Chapter 8

The Telescope

8.1   Purpose

In this lab, you will measure the focal lengths of two lenses and use them to construct a simple telescope which inverts the image like the one developed by Johannes Kepler. Because one lens has a large focal length and the other lens has a small focal length, you will use different methods of determining the focal lengths than was used in 'Optics of Thin Lenses' lab.

8.2   Introduction

8.2.1   A Brief History of the Early Telescope

Although eyeglass-makers had been experimenting with lenses well before 1600, the first mention of a telescope appears in a letter written in 1608 by Hans Lippershey, a Dutch spectacle maker, seeking a patent for a telescope. The patent was denied because of easy telescope duplication and difficulty in patent enforcement.

The instrument spread rapidly. Galileo heard of it in the early 1600s and quickly made improvements in lens grinding that increased the magnification from a relatively low value of 2 to as much as 30. With these more powerful telescopes, he observed the Milky Way, the mountains on the Moon, the phases of Venus, and the moons of Jupiter.

These early telescopes were a type of 'opera glass,' producing erect or 'right side up' images but having limited magnification. When Johannes Kepler, a German mathematician and astronomer working in Prague under Tycho Brahe, heard of Galileo's discoveries, he perfected a different form of telescope. Although Kepler's design inverts the image, it is much more powerful than the Galilean type.

This lab we will use the lenses supplied with the telescope kit. The kit consists of two lenses

and other components to hold the lenses in the proper alignment. The short focal length lens is called the eyepiece and the large focal length lens is called the 'objective' lens.

First, you will measure the focal length of the eyepiece (magnification) lenses using a *simple imaging method*. Next, you will measure the focal length of the larger objective lens using an *auto-collimation technique*.

After this is completed, you will construct a simple telescope. The length of the telescope, when in focus, will be compared with the value expected from your measurements of the focal lengths. As a final exercise, the magnification of the telescope will be determined experimentally and compared against the expected, calculated, values.

8.3 Procedure

8.3.1 Simple Measurement of Eyepieces Lens's Focal Length

As discussed in the 'Optics of Thin Lenses' lab, the *focal length* is the distance from the lens in which parallel light rays are bent and focused to a point (the *focal point*) after passing through the lens. The focal length is a characteristic of each lens and does not change. Refer to the following diagram.
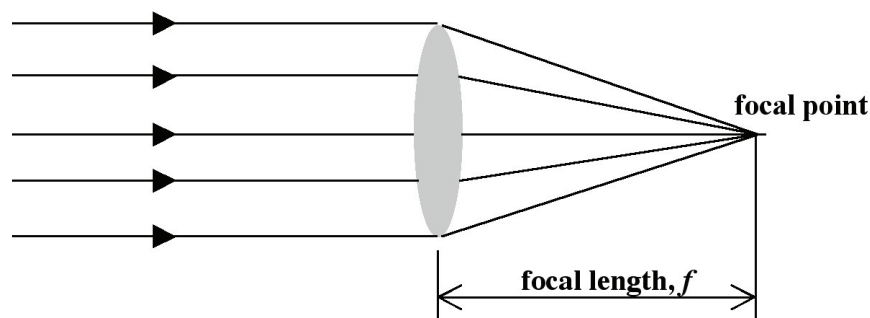

Figure 8.1: Focusing parallel light rays from a distant object

The eyepiece lens is the smaller diameter lens found inside of the foam holder with a small cardboard tube to align the lens in the foam.

1. Tape a sheet of white paper to the table directly under one of the fluorescent ceiling lights. The ceiling light serves as the light source and the paper serves as the imaging screen for focal length measurements.

2. Using a ruler, measure the focal length of the eyepiece lens by holding the lens between your fingers and varying the lens height until the image of the light source on the paper is smallest and in focus. (You should be able to see the lines of the light panel; that's how you know the image is in focus.). Record the value below

Eyepiece lens focal length _____

3. Be sure that the plane of the lens is horizontal and that the lens and white paper are immediately under the ceiling light. Try not to touch the surface of the lenses with your fingers. The focal length of the eyepiece lens is fairly small.

4. A single lens can act like a magnifying glass. Magnification occurs when an object is placed less than one focal length (f) away from the lens. Maximum magnification occurs when an object is placed *exactly one focal length* from the lens. If an object is placed farther from the lens than one focal length, the lens will minify instead of magnify. After you have measured the focal lengths of the eyepiece lens, put a piece of paper with some writing on it on your bench. Place the eyepiece lens on the paper and look through it. Slowly bring it back away from the paper. You may have to adjust the distance of your eye from the lens in order to keep the image in focus. Watch what happens to the magnification as you move the lens. As you approach the focal point, the image suddenly becomes very large. As you move through this point, the image inverts and starts getting smaller!

