum calibration must be specially made for each prism glass used, since the refractive index vs. wavelength is different for each material.

For any prism instrument with fixed slit widths, the resolution may change appreciably over the range of wavelengths being studied. This is because the quantity $\mathbf{dn/d\lambda}$ that, along with the prism size, determines the prism resolution changes significantly with wavelength (Eqs. 5/3-4 and 5/3-6). A prism monochromator can be provided with a cam that adjusts the slit width as the prism is turned to provide constant resolution. Such a cam must be specially made for each prism material.

In addition to increasing the size of prism, the resolution of a prism instrument may be increased by using several prisms in series. In Fig. 5/5-4, three identical prisms are used in series to provide three times the theoretical resolving power of a single prism. (The angular dispersion $\mathbf{D}$ is increased threefold while $\mathbf{W_2}$ is unchanged.)

Question 5/5:1. What happens to the resolving power of the triple prism spectrometer shown in Fig. 5/5-4 when the middle prism is turned over (points toward the bottom of the page)?

A prism used in a **Littrow** mounting, illustrated in Fig. 5/5-5, is double-passed and the resolution is doubled. In the Littrow mounting the light is reflected back along the entrance direction. The mirror is tilted slightly so that the entrance and exit beams are not actually overlapping.

In another type of Littrow mounting, shown in Fig. 5/5-6, the prism face that would be the bisecting face of a split 60° prism is aluminized, and light at minimum deviation is reflected back on itself.

A prism of this type has been used in a laser cavity with an active medium capable of causing laser oscillation at several wavelengths. The prism can be rotated to tune to the desired wavelength. Only the wavelength corresponding to minimum deviation for a fixed prism angle will be reflected back along the laser cavity axis. (See Chapter 7/3 for a fuller discussion of the concept.)

A very simple, although somewhat crude, prism spectrometer combines dispersion and focusing in a single element. This is illustrated in Fig. 5/5-7.

There are a large number of other prism mountings, but the ones mentioned above serve to illustrate the basic types and several of the problems involved in using prism instruments.

Prism monochromators can be used in series, with an isolation slit between them, as shown in Fig. 5/5-8. The isolation slit greatly reduces scattered light and improves the contrast and parasitic light qualities of the spectrometer. Such an arrangement is called a double monochromator.

Question 5/5-2. Is the dispersion of the double prism instrument shown in Fig. 5/5-8 increased over that of a single prism instrument? Would turning the right-hand branch over (making a U-shaped rather than Z-shaped instrument) change this situation?

1.2 5/5.2 Grating spectrometers

Grating spectromters have tended to replace prism spectrometers in the research laboratory because of the **L** · **R** advantage discussed in 5/3.3, and because of the possibility of producing efficient blazed gratings tailored to specific application at nearly any wavelength by proper choice of blaze angle, groove spacing, and radius of curvature (Chapter 5/4). We'll spend correspondingly more time on grating mounts than we did on prism mounts. Many important details will be passed over to keep within bounds, but we'll try to isolate enough of the important concepts to enable you to use and initiate the design of grating instruments with real understanding of how to get the most out of them. A final good word for prism dispersers: don't forget about them. There are many problems for which the simple and robust character of the prism might be just what you need.

1.3 5/5.3 Examples of plane grating spectrometers

Littrow spectrometers. We have frequently used the **Littrow** condition as our baseline for discussing the properties of diffraction gratings because of its simplicity. In the strict Littrow configuration the light diffracted by the grating comes back exactly on itself, so the entrance and exit slits are not separated. While the strict Littrow condition can be met in grating-tuned laser cavities (see Chapter 7/3), monochromators require that the entrance and exit slits be separated, as indicated in Fig. 5/5-9, by having the exit slit (or photographic plate) slightly above or below the entrance slit. A disadvantage of the spectrometer shown in Fig. 5/5-9 is the transmission limitation imposed by the lens. On the other hand, very good imaging can be achieved and spatial information along the slit is accurately preserved.

