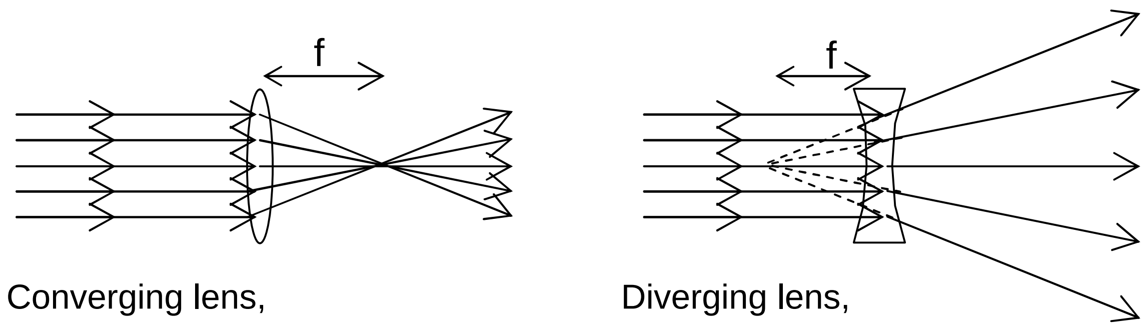
O5: Lenses and the refractor telescope

Introduction

In this experiment, you will study *converging* lenses and the lens equation. You will make several measurements of the focal length of lenses and you will construct a simple astronomical telescope. The components you will use are a kit from Learning Technologies, Inc. (www.starlab.com). At the end of the experiment the telescope is yours to keep.

Theory

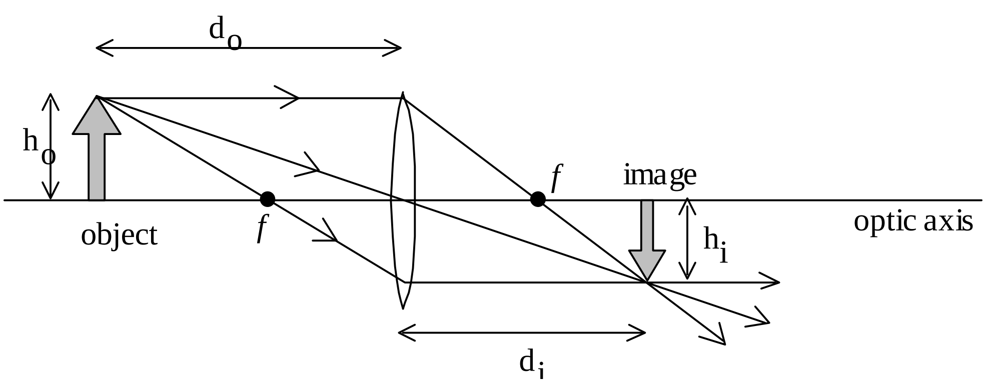
When a bundle of parallel light rays enters a converging lens, the rays are focused to a point in space a distance *f*, the focal length, from the lens. A converging lens is convex in shape, that is, thick in the middle and thin at the edges. A diverging lens is concave in shape, i.e. thin in the middle and thicker near the edges. Note that the diverging lens has a "virtual image" to the left of the lens, where the light rays never actually cross. The converging lens has a "real image" where the rays do cross.



A converging lens can be used to form an image on a screen of an object. *The lens equation* relates the focal length f of a lens, the object distance d_o and the image distance d_i ,

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}. \qquad (1)$$

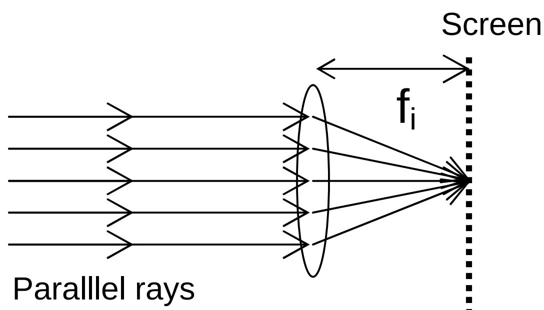
(This equation can used for both converging and diverging lens; the only difference is that the focal length f is positive for converging lenses, negative for diverging lenses.)



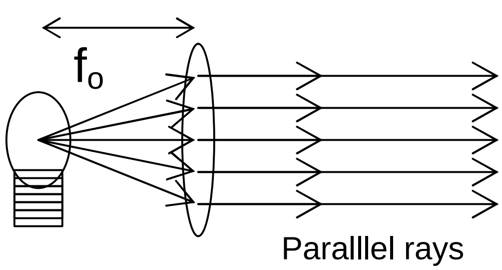
In the diagram above, the points labeled *f* are the focal points of the lens. *The lateral magnification*, m, of the image is defined as $m = \left|\frac{h_i}{h_o}\right|$. From the diagram above, one can show that m can also be written as: $m = \left|\frac{d_i}{d_o}\right|$.

In this lab, you will use two different techniques to measure focal lengths.

