

1 Laboratory 5: Basic Lens Design in OSLO

1.1 Abstract:

A very important tool for designing lenses or complete optical imaging systems is optical ray tracing software. Several examples of such software exist, including CODE V, Zmax, and OSLO. This lab deals with the last of these. We will first get familiar with OSLO by constructing a digital model of a simple lens and investigating the applicability of the thin lens formula, and then we will construct a couple of more complicated systems and investigate their imaging properties.

1.2 Theory:

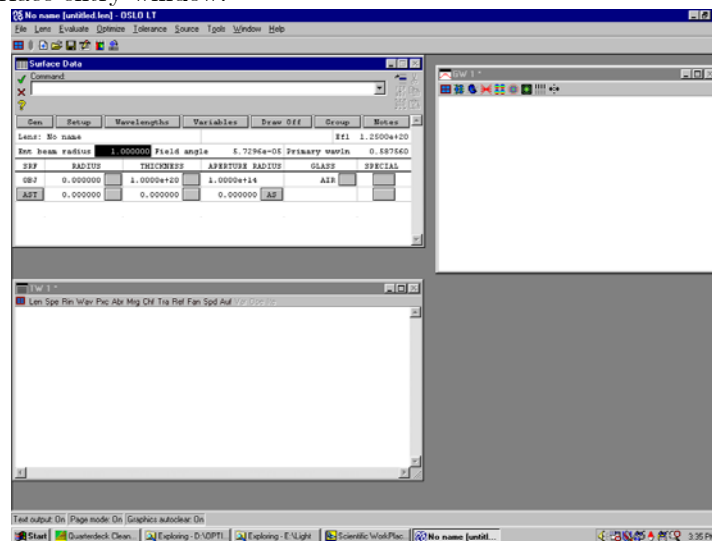
OSLO is an optical ray tracing package that has many features, and we're just going to scratch the surface in this lab. It can be used for such analyses such as (1) determining the best focus point of an optical system, (2) determine the amount of geometrical aberration that is present at various points on the image plane, (3) solve for quantities such as the aperture size needed to enclose the full ray bundle at any point in the optical system, and (4) investigate chromatic aberration.

The general idea is that we start with some initial ray or set of initial rays, which are characterized by their location and direction on the plane of the object. We then follow the ray through the optical system surface by surface until we arrive at the image plane. If an optical system is "perfect," all rays starting out at the same point on the object plane converge together on the image plane. No imaging system is perfect, and there are several important reasons why this assumption of "perfect" imaging fails.

In OSLO, one must first construct the optical system, surface by surface. Once complete, one can specify the locations and directions of the initial rays, and then ask the program to complete the ray diagram.

1.3 Procedure:

Begin by starting up OSLO program on the PC. You should see three windows at the start: in the upper left, there is a surface entry window. In the upper right is a graphics window, and in the lower left is a text window. We will use the first two extensively, but won't do much with the third. Begin with the surface entry window.



Initial OSLO display

The default surface entry screen should have two surfaces already listed: the object surface and the image surface. You can add surfaces in between by clicking on the icon near the upper right of the window. There are several icons there; the upper left one in the group is for adding a row of surface data. Highlight a row (click on the left-most box of the row) and then click the add row icon. A new row will appear above your highlighted row.

Next, specify the surface data. Think of the system as having the object on the left and the image plane on the right. In the surface data window, the first row is the leftmost surface, the second row is the next surface moving to the right, and so on. There are four main parameters to specify for each surface in the system: (1) the radius of curvature; the thickness of the material to the right of the surface; (3) the aperture radius; and (4) the index of refraction (or, alternatively, the glass type) of the material to the right of the surface.

