

AY 105 Lab Experiment #4: Optical aberrations

In this lab you will perform optical raytracing using the computer program 'Code V' on a PC in the lab, and compare the calculated results to the performance of actual lenses on the optical bench. In the first day's lab you will study lenses (an achromatic doublet and a plano convex lens) while learning the basics of the program, then in the second day's lab you will study far off-axis images from a concave mirror.

Lenses

At the beginning of the lab you will find the optical table already configured with a collimated light source to illuminate your test lenses and a microscope to examine the resulting images. The collimated light is provided by the QTH lamp, opal glass diffuser, and a condensing lens to concentrate the diffuse light onto a pinhole. One group's pinhole is 25 μm diameter, while the other group's is 30 μm diameter. Light emerging from the pinhole is then collimated by a photographic telephoto lens, producing a parallel beam roughly 75 mm in diameter in which you will locate your test lenses. The collimated beam travels the length of the optical rail, at the other end of which is a microscope that can make x , y , and z fine adjustments. Make sure there are lenses in the microscope (10x will do). The test lens holder will be mounted on top of the rotational stage on the rail carrier. Sketch the setup in your lab notebook, recording the diameter of your pinhole, the EFL (effective focal length) of your telephoto lens, and the magnification of your microscope. Ask the instructor to explain the x , y , z motions of the microscope and anything else about the initial setup which is unclear at the start. What angle in arcseconds is subtended by the pinhole diameter in the focal plane of the telephoto lens?

The **Code V** optical raytracing program runs on the black Lenovo PCs.

Start Code V by double-clicking its icon on a computer in the room. Eventually the Code V session will start and several windows will appear. First name your lens file by going to the File menu and choosing "Save As." The software will add ".len" to the end of the filename you specify and save the lens definition in C:\CVUSER. We'll begin by entering the parameters for the achromatic doublet lens. Enter a title for your lens by clicking on the Lens menu, choosing "System Data," then System Settings and the option to set a title. Something like "Ay 105 achromatic doublet" would be a good choice.

Go to "Lens \rightarrow System Data" and the wavelength section to indicate that you want to enter three wavelengths. Specify a red, green, and blue wavelength in nanometers (e.g. 750, 550, 400). Other fields in this dialog box can stay at their default

values.

Click on the input window at the center of the screen, where you will already see the object and image surfaces entered at infinity. Right click on the block that says “Image” and select insert. Insert two surfaces. The input window will then include lines for Stop and 2-3. Stop represents the aperture stop. For our lens, the stop is surface 1, so this is OK. You will enter the surface properties for the lens surfaces on these lines.

Specify the lens as follows.

Surface Name	Y Radius	Thickness	Glass	Refract Mode	X/Y Semi-Aperture
Stop	203.94	11.94	BK7_SCHOTT	REFR	31.75
2	-156.41	8.86	SF2_SCHOTT	REFR	31.75
3	-569.57	343.67		REFR	31.75

The X and Y semi-aperture may appear gray in the screen, and not allow you to enter values. If this is the case, right-click on the surface number column, and choose “Surface Properties.” Enter the Y semi-aperture, and the X semi-aperture should adjust accordingly since you have specified a circularly symmetric lens. The “Refract Mode” column specifies whether the surface is reflective or refractive. BK7 and SF2 are types of glass, and Schott is the manufacturer. Ignore any error messages about the glass no longer being available.

Specify that we want to trace $f/5.6$ rays through the system by going to the “Lens → System Data → Pupil.” Specifying a F/N value of 5.6. Save your lens definition.

You can see a lot of data about the lens you have entered by going to “Display → List lens data → All lens data.” You can also display a picture and a 3D model of your lens from the View menu or the various buttons at the top of the screen.

We would like to evaluate chromatic aberration of this doublet. We’ll do that by producing a spot diagram in front of, at, and behind the nominal focus. Go to “Lens → System Data → Through focus” to define the focus positions we want to look at. We’ll look at three positions, starting position -1.5, increment 1.5 (so we the nominal focus, plus 1.5 mm in front and behind).

Having done that, go to “Analysis → Geometrical → Spot diagram.” The three spot diagrams will appear in their own window. (You may have to wait a bit).

