

# **Lab 11 - Optical Ray Tracing and Optical Aberrations**

## **I. Objective**

To study the use of a standard ray tracing software and to solve problems in geometric optics by comparing simple experimental observations with ray tracing solutions.

## **II. Introduction**

Ray tracing is a way of generating optical path in a system based on the laws of geometric optics. By successively applying the laws of reflection and refraction on the optical surface (lens, mirror, screen, iris, etc.), a light ray can be propagated from the source to they target and thereby generating an *approximate* property of the optical system.

To simplify computation and usage, a number of assumptions on the optics have been made. For example, a ray is treated as a mathematical abstraction with a point of origination and a direction only. Properties such as energy, polarization are not included. Furthermore, in this experiment, the wave nature of light is not included. Therefore, the results derived from a ray tracing is treated as an approximation which, however, is usually adequate for general application.

The primary advantage of a ray tracing software such as “BEAM 2” is that it allows interactive analysis and design of simple optical system. By editing data into an “optics table” and a “ray table”, the user can readily produce the optical layout as well as the coordinates of the rays. This way, adjustment of the optical system can be made to reveal the underlying properties of the system.

## **III. Procedure**

Beam 2 can be invoked by clicking on its icon in the Windows environment. Before starting the experiment, read the BEAM 2 manual. Pay specific attention Chapters 7,8, and 9 which describe the coordinate system, the optics table, and the ray table.

### **A. Focal Length**

In this exercise, the focal length of a spherical mirror will be determined by adjusting the screen position in the optics table so that all rays approximately converge on the same point. Construct a system with:

1. A spherical mirror with a curvature of -0.8 and located at  $Z_0=1$  unit.
2. A screen located at position  $Z_0=0.5$  unit.
3. A source with 9 parallel rays with X-intercept ranging from 0.2 to -0.2.

Set your Xgoal to 0.

Run BEAM 2 to calculate the rms deviation between Xgoal and Xfinal. Adjust  $Z_0$ , the expected focal length, to minimize the rms error. Determine the focal length and compare

it to the theoretical value. (Note: The rms value will not attain perfect zero due to spherical aberration.)

## B. Spherical Aberration

In the previous exercise, the phenomenon of spherical aberration was observed as a slight divergence at the ideal focal point. This is due to the fact that rays striking the edges of the lens are refracted more strongly than the paraxial ones. A quick remedy is to use an iris to block off the perimetric region of the lens. Construct an optical system as follows:

1. A source with 9 rays, originating from  $Z=0$  and slopes varying between  $-0.3$  to  $0.3$ .
2. An iris at  $Z=4.5$  and Diameter  $D=4$
3. A convex lens located from  $Z=5$  to  $Z=6$  with curvature of the two surfaces equal to  $-0.3$  and  $0.3$  respectively.
4. A screen at  $Z=12$ .

With the diameter of the iris set at  $D=4$ , run BEAM 2 to determine the layout. Significant divergence of the rays should be visible. Print the layout. Adjust the diameter of the iris inward so that the remaining (unblocked) rays are nearly focused. Record the diameter of the iris for this nearly focused condition and print out a layout of the system.

## C. Aberrations due to tilted optics

In this part of the lab, you will examine the effect of a simple optical misalignment: tilted optics. Define an optics table of 4 surfaces consisting of

- (a) an iris at  $z=4.5$  with a diameter of 1.6
- (b) a  $0.3$  curvature surface at  $z=5.0$  with a diameter of 3.6
- (c) a  $-0.3$  curvature surface at  $z=6.0$  with a refractive index of 1.66 and a diameter of 3.6
- (d) a film at  $z=8.25$

(I.) With this optics table, use the following ray table: (this table represents a collimated laser beam along the optical axis)