Figure 5/5-10 shows a Littrow spectrometer using a focusing mirror –an off-axis parabola –

which avoids the transmission and wavelength dependent properties of the lens in Fig. 5/5-9. Aberrations are more severe than with a well-corrected lens; however, with careful optical design, diffraction-limited performance can be achieved.

Czerny-Turner spectrometer. An inconvenience of the spectrometers shown in Figs. 5/5-9 and 5/5-10 is that the entrance and exit focal planes are inconveniently close together, making it difficult to use them with various light sources and bulky experimental apparatus. This difficulty is solved by departing from the Littrow configuration as, for example, in the Czerny-Turner mounting shown in Fig. 5/5-11. The optical axis of the system (the bold line in the figure) misses being folded back on itself by an angle 2ϕ. Focusing is provided by two separate concave mirrors; the first sends collimated light to the plane grating while the second focuses the light onto the exit slit or photographic plate.

If the mirrors are used symmetrically the coma is corrected – at least in the approximation that the grating is replaced by a plane mirror. In fact, since the grating is inclined, minimum coma is achieved with a slightly asymmetric system. Some improvement in image quality is achieved with off-axis parabolic mirrors. The system is "near-Littrow" in the sense that the angle ϕ is rather small, and the general ideas developed for the Littrow condition apply quite well.

Ebert-Fastie spectrometer. A somewhat similar mounting is the Ebert-Fastie system (Fig. 5/5-12), which uses a single large spherical mirror. Again, this is a near-Littrow mounting since the angle 2ϕ is small. The slits are arcs of a common circle in the focal plane of the mirror and centered on its axis. With this system the angular height α of the slits can be made very large (about 0.1) producing a spectrometer with high $\mathbf{L} \cdot \mathbf{R}$ compared to similar spectrometers with straight slits. Note that if the two mirrors in the Czerny-Turner system have the same center of curvature we obtain the Ebert-Fastie system; thus some of the aberration correcting advantages of the Z configuration (if you unifold the monochromator at the grating) are realized in the Ebert-Fastie system. The advantage of curved over straight slits with the remaining astigmatism is easily understood by observing that the point **A** (front view, Fig. 5/5-12) on the entrance slit S_1 is imaged into a line $d\alpha$ perpendicular to the line from **A** through the optical center of the mirror; thus with the curved slits the astigmatic line always lies along the curve of the exit slit, minimizing its effect on the resolving power.

1.4 5/5.4 Plane grating monochromator tuning

Figure 5/5-13 shows a detail of the illumination geometry of a plane grating in the non-Littrow grating mounts we have considered. In these systems the light paths remain fixed, and the grating is rotated to change the wavelength emerging from the exit slit. The old grating equation (Eq. 5/3-7), of course, still works, but because the incidence and exit rays are fixed it is useful to express the angles $\mathbf{i}_1$ and $\mathbf{i}_2$ which they make with the grating normal as it rotates in terms of their angular separation 2ϕ (fixed by the geometry of the monochromator), and the angle θ between their bisector and the grating normal, as shown in the figure. Thus $\mathbf{i}_1 = \theta + \phi$ and

$i_2 = \theta - \phi$, and Eq. 5/3-7 becomes

$$k\lambda = a[\sin(\theta + \phi) + \sin(\theta - \phi)] = 2a \cos\phi \sin\theta \, (5/5-1) \tag{1.1}$$

When $\phi = 0$, we have a Littrow configuration, and Eq. 5/5-1 becomes the Littrow grating equation, $k\lambda = 2d \sin\theta$. We'll call ϕ the "off-Littrow" angle.

Question 5/5:1. Why is the following derivation of the resolving power **wrong:** From Eq. 5/5-1, one can get $\delta\lambda = 2(a/k)\cos\phi\cos\theta\delta\theta$. By combining this with Eq. 5/5-1, one gets $R = \frac{\lambda}{\delta\lambda} = \frac{[2(a/k)\cos\phi\sin\theta}{[2(a/k)\cos\phi\cos\theta\delta\theta]} = \frac{(\tan\theta)}{\delta\theta}$.

