13. Geometrical Optics

I. Focal Length and Magnification of a Concave Mirror

PURPOSE

The purpose of this experiment is to determine the focal length of a concave mirror and to measure the magnification for a certain combination of object and image distances.

THEORY

For a spherically curved mirror:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{1}$$

where f is focal length, d_o is the distance between the object and the mirror, and di is the distance between the image and the mirror. By measuring do and di the focal length can be determined. Magnification, M, is the ratio of image size to object size. If the image is inverted, M is negative.

<u>Part I: Object at Infinity</u>

In this part, you will determine the focal length of the mirror by making a single measurement of d_i with $d_o \cong \infty$.

Procedure

1. Hold the mirror in one hand and the half-screen in the other hand. Use the concave side of the mirror to focus the image of a distant bright object (such as a window or lamp across the room) on the half-screen. (See Figure 1.)

2. Have your partner measure the distance from the mirror to the screen. This is the image distance, d_i. d_i = _______________

Analysis

1. As d_o approaches infinity, what does $1/d_o$ approach?

2. Use the Equation (1) to calculate the focal length.

f = ___________

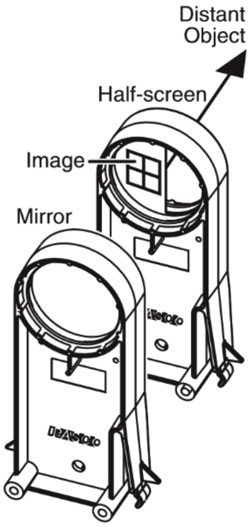

Fig. 1.

Part I: Object Closer than Infinity

In this part, you will determine the focal length of the mirror by measuring several pairs of object and image distances and plotting $1/d_o$ versus $1/d_i$.

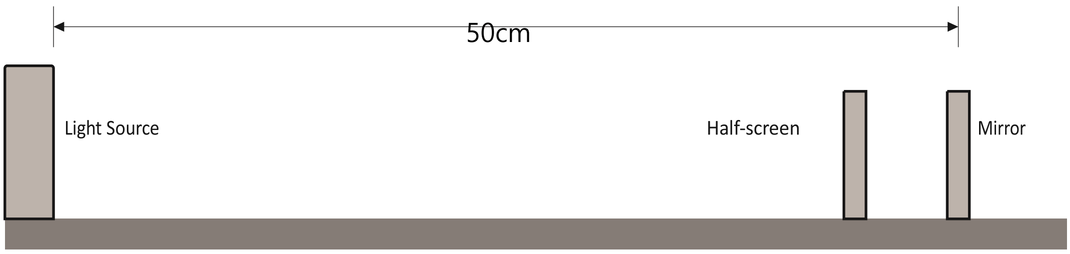

Fig. 2.

Procedure

1. Place the light source and the mirror on the optics bench 50 cm apart with the light source's crossed-arrow object toward the mirror and the concave side of the mirror toward the light source. Place the half-screen between them (see Figure 2).
2. Slide the half-screen to a position where a clear image of the crossed-arrow object is formed. Measure the image distance and the object distance. Record these measurements (and all measurements from the following steps) in Table 1.
3. Repeat step 2 with object distances of 45 cm, 40 cm, 35 cm, 30 cm, 25 cm.

4. With the mirror at 25 cm from the light source and a clear image formed on the half-screen, measure the object size and image size. To measure the image size, hold a small scrap of paper against the half-screen and mark two opposite points on the crossed-arrow pattern (see Figure 3). If at least half of the pattern is not visible on the screen, have your partner slightly twist the mirror to bring more of the image into view. Remove the paper and measure between the points. Measure the object size between the corresponding points directly on the light source.

Table 1: Image and Object Distances

d_o	d_i	$1/d_o$	$1/d_i$	**Image Size**	**Object Size**
50.0 cm					
45.0 cm					
40.0 cm					
35.0 cm					
30.0 cm					
25.0 cm					

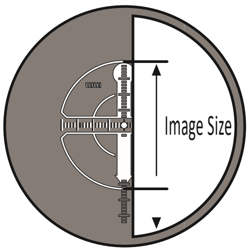

Fig. 3.

