Optics Segment Handout

AST 351 Spring 2004

1. Background

Before you can measure the light from an astronomical object, you have to bring it to a focus and perhaps disperse it. To figure out how to do this requires understanding first-order optics (where an image is formed and what its magnification is), aberrations (do all of the rays go where you want them to?), diffraction (how the wave properties of light affect an image), and dispersion devices, such as gratings.

2. Goals

At the end of this segment, you should know...

(1) The basic principles of geometric optics.

(2) How to work with the two-lens telescope in its various forms.

(3) Qualitatively, the nature of the lowest order optical aberrations.

(4) The effects of diffraction on optical systems.

(5) How a diffraction grating works and how to use it in a spectrometer.

(6) How to assemble and handle simple optical systems.

(7) How to work with the optics CAD program Zemax.

3. Safety

There are two important things to remember.

For You: Never look directly into the HeNe laser beam. Reflections off of a card are ok. You can see the red glow even when you are outside the cone of the beam. This glow is too weak to hurt you. What you need to avoid is having the direct beam incident on your eye. The best way to avoid problems is only to turn on the HeNe when it is in its mount, always to keep your eyes above the level of the optical bench when the HeNe is on, and never to insert hand-held mirrors into the beam. You should also avoid staring at the discharge lamps. While these are not harmful in moderate doses, they do emit ultraviolet radiation. We have 5 pairs of UV-filtered lab goggles available for your use. Please use them if the lamp is on.

For the Equipment: Optics are delicate things, which can be destroyed easily. Don't drop them. Handle them as little as possible, and **handle them only by the edges**. Fingerprints are very nasty things which are hard to get off without ruining fragile coatings on the optics. This is espcially true of the diffraction gratings. **Do not touch the front surface of a grating, and if someone else does, do not attempt to clean it.** Lenses aren't quite so fragile. They can be wiped gently with a cotton cloth or lens tissue (not a kimwipe).

4. Segment Organization, What to do

There are four parts to this unit: reading about the basics of optics, problems to test your knowledge of the reading, raytracing with the program Zemax, and laboratory exercises. By the end of this segment, you must do the following: 1) Do the reading, do the problem set, and hand your problem set in. 2) Learn to use Zemax well enough to do the raytracing exercises, and hand in a printout of your results. 3) Do the laboratory exercises, and hand in a brief description of what you did. The above order seems most logical to us, but you may arrange the work in any order that seems best to you.

You must each do the problem set individually, but you may compare results and correct each other. Zemax and the lab excercises may be done as a group, but each of you must be able to show how to run a simple zemax raytrace.

5. Reading

There are numerous texts and reference books on optics. Rather than assigning reading in one of them, we list suggested books, and topics you should be familiar with. You shouldn't have to read all of any book. Rather, read selectively to learn about the topics listed. Check with each other about where to find the most useful material on each topic. Share that information with me at the end of the segment. The problems cover most of the topics, so you can use them as a test of what you have learned.

Optics catalogs have good summaries of formulae and give a good look at some of the devices. The *Melles Griot* catalog, in particular, has good drawings and explanations at the beginning, together with many of the formulas you need. Later in the catalog, there is a useful explanation of how a Helium Neon laser works. (We will leave a copy of this catalog in the lab. Please don't remove it.) The *Diffraction Grating Handbook* from SpectraPhysics – Richardson Gratings (http://www.gratinglab.com/library/handbook/handbook.asp) has tons of good formulae and information about diffraction gratings and grating spectrometer configurations. If you are nice, you can probably get the companies to send you copies of these volumes for free.
Smith, *Modern Optical Engineering* - a good introduction with practical stuff
Hecht (& Zajac), *Optics* - a good introductory text
Jenkins & White, *Fundamentals of Optics* - another good introduction

Welford, *Useful Optics* - practical, with less introductory material
Moore, et al., *Building Scientific Apparatus* - ditto
Born & Wolf, *Principles of Optics* - very complete coverage of optics

5.1. Topics and Formulas

As a background for what we will do, you should know from previous course work or gather from reading a good qualitative understanding of: the wave and photon pictures of light, refraction and reflection, diffraction and interference. From the texts plus the notes at the end of this handout, you should be looking out for an understanding and relevant formulae for the following phenomena or properties:

First order optics: the connection between focal length, image and object distances
Reflection, the focal length of a spherical mirror
Refraction, Snell's law
Thin lens equation: focal length, focal ratio
Thick lenses: Effective focal length, back focal length.
Two lens systems (telescopes): magnification, plate scale, pupil (Lyot) stop, collimation
Qualitative knowledge of aberrations: spherical, coma, astigmatism.
Diffraction: Resolution limit, spot size.
Diffraction gratings: Orders, free spectral range, dispersion, resolving power, blaze angle
Grating Spectrometers: Basic layout.