This "Resolution" is wrong by a factor of 2 as we see from Eq. 5/3-19 in which $\delta\theta = \beta$.

Hint: Read the lines between Eq. 5/3-1 and Eq. 5/3-2. Now try this approach using the basic grating equation $k\lambda = a(\sin i_1 + \sin i_2)$ remembering that i_1 is held fixed.

1.5 5/5.7 Practical resolving power of slit monochromators

We need to take a closer look at the practical resolving power of grating monochromators, and it seems reasonable to clean up this matter now that we're talking about real instruments and have to get serious about how wide to set the slits. The problem stems from our assumption back in 5/2.1 that the dispersing element had unit magnification. The fact that a plane grating or prism can, and generally does, introduce magnification in the direction of dispersion is readily demonstrated from the grating equation. We ask how the angular width δi_1 of the entrance slit is related to the angular width δi_2 of the exit slit. Differentiating Eq. 5/3-7 with k, λ, and a fixed we obtain

$$0 = \cos i_1 \, \delta_i + \cos i_2 \, \delta i_2 \, (5/5-2) \tag{1.2}$$

and the magnification is

$$M = \left|\frac{\delta i_2}{\delta i_1}\right| = \frac{\cos i_1}{\cos i_2} \, (5/5-3) \tag{1.3}$$

As we said in 5/2.1, $M = 1$ for a symmetric system in which $i_1 = i_2$, namely the Littrow configuration.

Example 5/5:1. In a certain Czerny-Turner monochromator (Fig. 5/5-11) with equal focal length mirrors, the grating is used with $\theta = 60^0$ and $\phi = 5°$. If the entrance slit has a width of 0.5 mm, how wide should the exit slit be for optimum $L \cdot R$ product?

Answer. At optimum $L \cdot R$ the exit slit width matches the width of the image of the entrance slit. Now there is magnification, so
$\delta i_2 = \delta i_1(\cos i_1/\cos i_2) = \delta i_1(\cos 55/\cos 65) = \delta i_1(1.36)$.
Then the actual width of the exit slit should be $1.36 \times 0.5\ mm = 0.68\ mm$.

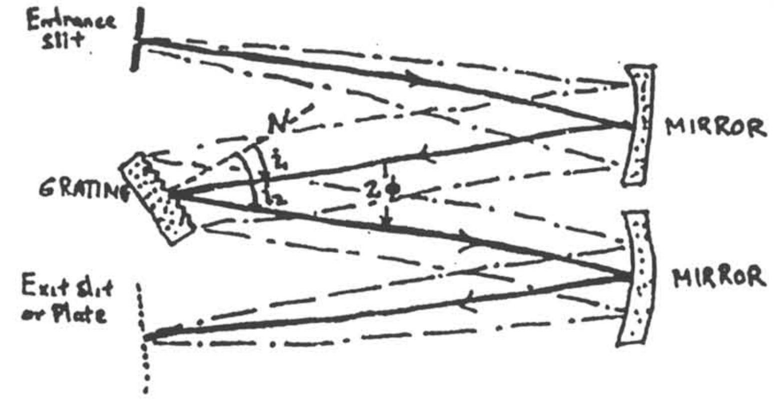

Figure 5/5-11. The Czerny–Turner spectrometer.