Analysis Part A : Focal Length

1. Calculate $1/d_o$ and $1/d_i$ for all six rows in Table 1.

2. Plot $1/d_0$ versus $1/d_i$ and find the best-fit line (linear fit). This will give a straight line with the x- and y-intercepts equal to $1/f$. Record the intercepts (including units) here:

   y-intercept = $1/f$ = _______________

   x-intercept = $1/f$ = _______________

Note: You can plot the data and find the best-fit line on paper or on a computer.

3. For each intercept, calculate a value of f and record it in Table 2.
4. Find the percent difference between these two values of f and record them in Table 2.
5. Average these two values of f. Find the percent difference between this average and the focal length that you found in Part I. Record these data in Table 2.

Table 2: Focal Length

	f
Result from x-intercept	
Result from y-intercept	
% difference between results from intercepts	
Average of results from intercepts	
Result from Part I	
% difference between Average of results from intercepts and result from Part I	

Analysis Part B : Magnification

1. For the last data point only (d_o = 25 cm), use the image and object distances to calculate the magnification, M. Record the results in Table 3.

$$M = -\left(\frac{d_i}{d_o}\right) \quad (2)$$

2. Calculate the absolute value of M using your measurements of the image size and object size. Record the results in Table 3.

$$|M| = \frac{image.size}{object.size} \quad (3)$$

3. Calculate the percent differences between the absolute values of M found using the two methods. Record the results in Table 3.

Table 3: Magnification

M calculated from image and object distances	
$\lvert M\rvert$ calculated from image and object sizes	
% difference	

Questions

1. Is the image formed by the mirror upright or inverted?
2. Is the image real or virtual? How do you know?
3. By looking at the image, how can you tell that the magnification is negative?
4. You made three separate determinations of f (by measuring it directly with a distant object, from the x-intercept of your graph, and from the y-intercept). Where these three values equal? If they were not, what might account for the variation?

II. Telescope

PURPOSE

In this experiment, you will construct a telescope and determine its magnification.

THEORY

An astronomical telescope consists of two convex lenses. The astronomical telescope in this experiment will form an image in the same place as the object (see Figure 4).

The lenses are thin compared to the other distances involved, which allows the Thin Lens Formula to be used:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{4}$$

where f is focal length, d_o is the distance between the object and the lens, and d_i is the distance between the image and the lens. The magnification, M, of a two-lens system is equal to the product of the magnifications of the individual lenses:

$$M = M_1 M_2 = \left(\frac{-d_{i1}}{d_{o1}}\right)\left(\frac{-d_{i2}}{d_{o2}}\right) \tag{5}$$

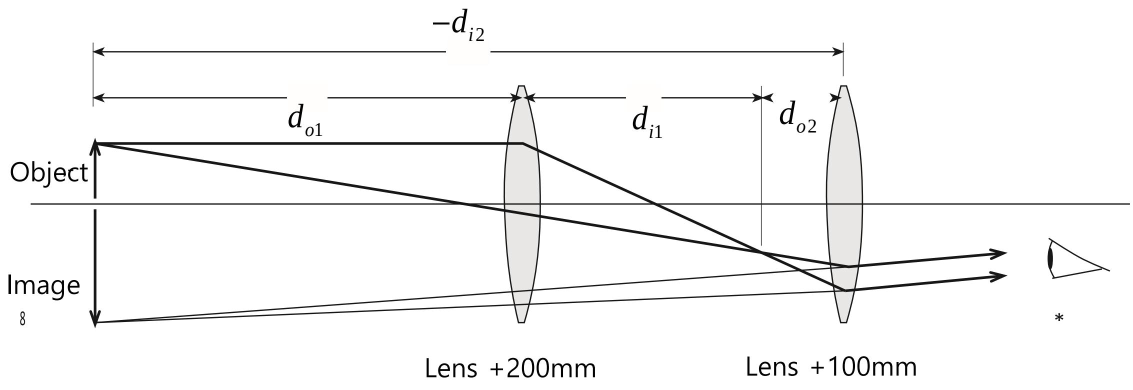

Fig. 4.

SETUP

1. Tape the paper grid pattern to the screen to serve as the object.

2. The +200 mm lens is the objective lens (the one closer to the object). The +100 mm lens is the eyepiece lens (the one closer to the eye). Place the lenses near one end of the optics bench and place the screen on the other end (see figure 4). Their exact positions do not matter yet.

Fig. 5.