Print the spot diagram using “File → Print.” Make sure the spot diagram window is in front. You can print to the lab printer – it’s called HP Laserjet 1100. If you prefer to print a pretty colored plot, you can always ftp your files to another computer and print elsewhere.

Which focus setting is best for red? for green? for blue? What does this tell you about the achromatic doublet?

Now, let's make a field map showing the RMS spot size as a function of x and y field angle. That is, we'll see how the image of a point grows as we move off-axis. Go to "Analysis → Diagnostics → Field Map." On the first panel page, open the drop-down menu for type of display and choose "RMS Spot Diameter." On the panel including "Field Description," we want a range of field angles, so switch the pull-down menu to "Field Angle" and specify the X and Y field angles as having a minimum of -10 degrees and a maximum of 10 degrees. Then hit okay and wait until the diagram appears. Print it, if you'd like, and note your observations.

You can perform other analyses by exploring menus. Remember to hit the okay after setting the parameters, and look for plots in the plot window and textual results in the command window.

If you want to add off-axis rays to spot diagrams and raytraces, you can add them from the "Lens → System Data → Fields/Vignetting" menu by specifying more X angles. Is the focal surface of the achromat a plane?

Next you must apply Code V commands you've experimented with in order to perform a raytrace analysis of the 50 mm diameter 150 mm EFL plano-convex lens you used as the camera in front of the photodiode during Lab #1. This lens is in the envelope labeled #32974; unpack it and lay it flat side down onto the tissue packing paper on the optical table or computer work area. The lens is made of Schott glass BK7, but in order to input its design into Code V you will need to measure its radii of curvature and center thickness. Your "Optics" drawer contains a device called a "spherometer" to measure the radius of a spherical surface. Remove this device from its package and describe its operation in your lab notebook (you might also find it interesting to examine the other group's spherometer—which is different—after they are finished with it). The instructor will give you a small reference flat with which you can determine the zero-point of the spherometer. Three things you should keep in mind when using the spherometer are: (1) the lens surface should be free from dust; (2) the test point(s) of the spherometer are hardened steel, and can scratch the lens if dragged across it—instead you should lower the spherometer straight down onto the surface of the lens and lift it straight off before moving it, rather than dragging it across the surface; and (3) the dial is calibrated in units of diopters, which are the reciprocal of the focal length in meters a thin lens would have if one surface had the measured radius, the other surface was flat, and the index of refraction of the material was 1.523, so you must use the thin lens maker's formula to convert your diopter measurement into an actual radius. If your group has the "3-point" spherometer, one additional thing you must keep in mind for accurate measurements is the angle the spherometer makes with the surface normal—use a slight rocking motion while watching the dial, and record the extreme reading when the spherometer is normal to the lens surface. Along with the diopter measurement record an uncertainty estimate in your lab notebook (in

diopeters), and when converting from diopeters to radius in millimeters also determine the \pm error bounds on the measured radius.

Flip the lens over on the tissue and measure the other surface with the spherometer. Is your measurement consistent with this surface being flat and the lens plano-convex? What is the smallest radius the “flat” surface could have and still be consistent with your measurement uncertainty?

Next you must measure center thickness of the lens, and there is a third gauge designed for this purpose. Make sure the central regions of the two lens surfaces are dust-free, and carefully separate the gauge calipers, move the calipers to the center of the lens, and carefully let them close. For best results the gauge calipers must be at the center of the lens and normal to each surface; try to keep any dragging motion to a minimum, but some motion will be necessary to locate the lens center. As you might imagine from the usefulness of the “thin” lens equation, the lens design is not likely to depend critically on the center thickness, so it is not necessary to spend a long time trying to measure the center thickness with the utmost accuracy (especially if another group is waiting to use the lens thickness gauge). Record your center thickness measurement and uncertainty estimate in your lab notebook.

When you’re ready to enter the singlet lens, reset Code V with “File \rightarrow New” and specify wavelengths, the entrance pupil, and surfaces as you did before. Enter the lens parameters, using 140 mm as the distance from the last lens vertex to the next surface. In other words, you can set the thickness of the surface 2 to 140 mm, and its radius of curvature to what you calculated for the lens. Set the thickness of the stop to whatever you measured for the lens.