8.3.2 Using an Auto-Collimation Technique to Measure the Focal Length of the Objective Lens

The Simple Method is really just an approximation. In the previous lab, we used a more exact method based on the *Thin Lens Equation*:

$$\frac{1}{f} = \frac{1}{d_{object}} + \frac{1}{d_{image}}, \tag{8.1}$$

where f is the focal length, and d_{image} and d_{object} are the distances from the lens to the object and image, respectively.

In the simple method, we were able to make the approximation that the distance to the lights was a lot greater than the distance from the lens to the paper *i.e.* $d_{object} >> d_{image}$. How would this approximation change the thin lens equation? Notice that the approximation is appropriate only for a lens like the eyepiece lens which has a small focal length. In fact, for our purposes, we'll assume that the Simple Method yields sufficiently accurate results for the measurement of the eyepiece's focal length.

But, since the distance to the lights is only a few times the distance to the paper when we used the objective lens, we've got a problem—if we're going to use the Simple Method and get good results for the objective lens, where do we have to place the object?

A clever method to get around this obstacle is called *Auto-Collimation*. Auto-collimation exploits the forward-backward symmetry of light rays passing through the optical system, as shown in Figure 8.2.

In the Auto-Collimation procedure, a source of light is placed at a distance, d, to the left of a lens of focal length f. Rays emerge from the right hand side of the lens, bounce off a plane mirror, and travel back through the lens.
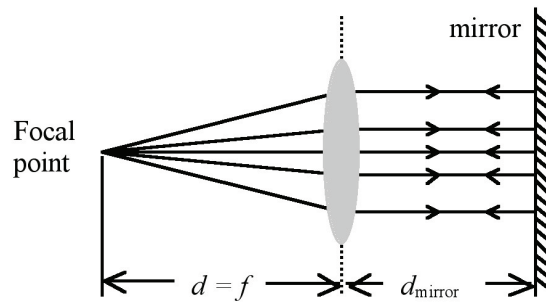
Figure 8.2: Auto-Collimation

If $d = f$, then the emerging rays are parallel to each other. These rays reflect from the mirror, pass back through the lens, and form an image at d. Since the rays incident upon the mirror are parallel, the reflected image is *independent* of the lens mirror distance, d_{mirror}! If, however, $d \neq f$, then the rays emerging from the lens are *not* parallel and the quality of the reflected image *will* depend on d_{mirror}.

The method isn't practical for the small eyepiece lens, so we'll only do it with the objective lens.
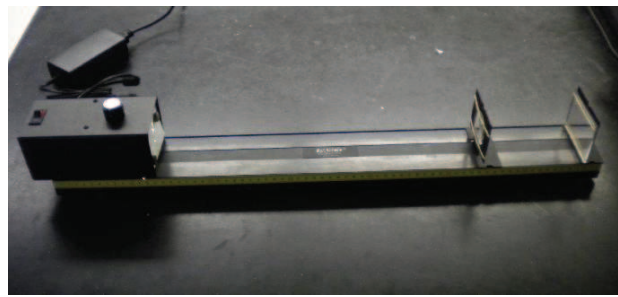

Figure 8.3: Setup for the auto collimation procedure. The light source has an aperture to produce a narrow slit of light. The mirror is at the far end of the optic rail. The objective lens is attached to the holder 35-45 cm from the light source.

1. Attach the cardboard aperture slit to the light source face with a small magnet to define a narrow vertical beam of light.

2. Attache the object lens to a holder with rubber bands at the edge of the lens. Attach the mirror to another holder. Place the mirror at the far end of the optics rail from the light source. Place the lens 35 - 45 cm from the light source. See figure 8.3

3. Vary d until a sharp reflected image is produced at the source position. Refer to Figure 8.4

4. Confirm that the reflected image in independent of d_{mirror} Change the position of the mirror and make sure that the quality of the image is not affected. Use your hand to
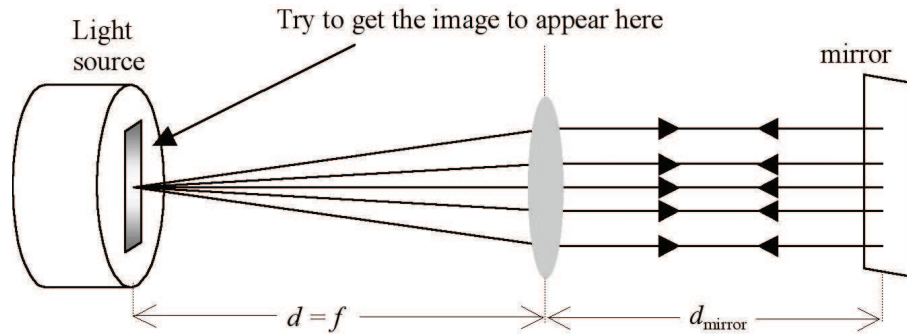
Figure 8.4: Auto-Collimation Set-up