PROCEDURE

1. Put your eye close to the eyepiece lens and look through both lenses at the grid pattern on the screen. Move the objective lens to bring the image into focus.
2. In this step, you will adjust your telescope to make the image occur in the same place as the object. To do this, you will look at both image and object at the same time and judge their relative positions by moving your head side to side. If the image and object are not in the same place, then they will appear to move relative to each other. This effect is known as parallax.

   Open both eyes. Look with one eye through the lenses at the image and with the other eye past the lenses at the object (see Figure 6). The lines of the image (solid lines shown in Figure 7) will be superimposed on the lines of the object (shown as dotted lines in Figure 7). Move your head left and right or up and down by about a centimeter. As you move your head, the lines of the image may move relative to the lines of the object due to the parallax. Adjust the eyepiece lens to eliminate parallax. Do not move the objective lens. When there is no parallax, the lines in the center of the lens appear to be stuck to the object lines.

   Note: You will probably have to adjust the eyepiece lens by no more than a few centimeters.
3. Record the positions of the lenses and screen in Table 4.
4. Estimate the magnification of your telescope by counting the number of object squares that lie along one side of one image square. To do this, you must view the

image through the telescope with one eye while looking directly at the object with the other eye. Remember that magnification is negative for an inverted image. Record the observed magnification in Table 4.

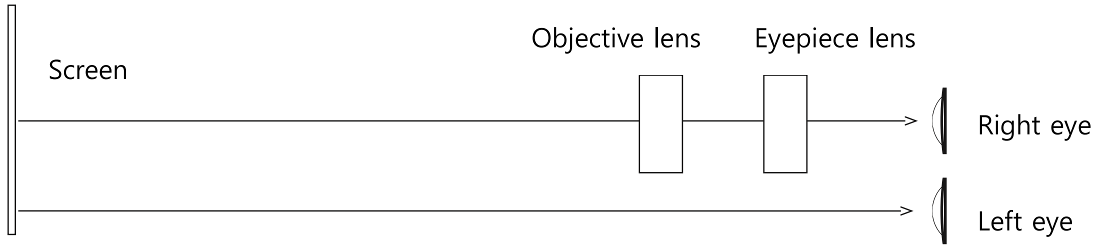

Fig. 6.

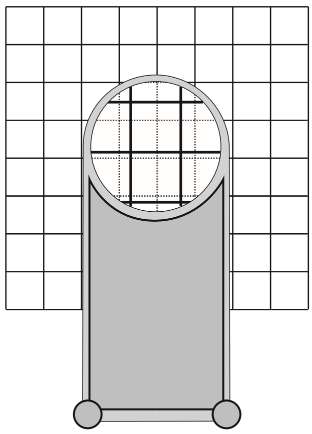

Fig. 7

Analysis

To calculate the magnification, complete the following steps and record the results in Table 4 :

1. Measure d_{o1}, the distance from the object (paper pattern on screen) to the objective lens.

2. Determine d_{i2}, the distance from the eyepiece lens to the image. Since the image is in the plane of the object, this is equal to the distance between the eyepiece lens and the object (screen). Remember that the image distance for a virtual image is negative.
3. Calculate d_{i1} using d_{o1} and the focal length of the objective lens in the Thin Lens Formula (Equation 4).
4. Calculate d_{o2} by subtracting d_{i1} from the distance between the lenses.
5. Calculate the magnification using Equation 5.
6. Calculate the percent difference between the calculated magnification and the observed value.

Table 4: Results

Position of Objective Lens	
Position of Eyepiece Lens	
Position of Screen	
Observed magnification	
d_{o1}	
d_{i2}	
d_{i1}	
d_{o2}	
Calculated Magnification	
Percent Difference	

Questions

1. Is the image inverted or upright?
2. Is the image that you see through the telescope real or virtual?

Further Study

Image formed by the objective lens

Where is the image formed by the objective lens? Is it real or virtual? Use a desk lamp to brightly illuminate the paper grid (or replace the screen with the light source's crossed-arrow object). Hold a sheet of paper vertically where you think the image is. Do you see the image? Is it inverted or upright? Remove the sheet of paper and hold a pencil in the same place. Look through eyepiece lens; you will see two images, one of the pencil and one of the grid pattern. Are both images inverted? Use parallax to determine the location of the pencil image.

Object at infinity

Remove the screen and look through the lenses at a distant object. Adjust the distance between the lenses to focus the telescope with your eye relaxed. Estimate the observed magnification. Now calculate the magnification by taking the ratio of the focal lengths of the lenses. Compare the calculated magnification to the observed magnification. How is the distance between the lenses related to their focal lengths?