Conduct an analysis similar to the one you did for the achromat. How do the best focal distances for the red, green, and blue rays compare? How is this different from the achromat?

The “Analysis \rightarrow Diffraction \rightarrow Wavefront Analysis” option may help you evaluate focus by finding the best focus. Note that it finds the best focus for each wavelength being studied, and weights them according to the weights in the “Lens \rightarrow System Data \rightarrow Wavelengths” menu. It expresses them relative to the “reference wavelength” specified there. To get the focus shift from the reference for a single wavelength, set the weights for the other wavelengths to zero.

In Lab #1 you measured the focus translation necessary to maximize the signal detected by the photodiode for each interference filter wavelength. Compare the separation you measured in Lab #1 between the 400 nm and 700 nm foci to the results from Code V. At what intermediate focus position does Code V predict the smallest blur circle (for white light)? What is the image diameter at this best focus?

Now take the plano-convex lens and mount it in the lens holder, then insert the

lens holder into the post holder on the rotational stage. Adjust the vertical height to align the lens center with the center of the telephoto lens (to within an accuracy of a few millimeters—remember that the light emerging from the telephoto is ~ 75 mm diameter and parallel, so that vertical (z) and horizontal (y) centering are not especially critical).

You can achieve an approximate y -centering by rotating the stage until the post-holder knob is aligned with the direction of the rail; this rotation will then correspond to “zero” degrees off-axis. Turn on the QTH lamp, and move the lens carrier along the rail until the image of the pinhole is seen just in front of the microscope objective (you will need to turn out the room lights to be able to see the pinhole image at the lens focus). Move the microscope stage in y and z to center the pinhole image formed by the lens in the objective, and then focus the microscope while looking through the eyepiece until the image size is smallest. Describe in your lab notebook what you see when you sweep the microscope focus in and out from the best focus by moving the stage in the x direction, and compare your observations to the translation data from Lab #1 and Code V results (qualitatively). If using Code V went smoothly and time permits, you may wish to quantify your microscope observations of the spot diagram using the micrometer eyepiece. The instructor or T.A. can give you a “Ronchi Ruling” to calibrate the eyepiece scale divisions when used with the microscope.

Next, rotate the lens about the vertical axis of the rotational stage by a few degrees and notice any changes to the image as viewed through the microscope (refocus the microscope as necessary). Choose a particular rotation angle (or two) and specify the field angle(s) in Code V to produce a series of spot diagrams over the focus range. Qualitatively compare the appearance of the actual image to the spot diagrams. Estimate from the Code V results the size of the image at your off-axis angle, and convert this linear spot size to arcseconds in the focal plane.

Save the Code V plano-convex lens design to a file on the disk, and then read back in the achromatic doublet design. Replace the plano-convex lens on the bench with the doublet lens (#31402) and repeat the comparison between theory and observation as outlined in the previous two paragraphs. Quantify wherever possible how much better is the achromat performance as compared to the plano-convex singlet lens.

If you finish early you may wish to examine the images (off-axis especially) produced by the 80mm EFL $f/2.8$ triplet lens, which is an example of the Cooke triplet design. In Code V there is a sample lens file for a Cooke triplet, but this does not describe the identical lens used on the bench.

Analysis. Convert any “raw” measurements made during the lab to more meaningful units. For both the plano-convex lens and the achromatic doublet, use the on-axis spot size you derived to estimate the resolving power of the lens in “line pairs per millimeter” units. Lastly, take the lens data for the achromat given in the Cookbook and calculate (with pencil, paper, and a hand calculator—not with Code V!) the

power of the individual crown and flint elements under the thin lens approximation. If the Abbe number ν_d of the BK7 crown glass is 64.17 and that for the SF2 flint glass is 33.85, are your approximate element powers consistent with the combination being achromatic?

Mirror

Starting from the optical table setup used above, remove the lens holder and microscope from the path of the collimated light. Bolt a post holder to the optical table breadboard in the beam beyond the microscope's location, and insert the support post of the adjustable mirror mount. Reposition the microscope alongside the rail (but now pointed in a direction towards the mirror). Ask the instructor for details of how to set up the microscope near the mirror focus. The mirror is spherical and has a 1000 mm radius of curvature, for a focal length of 500 mm. So as to see images from the mirror with the microscope, you will be using the mirror off-axis today.