6. Problems

You may work together to figure out *how* to answer the problems, but you should then go away and write down your exact solutions on your own.

1. Do a simple raytrace by hand using Snell's law. (a) Start with a ray incident from the left, 10 mm above the optical axis. At some position along the axis, place a convex spherical surface with a radius of curvature of 200 mm and its center farther to the right on the axis. To the right of this surface is a glass with refractive index 1.5. What is the angle between this ray and the normal to the surface where it hits that surface? What is the angle of the refracted ray from the surface normal and from the horizontal? Where does the ray intersect the optical axis? Repeat this procedure for a ray 20 mm from the axis.
(b) Now, after your rays pass through the spherical surface, imagine a flat surface, perpendicular to the direction of propagation, 10 mm to the right of the vertex of your spherical surface. After this flat surface, the refractive index returns to 1. Where do your rays intersect the optical axis now? Does this agree with the formula for the focal length of a thick or thin lens?

2. (a) For a 200 mm focal length thin lens, calculate the image distance and transverse magnification for objects at 5000 mm, 500 mm and 250 mm from the lens.
(b) Place your object 200 mm from this lens. After the lens the light beam will be collimated. If you put a 50 mm focal length lens in the collimated beam, how many times larger or smaller than the object will the image be?

3. Suppose you have a refracting telescope with a 1-m diameter and 5-m focal length primary lens. You can add a second lens to the telescope to obtain an effective focal length of 20 m, either putting a negative lens in front of the focus of the primary lens or putting a positive lens after the focus. For each of these options put the lens 1 m from the focus and calculate the necessary size and focal length of the secondary lens and the distance of the final focus from the secondary lens.

4. Consider a 1 mm diameter glowing sphere placed 1 m from a 1 cm diameter lens, which forms an image of the sphere 2 m beyond the lens.
What is the area-solid-angle product of the light emitted by the sphere that passes through the lens?
What is the diameter of the image of the sphere?
What is the area-solid-angle product of the illumination at the image?

5. Find out what diffraction gratings we own. What is the blaze wavelength of these gratings? What is the blaze angle of these gratings? What order is closest to the blaze angle for light at 633 nm? At 633 nm, calculate the angular dispersion and the diffraction limited resolving power of our gratings.

7. Raytracing

Since raytracing programs are now widely available, most people find it most efficient to first do a pencil-and-paper first-order design of an optical system (calculating the positions of foci, layout of optics, magnification, dispersion, etc.), then use a raytrace program to calculate aberrations and optimize the design. We will use Zemax, which appears to offer the best combination of capabilities and affordability.

The Zemax manual is not designed for beginners. In particular, they do not explain what their image quality diagnostics mean, taking the attitude that if you don't understand them you shouldn't be using the program. From your reading you should understand enough to get started. If you get lost, ask one of the local experts. You can learn enough about Zemax to get started by reading chapters 1-3 of the manual and doing the tutorial examples in ch. 4. Also glance through the rest of the manual, so you can find more information when you need it. Another helpful resource is a library of Zemax solutions maintained by Focus Software at **(http://www.zemax.com/file_exchange/)** . In particular, the examples from Daniel Schroeder's book on Astronomical Optics may be interesting. Then try the following:

1. Start by doing the Zemax equivalent of the first problem. Set the entrance aperture of the system to 20 mm. At the first surface, place a spherical surface with a radius of curvature of 200 mm followed by an index 1.5 material. Verify that you get the same answer as in the first part of problem 1(a). Now insert the flat surface as in problem 1(b) and confirm that the extreme ray in this case also intersects the axis at the position you calculated in the problem. You now have a plano-convex spherical lens. Zemax plots the diffraction limited spot size as a circle. For your lens with a 20 mm diameter entrance pupil, how big is the ray bundle at the focus, compared to the diffraction spot? How does the answer change if the entrance pupil is 40 mm? Why is the ray bundle bigger than the diffraction spot? Try turning the lens around. Is there a "best" way to put a spherical lens in a collimated beam?