Method I: You will take a collimated beam of light (parallel rays) and focus this to a point using each of the converging lens from your telescope. The distance from the center of the lens to the screen when the optimal focus is formed tells us the focal distance of the lens. Equation (1) can also be applied to this situation. Since the incoming rays are parallel, the distance to the object d_o = infinity, or $1/d_o$ = zero. In this case it is clear that d_i=f.



To do this in the experiment you will first need to produce the parallel beam of light with which to measure the focal distances of your telescope lenses. This will be produced by the complementary method where a (different) lens is used to convert a point source of light (the filament at the center of the light bulb) into a parallel beam of light, as shown below.



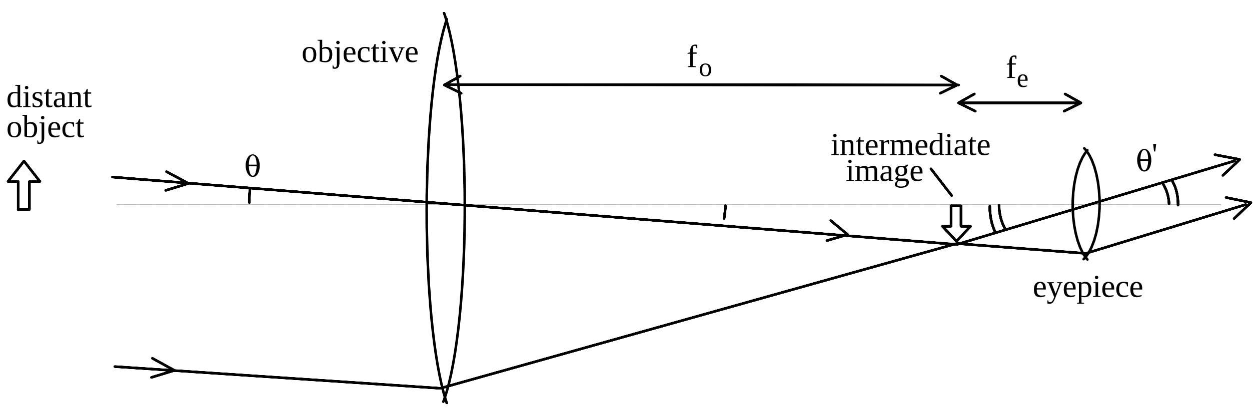
The point source is the object and the object distance d_o is the focal length f. With d_o = f, equation (1) predicts that $d_i = \infty$. The rays from the lens converge "at infinity".

Method II: Use the lens to form an image of an object, measure the distances d_i and d_o, and then use eq'n (1) to compute f.

In the last part of this lab, you will construct a simple astronomical telescope. The astronomical telescope consists of two lenses: an *objective lens* with a long focal length f_o, and an *eyepiece lens* with a short focal length f_e . The objective lens forms an image of a distant object (an object "at infinity"). By the lens equation, if the object distance is $d_o = \infty$, then the image distance is $d_i = f_o$. This image, which appears a distance f_o behind the objective lens, is called an intermediate image, because it is intermediate between the objective and eyepiece lens. The observer views this image through the eyepiece lens which acts as a magnifying glass. Note that a magnifying glass produces the largest magnification when the magnified object (i.e., the intermediate image in this case) is held a distance f_e from the magnifying glass.

The *angular magnification* M of the telescope is defined as the ratio $M = \frac{\theta'}{\theta}$,

where (as shown in the diagram below) θ' is the angular size of the image as viewed by the observer through the telescope and θ is the angular size of the distant object as viewed without the telescope.



Notice that the distance between the two lenses is $\ell = f_o + f_e$. From the diagram above, one can show that the angular magnification can also be written as $M = \frac{f_o}{f_e}$, the ratio of the focal lengths of the objective and eyepiece lenses.

Experimental Procedure

In this lab, you will use an optics bench, which is simply a rail, on which lenses are placed, with a ruler on the side for measuring distances. The other equipment includes a bright light source, which acts nearly like a point source, and a converging lens labeled "Lens A" which is in a brown fiberglass ring of an inch or so diameter. There is a frosted glass screen mounted on a similar brown holder and a metal plate with an aperture (a hole) in the shape of an arrow. The hole is covered with a frosted, translucent material (scotch tape). When this aperture is placed in front of the light source, it forms a convenient object for image-forming experiments.

In addition to these parts will be your own telescope consisting of two cardboard "telescoping" tubes, a small eyepiece lens in grey foam, and a large objective lens in a red plastic holder.

Part I. Use of a collimated beam

Here you will use Method I to measure the focal length of each of your telescope lenses. Attach the light source to the end of your rail (there is a thumbscrew that you can use to attach it). Connect the light source to the power supply and momentarily depress the "start" switch to turn on the light. You should not have the frosted arrow plate attached to the source yet. The filament inside the light source is very small and can be considered to be a point source. Use lens A (in the brown fiberglass ring) to form a parallel beam of light by arranging positioning the lens so that its focus coincides with the filament of the light bulb. You can do this by studying the image of the lens on a piece of paper and moving the paper in and out by a few feet. When the lens is positioned properly the size of the light spot on the paper should not change with the paper position, and it should be the size of the lens. Note that depending upon whether the paper is very close or far from the lens you may see a blue or a red "halo" around the beam spot, which has to do with chromatic aberration of the lens (different colors are focused slightly differently). You should be working far from the lens where the halo is red.