The image of the pinhole formed by the mirror is very difficult to find, and so once the mirror and microscope are setup (you will want the microscope located as close to the rail as possible without blocking the parallel light between the telephoto lens and the mirror, so that the off-axis angle will be as small as possible) it will help tremendously if you replace the QTH light source with the HeNe laser. Without changing the position of the post collars, remove the QTH light source and condensing lens (but leave the pinhole where it is), and insert the post of the laser mount into the post holder used for the light source. By adjusting the laser alone, you should be able to get some laser light to pass through the pinhole. This will then produce a more visible beam (no more than a centimeter in diameter, however) which you can follow as it reflects off the mirror. *DO NOT LOOK DIRECTLY INTO THE BEAM*; even though it has been attenuated by the pinhole and expanded in diameter by the collimated lens, the laser light is still intense and would be focused by your eye lens back to a point on your retina, so avoid eye contact with it and **as always** remember to be conscious of where reflections send the laser light. You may now adjust the spherical mirror so that the reflected beam is directed towards the microscope (*BUT DO NOT LOOK THROUGH THE MICROSCOPE AT THE LASER LIGHT*); use a piece of paper to establish approximate alignment.

Once you have approximate alignment using the laser, measure the off-axis angle between the microscope angle and the pinhole (= optical axis of the telephoto lens) as seen from the mirror. You may use the nominal 0.5 m focal length of the mirror in your derivation of this off-axis angle. Then turn off the laser and return the QTH light source and condensing lens to their former positions. Alignment prior to the pinhole is not critical given the diffuse illumination following the opal glass. You should now be able to pick up the image of the pinhole formed by the mirror in the microscope.

Adjust for focus and best alignment.

To enter the spherical mirror's parameters into Code V, reset the software with "File → New." Set a single wavelength of 550 nm and an entrance pupil diameter of 50 mm, using the "Lens → System Data → Wavelengths" and "Lens → System Data → Pupil" menus. Insert 3 surfaces:

Surface	Radius	Thickness	Glass	RMD	Aperture
STO		600			25
2	-1000	0		REFL	25
3		500			25

Now you need to specify the tilt of the mirror. Find instructions for this in the small Code V manual and ask if you need help. Make sure the surface type is "reflect" and you have specified it to decenter and tilt. Specify an A-tilt of however many degrees you measured the mirror tilt to be.

Repeat this for surface 3. You can now draw the lens and perform other analyses as you did before.

Finally, switch to the measuring eyepiece, calibrate its divisions with the Ronchi Ruling, and determine the length and width of the image when the focus is adjusted to minimize the image size. Make the same measurement using Code V and compare theory to observation. Do you see color in the image when viewed through the microscope? Where does this most likely come from? If your theory can be tested, do so before turning off the light source and record the results of your tests.

Analysis. Calculate (not using Code V!) the spherical aberration you would expect to be present were the 50 mm diameter 0.5 m focal length spherical mirror used on-axis, and compare to the spot sizes observed at the off-axis angle used in this lab. What is the minimum spherical aberration blur size on-axis in units of arcseconds?

Discussion. Compare the range of image spot sizes encountered in this lab to the diffraction limit for $\lambda = 500$ nm light in a 50 mm aperture lens or mirror. By what factor would the observed spot sizes need to decrease before these optics would become "diffraction-limited?" Would you expect that aberrations or diffraction effects are more important in practice usually with lenses of 2-inch and larger diameters? Why?

Without searching through textbooks or the literature or performing tedious calculations, consider finally your achromatic doublet lens: this lens is designed to bring two wavelengths of light to a common focus. The residual chromatic differences at intermediate wavelengths is known as "secondary chromatic aberration" (or "secondary color" in the vernacular). Was the image produced by the achromat you observed white (i.e. entirely colorless)? Do you think it is possible to design a system of lenses which is corrected for secondary color—that is, one which brings three wavelengths to

a common focus? Speculate (don't do any real work) on what this might involve.