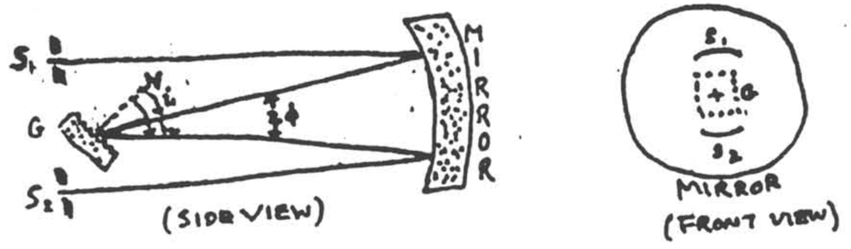

Figure 5/5-12. The Ebert-Fastie system. The bisector of the incident and exit rays passes through the center of the grating and the center of the mirror and forms the axis of the instrument. The front view shows the slits as arcs of a circle about the axis. A point A is imaged as a short line $d\ell$ along the curved exit slit, providing compensation for astigmatism.

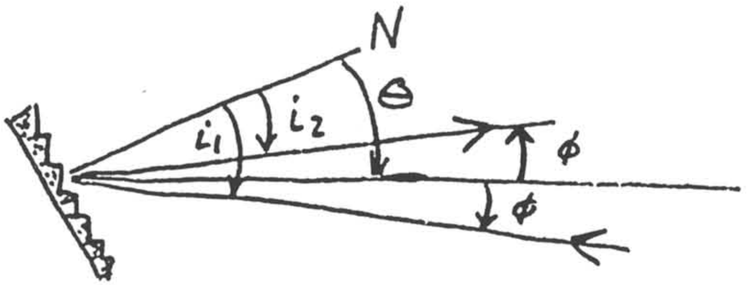

Figure 5/5-13. Geometry for the light rays at the grating in a typical plane grating monochromator.

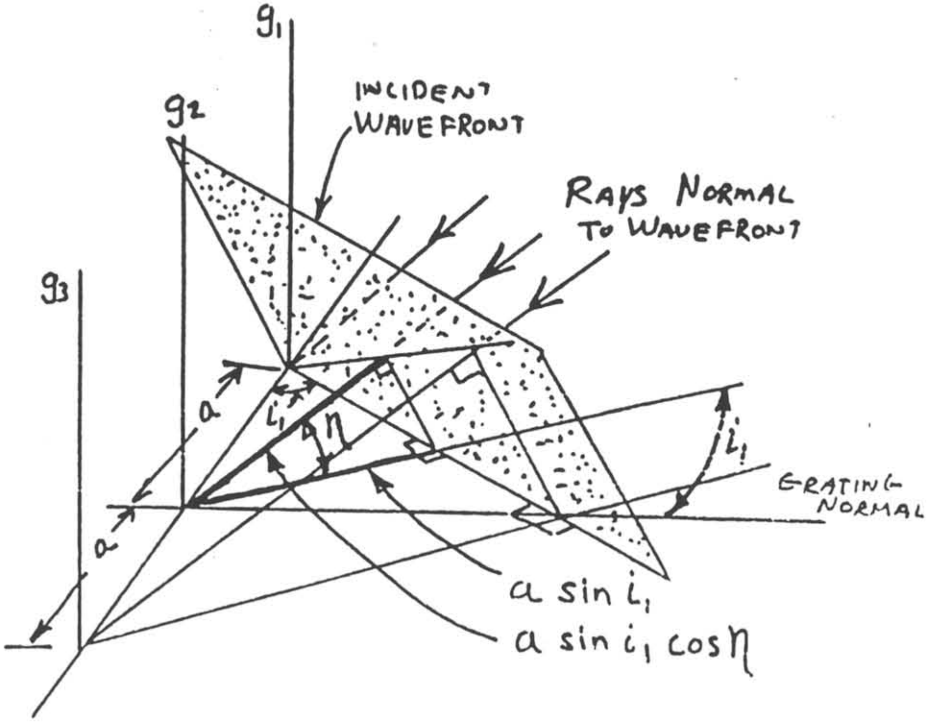

Figure 5/5-14. Illumination of a grating with rays inclined by an angle η to the center plane which is perpendicular to the grating grooves g_1, g_2, g_3, etc., with separation a. Only the incident rays are shown for clarity.