You can use the graphics window to look at various aspects of your optical system. There is a bar of icons near the top of the graphics window. Each one makes a different plot of system parameters. We will be interested primarily in the ray diagram and the spot diagram. The former is similar to what you might draw by hand, showing how rays progress through the system. The latter shows what the image looks like (provided that you have the system properly focused). If you don't specify an object in OSLO, it assumes a perfect point source located on the optical axis, and therefore the image also characterizes the blur circle. When OSLO displays the blur circle, what you see is lots of points, which together give you the impression of the blur. Each point in the pattern corresponds to one ray as it crosses the image plane. OSLO begins with a uniform cone of rays originating from the object, but lens aberrations and diffraction effects generally change that uniform pattern into the final image. So, the density of points in the spot diagram tells you how bright the image at that location.

When you start a new lens system, you can enter the number of surfaces at the beginning or you can add and/or delete surfaces later on.

Note that OSLO adds the reference "AST" to one of the surfaces. This stands for "aperture stop" and is not very important to us at this point.

1.3.1 A Plano-Convex Lens

1. As a first exercise, construct a simple planar-convex lens modeled on the big lens used to look at the Christmas tree lights and the aberrations in the previous laboratory.
2. Specify that the planar side is toward the object. (NOTE: for a flat surface, OSLO expects a radius of curvature of zero, rather than $+\infty$ as you might expect). Let the curved side have radius of curvature of 18.6 INCHES, let the lens be 1 INCH thick, and use an aperture radius of 5.25 INCHES. (You can fix/change the units of the system by clicking on the "Gen" button near the top left of the surface data window if the default is not mm.) Once you have selected the units, click on the green check mark to accept the change and go back to the surface data. You can graph the system by clicking the "draw system" icon in the graphics window. If the entire system is not graphed, you made need to change some of the parameters for "lens drawing conditions" under the "lens" menu.
3. Specify the glass for the lens to be *BK7* selected from the Schott catalog (use "Catalog" by clicking on the button next to the glass column entry for the row of interest.).
4. Plot the *spot diagram* for the image of an object at $+\infty$ distance away and at a distance of 100 inches. The "spot diagram" icon is located in the graphics window.
5. Plot the *spot diagram* for the image of an object at $+\infty$ distance away and at a distance of 100 inches with field angles of 20° and 30° (option under SETUP, default units are degrees).
6. Reverse the lens so that it is "curved side forward" and repeat the spot diagrams. Which orientation gives better images?
7. Decrease the aperture radius by half (i.e., you are "stopping down" the lens).

8. Under the “Evaluate” menu item at the top of the OSLO screen, you’ll find an item called “Autofocus.” If you select autofocus, the distance between the last surface and the image plane will change to the point where the best focus is achieved. That is, OSLO will send rays through the system and determine where the “blur circle” of the rays on the image plane is the smallest. By changing the object distance, you can check the thin lens formula. Do this for several object distances and record your image distances. Plot s_i as a function of s_o . What error would be produced by a graph obtained from the thin lens formula if the lens is assumed to be halfway between the vertices?
9. Do a *spot analysis* in the graphics window. Does the focused image have a different width if you change the thickness of the lens? (Don’t forget to do an autofocus every time you change the thickness.)
10. Now go back and change the glass type for the lens. Change the index of refraction just slightly for the blue wavelength (486 nm) to 1.52, and for the red wavelength (656 nm) use 1.48. Now do a spot analysis and compare the width you get here versus what you got in the previous step. This time you should see three different colored dots in the spot diagram pattern. Each one corresponds to one of the three wavelengths where you have specified the index of refraction: blue, green, and red.

Save this lens design, because we will come back to it at the end.

1.3.2 The Keplerian Telescope

Last week we built a Keplerian Telescope using real lenses. Now, try to reproduce that design in OSLO. Make your lenses pretty thin, say 5 mm thick or so. Remember that (1) The system is afocal (so it has no focal points, or equivalently, that the focal points are at $\pm\infty$), and (2) the separation between the lenses should be equal to the sum of the two focal lengths. Specify two convex lenses of your own design. Click on “gen” (general setup) and change the mode to of the optical system “afocal” (this “turns on” some of the options, such as magnification). After you have configured your telescope, check the following things:

1. Make sure that your object is at a very large distance, e.g., $1e20$. After an autofocus, if your telescope is working properly, you should get a large image distance also. (Remember, a telescope system is *afocal*)
2. The drawing of the system should form an intermediate image in between the two lenses. Now, if you click on “setup” again, look for the magnification of the system and note it.
3. Go back and change the lens design so that the focal length of at least one of the lenses is different. To make the system function as a telescope, you’ll also have to change the distance in between the lenses appropriately. Note the magnification again. Do this a couple of more times, varying the ratio between the focal lengths of the two lenses.
4. Finally, plot the listed magnification as a function of $\frac{f_2}{f_1}$. What does the curve look like? Place the two lenses very close together, (say, 0.1 mm \simeq 0.0039 in apart). Put the object at several different distances and record s_o and s_i in each case. For two thin lenses in contact, the effective focal length of the combination should be given by:

$$\frac{1}{f_1} + \frac{1}{f_2} = \frac{1}{f}$$

where f_1 and f_2 are the focal lengths of the two lenses making up the system. Do your two lenses obey the Gaussian lens formula,

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$$

provided you use the focal length you get from (1)?

1.3.3 The “Achromat”

You have seen how even a small change in the index of refraction across the visible region of the electromagnetic spectrum can really cause problems for achieving a good focus. Where the blue light is focused, the red light is out of focus, and so on. In this section, you’re going to try to reduce this effect by creating an achromat. An achromat is a two-lens system, where the two lenses have been cemented together at the interior surfaces. We can model this as a three-surface lens in OSLO:

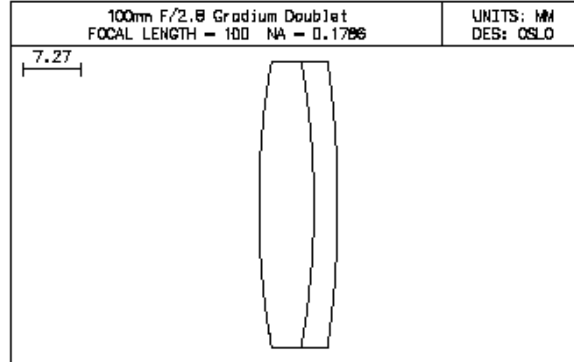


Figure 1: Design of a typical acromatic lens (an “acromat”)

Most optical companies have catalogues of achromats, and you can pick one according to your needs. For example, here are the properties of one such lens:

Radius	Thickness	Aperture Radius	Glass
64.28 mm	6.23 mm	15 mm	SK11
-44.98 mm	2.5 mm	15 mm	SF5
-180.43 mm	0 mm	15 mm	Air

The glass types are both Schott glasses, you can specify these in OSLO by clicking on the button next to the glass entry in the surface data table and selecting the Schott Catalog. So, put this achromat into OSLO and look at the spot diagrams. You will see that the lens does a pretty good job of bringing the red and blue light to the same focus. (Use the “best polychromatic focus” from the autofocus routine.)

Next, go back to your planar convex lens, with the three indices of refraction, and add another surface. Let the indices of refraction at the three wavelengths here be $n_{blue} = 1.61$, $n_{green} = 1.60$, and $n_{red} = 1.59$. Now, vary the curvature of the back surface until the spot diagrams give you the best focus. What value did you get for the curvature?

1.4 Analysis

Be sure to include the following items in your lab write-up.

1. A description of each of the lens systems you modeled.
2. Ray diagrams of each system.
3. At least one spot diagram from each system (except the telescope, since it is an afocal system).
4. A graph of the thin lens formula versus the result for the first lens. Remember, for the thin lens comparison, you’ll have to add half the thickness of the lens to both your object and image distances from OSLO.
5. Plot s_i as a function of s_o for the two lenses in contact. Plot also the curve expected using the distance from the object to the midpoint of the system as so and the focal length from formula (1).
6. A graph of the magnification of the telescope as a function of the ratio of the focal lengths of the individual lenses.