Galilean Telescope

Make a new telescope using the -150 mm lens as the eyepiece and the +250 mm lens as the objective lens. Look through it at a distant object. Adjust the distance between the lenses to focus the telescope with your eye relaxed. How is the distance between the lenses related to their focal lengths? How does the image viewed through this telescope differ from that of the previous telescope? Is the magnification positive or negative?

III. Microscope

PURPOSE

In this experiment, you will construct a microscope and determine its magnification.

THEORY

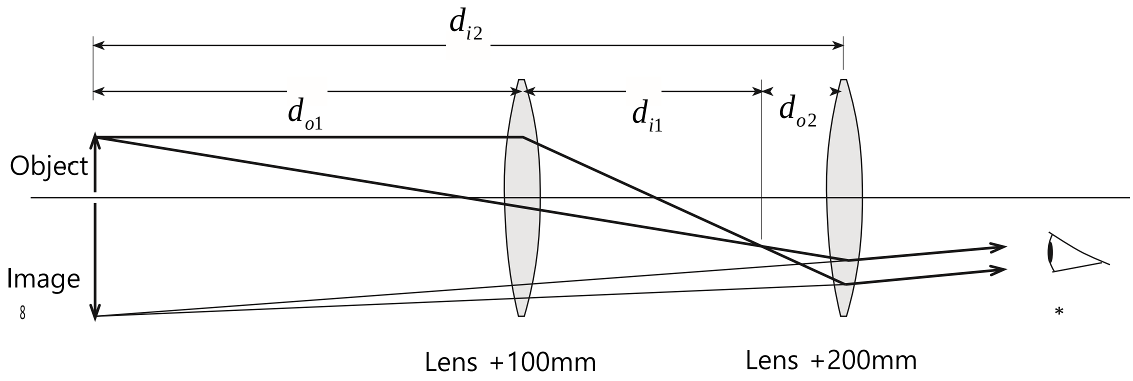

Fig. 8.

A microscope magnifies an object that is close to the objective lens. The microscope in this experiment will form an image in the same place as the object (see Figure 8).
The lenses are thin compared to the other distances involved, which allows the Thin Lens Formula to be used:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{6}$$

where f is focal length, d_o is the distance between the object and the lens, and di is the distance between the image and the lens. The magnification, M, of a two-lens system is equal to the product of the magnifications of the individual lenses:

$$M = M_1 M_2 = \left(\frac{-d_{i1}}{d_{o1}}\right)\left(\frac{-d_{i2}}{d_{o2}}\right) \tag{7}$$

SETUP

1. Tape the paper grid pattern to the screen to serve as the object.
2. The +100 mm lens is the objective lens (the one closer to the object). The +200 mm lens is the eyepiece lens (the one closer to the eye). Place the lenses near the middle of the optics bench and place the screen near the end of the bench (see Figure 9).

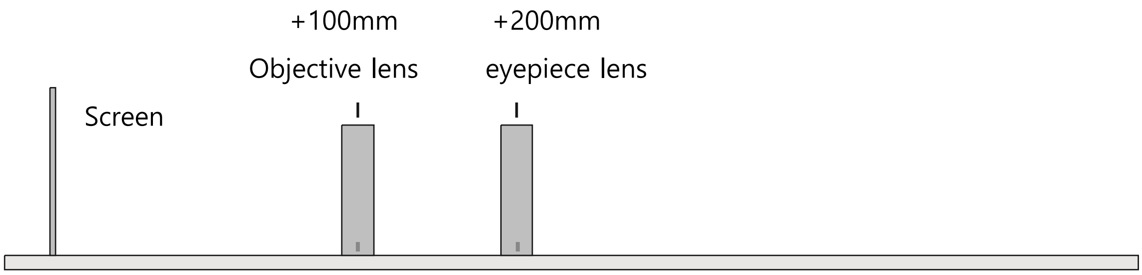

Fig. 9.

PROCEDURE

1. Put your eye close to the eyepiece lens and look through both lenses at the grid pattern on the screen. Move the objective lens to bring the image into focus.
2. In this step, you will adjust your microscope to make the image occur in the same place as the object. To do this, you will look at both image and object at the same time and judge their relative positions by moving your head side to side. If the image and object are not in the same place, then they will appear to move relative to each other. This effect is known as parallax.