2. Pick a pair of lenses from the set we have, one a simple lens and the other an achromat. Use each lens to bring 450 nm collimated light to a focus. Holding the position of your focal plane constant, look at the ray distribution for 650 nm light. How does it differ? How much does the best focus change between the two wavelengths in each case?

3. For a diffraction grating like the one we have, lay out a spectrometer using a lens as a collimator and a different lens as a camera. Also lay out a reflective Ebert-Fastie or Czerny-Turner design using the parabolic mirror we have available. Ask if you need help getting started.

As a group, you need to hand in a printout of Zemax optical layouts and spot diagrams showing your results.

8. Laboratory Exercises

For each of these, your group must hand in a sketch of your optical arrangement and a sketch or a brief description of what you saw or measured.

1. (a) Take one of the lenses from our lens set and measure its focal length. In order to do this, you will need to create a collimated HeNe laser beam. We don't have a commercial collimator. The best way for you to collimate the beam is with two lenses. With the first, you bring the beam to a focus. If you place the second lens one focal length beyond the focus of the first, the output beam should be collimated. Adjust the separation of these two lenses until the output beam stays a constant size with distance. (You can test your collimator by observing the beam far away or by 'autocollimation' - ask us.) It is best to set up your laser and collimator on one breadboard and to have your test optics on another. (Note that your collimator will produce a more useful beam if the first lens has a much shorter focal length than the second.)
(b) Now insert your test lens and measure its focal length. How accurate do you think your measurement is? How much error do you think you introduced by failure to collimate precisely? How well does the focal length you derive agree with the nominal focal length of the lens? Is the difference within the accuracy quoted in the catalog for this part? (Note: Ask me to show you about the knife-edge test.)

2. For your test lens, take the collimated beam and watch how the spot moves or changes in shape as you tilt/translate the lens. Try replacing the test lens with one of our paraboloidal mirrors, with the light hitting the mirror off-center at various angles. Describe what you see. (It will be easier to see aberrations if you place another lens after the image formed by your test lens at a position so it forms another image several meters away.)

3. Set up and carry out an experiment to measure the transverse magnification of a simple lens at different object distances. How well does the result agree with your formula?

4. Devise a two lens optical system and place it in collimated light. Confirm that the focus position and magnification of your system agree with your pencil and paper calculation.

5. Play around a bit with a diffraction grating in collimated light from a HeNe laser. Describe and explain some of the phenomena you observe.

6. Place one of the discharge lamps behind a slit. Use collimated light from this slit to illuminate a grating. Reimage the diffracted beam onto a white card. Describe your setup and explain what you see.

9. Rules of Thumb and Design Philosophy

1) In any system, you need to make a choice between reflective (mirror) and transmissive (lens) optics. Mirror systems may have higher efficiency and work well over a broad range of wavelengths. Their major defect is that the conic surfaces must often be used off-axis which introduces aberrations. Lens systems are usually more compact, easier to align, and can be used closer to on-axis. Their disadvantage is the restricted wavelength range imposed by the material, thermal emission from the lenses (in the infrared), and chromatic aberration.

2) You can usually rough out your system on paper by treating all lenses as thin lenses and all mirrors as spherical and then going over to your ray tracing software.

3) Plate scale: This quantity, in arc seconds/mm gives the relation between the angular size of an object at infinity and its linear size in the focal plane:

$$platescale = (206265/f)arcsec/mm = (1/f(mm))radians/mm,$$

where f is the effective focal length in millimeters (determined for a telescope by multiplying the final f/ratio of the beam and the diameter of the primary.
Example: The NASA IRTF telescope is f/35 with a 3m diameter primary. Its effective focal length is 105m, and the plate scale in the focal plane is 2 arcsec/mm.

4) As seen through a telescope of diameter D, a point source will have an angular blur of $\theta = \lambda/\mathrm{D}$, due to diffraction. The diffraction-limited size of the image of a point source is $(\mathrm{f}\#)\lambda$,

where f# is the focal ratio at the telescope focal plane. So at a wavelength of 0.5 μm an f/20 lens or telescope will have a spot size of 10 μm.

5) Conservation of energy requires that the area-solid angle product, AΩ be the same throughout a lossless optical system. (Recall problem 4.)