Now that you have a parallel beam of light, use this to determine the focal distance of each of your two telescope lenses. You can do this by placing each telescope lens in the collimated beam and focusing it on the frosted glass screen so as to find the distance to the image. To center the small eyepiece lens on the track you will need to rest it on the small "v" shaped aluminum block (this raises it's height). Note that you will want to measure distances from the center of the lens, which is not trivial to do for the small objective lens. Make a few measurements of the focal distance for each lens so as to be able to estimate an uncertainty. For each new trial also readjust the collimation of the parallel beam of light so that any errors from this step of the measurement are also averaged out.

Part II. Images and Magnification.

In this part, you will use Method II to measure the focal length of lenses your two telescope lenses

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(1) Place the light source at the end of the optics bench and attach it with the thumbscrew in the slot. Place the arrow aperture on the front of the light source; there is a magnet to hold it in place. It will save a little trouble in your calculations if you position the source so that the object (the frosted arrow) is exactly beside an integer mark (e.g. 2.0 cm) on the scale of the bench. Gently tighten the thumbscrew to secure the source, and record the position of the object.

(2) Arrange the small telescope eyepiece lens and the frosted glass screen so that a sharp image of the arrow appears on the screen (the situation will be similar to the bottom figure on page 1). Measure the distances d_i and d_o, as well as the image height h_i and object height h_o. Compute the lateral magnification $m = \left|\frac{h_i}{h_o}\right|$ and compare with the expected value $\left|\frac{d_i}{d_o}\right|$. Do the same but for a different set of distances (near the edge of where you can get things to work) d_i and d_o, again measuring height h_i and height h_o. Check how close equation (1) works for each of these cases.

(3) Do the same thing as (2) but for the large objective lens of your telescope.

Part III. The astronomical telescope.

Choose the lens with the longest focal length. This will be the objective lens with focal length f_o . Also choose the lens with the shortest focal length. This will be the eyepiece with focal length f_e. Place the eyepiece at one end of the optics rail and place the objective lens a distance $\ell = f_o + f_e$ from the eyepiece.

Aim the telescope towards the far end of the room, where there is an arrow and a graduated scale mounted on the wall, and adjust the telescope position until you can see the arrow through the telescope. It may be difficult to find the image since your telescope has a narrow field of view. Also, you may need to adjust the position of the eyepiece lens to get a sharp image. Is the final image you are looking at upright or inverted? Real or virtual? Explain your answers with words and diagrams.

Once you have found a clear image looking through the telescope, open your other eye so that you can look simultaneously at the enlarged image with one eye and the unenlarged image with the other eye. If you position the telescope just right, you can see the two scales side by side and hence estimate the angular magnification M of your telescope. It may be helpful to compare the full height of the piece of paper to the distance between each of the markings (which are 1/10 of the height of the paper). Compare your answer with the theoretical value of M .

Pre-Lab Questions.

1. What is the definition of the focal length of a converging lens? Illustrate your answer with a diagram.

2. Consider a lens with a focal length of f =20.0 cm which is used to image an object of height h_o = 4.0 cm, a distance d_o = 40.0 cm away. On graph paper, draw a diagram showing the size (h_i) and position (d_i) of the image formed by this lens. Check that the value of d_i obtained from your graph agrees with a calculation of d_i made by equation (1).

3. In the diagram on page 4.1, show that $\left|\frac{d_i}{d_o}\right| = \left|\frac{h_i}{h_o}\right|$.

4. Redo problem 2 but with the distance d_o=30.0 cm. What is the image distance d_i? What will the image height h_i be?

5. What is a collimated beam? Draw a sketch showing how you could produce one. Could you make a collimated beam using only a point source and a diverging lens?

6. An astronomical telescope has an objective lens with a focal length of 600mm and an eyepiece lens with a focal length of 30mm. What is the angular magnification of this telescope?

7. The Earth's moon as seen from the surface of the Earth has an angular size of roughly 0.5 degrees. We say that it 'subtends' an angle of 0.5 degrees. What is this angle in radians? The radian angular measurement is convenient because (by definition) the angle in radians is the ratio of the length of arc subtended to the radius of the circle.

8. If the Moon is roughly 385,000 km from the Earth, what must the Moon's diameter be to subtend this angle? How does that diameter compare to the Earth's diameter? How does the angle subtended by the Moon compare with the angle subtended by your thumbnail when you hold your arm straight out?

9. During a full solar eclipse, the Moon almost exactly covers the disk of the Sun. In other words, they subtend the same angle. If the distance from the Earth to the Sun is roughly 150 million kilometers, what is the diameter of the Sun?

10. If you were to look at the moon with the telescope described in problem 6, what effective angle would the moon subtend as viewed through the telescope?