   Open both eyes. Look with one eye through the lenses at the image and with the other eye past the lenses at the object (see Figure 10). The lines of the image (solid lines shown in Figure 11) will be superimposed on the lines of the object (shown as dotted lines in Figure 11). Move your head left and right or up and down by about a centimeter. As you move your head, the lines of the image may move relative to the lines of the object due to the parallax. Adjust the eyepiece lens to eliminate parallax. Do not move the objective lens. When there is no parallax, the lines in the center of the lens appear to be stuck to the object lines.

Note: Even when there is no parallax, the lines may appear to move near the edges of the lens because of lens aberrations. Concentrate on the part of the image seen through the centers of the lenses. Be sure that the eye looking at the object (the left eye in Figure 16.3) is looking directly at the object and not through the objective lens.

3. Record the positions of the lenses and the object in Table 5.
4. Estimate the magnification of your microscope by counting the number of object squares that lie along one side of one image square. To do this, you must view the image through the microscope with one eye while looking directly at the object with the other eye. Remember that magnification is negative for an inverted image. Record the observed magnification in Table 5.

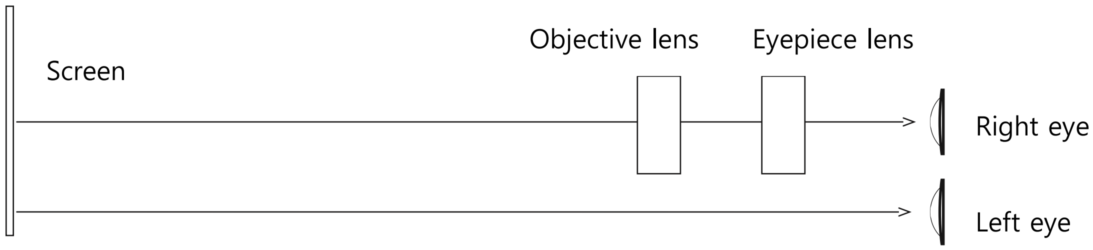

Fig. 10.

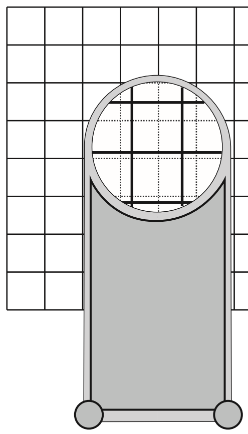

Fig. 11

Analysis

To calculate the magnification, complete the following steps and record the results in Table 5 :

1. Measure d_{o1}, the distance from the object (paper pattern on screen) to the objective lens.

2. Determine d_{i2}, the distance from the eyepiece lens to the image. Since the image is in the plane of the object, this is equal to the distance between the eyepiece lens and the object (screen). Remember that the image distance for a virtual image is negative.
3. Calculate d_{i1} using d_{o1} and the focal length of the objective lens in the Thin Lens Formula (Equation 6).
4. Calculate d_{o2} by subtracting d_{i1} from the distance between the lenses.
5. Calculate the magnification using Equation 7.
6. Calculate the percent difference between the calculated magnification and the observed value.

Table 5: Results

Position of Objective Lens	
Position of Eyepiece Lens	
Position of Screen	
Observed magnification	
d_{o1}	
d_{i2}	
d_{i1}	
d_{o2}	
Calculated Magnification	
Percent Difference	

Questions

1. Is the image inverted or upright?
2. Is the image that you see through the microscope real or virtual?

Further Study

Image formed by the objective lens

Where is the image formed by the objective lens? Is it real or virtual? Us a desk lamp to brightly illuminate the paper grid (or replace the screen with the light source's crossed-arrow object). Hold a sheet of paper vertically where you think the image is. Do you see the image? Is it inverted or upright? Remove the sheet of paper and hold a pencil in the same place. Look through eyepiece lens; you will see two images, one of the pencil and one of the grid pattern. Are both images inverted? Use parallax to determine the location of the pencil image.

Increasing magnification

While looking through your microscope, move the objective lens a few centimeters closer to the object. Which way do you have to move the eyepiece lens to keep the image in focus? How close can you move the objective lens and still see a clear image? (Make a pencil mark on the paper grid so you have something very small to focus on.) What is the theoretical limit to how close you can move the objective lens?