17 rays		Lab11.RAY				
X0	Y0	U0	Xfinal	Yfinal	notes	
2.0	:	-0.0	:	:	:	
1.5	:	-0.0	:	:	:	
1.0	:	-0.0	:	:	:	
0.5	:	-0.0	:	:	:	
0.0	:	-0.0	:	:	:	
-0.5	:	-0.0	:	:	:	
-1.0	:	-0.0	:	:	:	
-1.5	:	-0.0	:	:	:	
-2.0	:	-0.0	:	:	:	
0.0	-2.0	-0.0	:	:	:	
0.0	-1.5	-0.0	:	:	:	
0.0	-1.0	-0.0	:	:	:	
0.0	-0.5	-0.0	:	:	:	
0.0	0.5	-0.0	:	:	:	
0.0	1.0	-0.0	:	:	:	
0.0	1.5	-0.0	:	:	:	
0.0	2.0	-0.0	:	:	:	

Run and print the layout. Then use the plot function with the random function to generate a 2-plot of the image.

(II.) Use the following ray table: (this table represents a collimated laser beam which is incident on the lens at a large angle relative to the optical axis)

17 rays			Lab11a.RAY			
X0	Y0	U0	Xfinal	Yfinal	notes	
4.0	:	-0.4	:	:	:	:
3.5	:	-0.4	:	:	:	:
3.0	:	-0.4	:	:	:	:
2.5	:	-0.4	:	:	:	:
2.0	:	-0.4	:	:	:	:
1.5	:	-0.4	:	:	:	:
1.0	:	-0.4	:	:	:	:
0.5	:	-0.4	:	:	:	:
0.0	:	-0.4	:	:	:	:
2.0	-2.0	-0.4	:	:	:	:
2.0	-1.5	-0.4	:	:	:	:
2.0	-1.0	-0.4	:	:	:	:
2.0	-0.5	-0.4	:	:	:	:
2.0	0.5	-0.4	:	:	:	:
2.0	1.0	-0.4	:	:	:	:
2.0	1.5	-0.4	:	:	:	:
2.0	2.0	-0.4	:	:	:	:

Run and print the layout. Then use the plot function with the random function to generate a 2-plot of the image.

How does the tilted lens effect the location and shape of the focal point?

#### D. Imaging properties of a converging lens.

In this part of the lab, you will make observations concerning the imaging properties of a converging lens that will be compared to the ray tracing results.

- 1) Mount a large 3" diameter lens with a focal length of 10cm (4").
- 2) By placing an index card at the focal point, use the positive lens to form an image of a scene outside.
- 3) Do all parts of the image focus at the same point? In answering, compare the focusing of different colors. Compare the image near the center with that near the periphery. Using physical reasons explain the distortion of the image.
- 4) Turn the lens 30° relative to the direction of incident light. What happens to the image at the focal plane?
- 5) Now mount a 1" diameter lens with the same focal length. Compare the images produced by the large diameter lens and the 1" lens. How are they different? Why does the difference depend on the physical size of the lens?

- 6) Turn the lens  $30^\circ$  relative to the direction of incident light. How do the results compare to III.D.4?

### **E. Eyeglass Challenge**

Myopia (near sightedness) is caused by a defect of the eye whereby light is focused in front of the retina. A concave lens may be used to correct this problem.

Given the following parameters for the eye:

	<b>Location</b>	<b>Refraction index</b>	<b>Diameter</b>	<b>Curvature</b>
<b>Cornea</b>	0 -- 4 mm	1.38		0.125
<b>Iris</b>	3.5 mm	2.5	2.5	
<b>Eye lens</b>	4 -- 8 mm	1.38		0.05 convex
<b>Interior Eye</b>	8 -- 29 mm	1.44		
<b>Retina</b>	34 mm			

use BEAM 2 to determine the focal point inside the eye. Design a corrective eyeglass at location -8 mm --- -7mm to re-focus the image onto the retina. (Note: Try the auto-adjust function to determine the focus and the plot function to generate a 2-d x-y view of the image)

### **IV. Discussion Questions**

1. Compare the simulation results of III.A and III.B to the experimental results of III.D.3 and III.D.5. In particular, do the experimental observations match the trends of the simulations? You may wish to consult Hecht for descriptions of the various aberrations.
2. Compare the simulation results of III.C to III.D.4 and III.D.6. Do the experimental observations match the trends of the simulations?
3. Based on your lab results, why is it important when using lenses to (a) have the lens perpendicular to the direction of the incident light (b) have light pass near center of lens?