block the light between the lens and the mirror. The image should disappear. If it does not then it's just a reflection from the front surface of the lens, and not what we want.
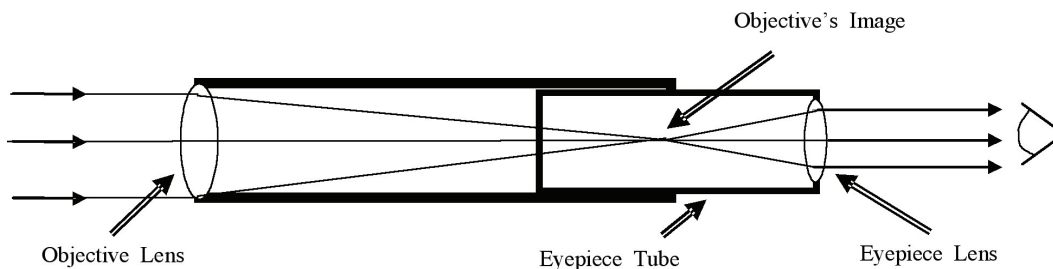
5. Then $f = d$. Record the focal length of the objective lens below.

Object lens focal length ⎯⎯⎯⎯⎯⎯

6. Block part of the light from the slit with your finger or an object like a pencil. Does the top or bottom of the image disappear? Is it right-side-up or inverted?

Image right-side-up or inverted? ⎯⎯⎯⎯⎯⎯

8.3.3 A Two-Lens System: The Telescope

A telescope is designed to perform two functions simultaneously. The first is light collection, and the second is magnification.

Light Collection by the Objective Lens

The size of the objective lens is the most important feature of modern astronomical telescopes. The light-gathering property of a telescope is proportional to the surface area of the objective lens (πr^2). A large objective lens allows the observation of extremely faint astronomical objects and is the telescope's most costly component. Objective lenses are more expensive because they are large and still must accurately focus the incidence light.

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Image Magnification

In addition to light collection, the telescope magnifies the image formed by the objective lens. A second lens, called the *eyepiece lens*, performs this magnification. This lens is usually the telescope's most inexpensive component.

A telescope works by first collecting and focusing the light from an object with an objective lens. **If the object is very far away, the image of the object is focused at a distance (d_{image}) approximately equal to the objective lens's focal length away from the lens** (see the lens equation and convince yourself of this)[1]. To properly magnify, the *eyepiece* must be placed at a specific distance away from the *focal point* of the objective lens. This distance must be equal to its own focal length (see Figure 8.5).
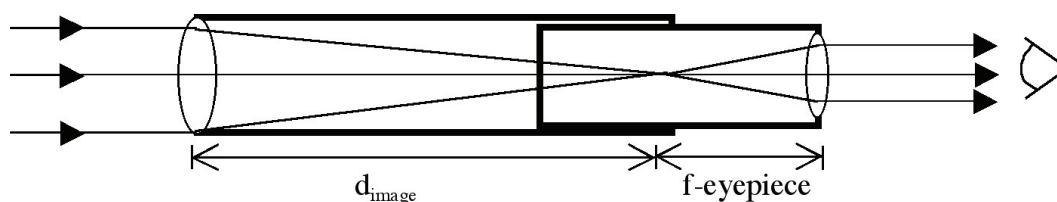

Figure 8.5: Determining the Length of a Telescope

In our telescope, the image will be inverted. This is usually not a problem for astronomical viewing. Terrestrial telescopes include another lens to right the image.

In this section of the lab, you will use the two lenses and a telescope kit to assemble a small telescope. You will then measure its properties and confirm your observations with predicted values.

8.3.4 Investigating Properties of a Telescope
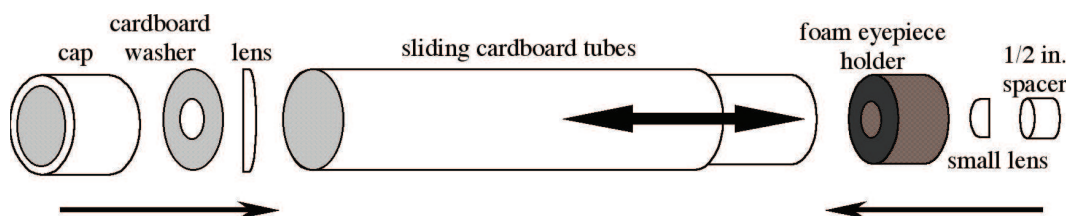
Constructing the Telescope from the Kit

Figure 8.6: Assembling the Telescope

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[1]The image is *always* formed at a distance, d_i, from the objective lens, in accordance with the thin lens equation. But, when $d_o \approx \infty$, then $d_i \approx f$. It's important to realize that f is a characteristic or attribute of the lens. It **does not** change. d_i *does* change as d_o changes

1. Pick up the large lens, being careful not to smudge it with your fingers. Fit the curved side of the lens snugly against the front of the outer tube, making sure it is positioned perpendicular to the tube. Also make sure that it is centered on the tube. Slip the plastic cap over this end of the tube so that the lens is firmly held in place.

2. Being careful not to smudge it, push the small lens into the foam lens holder.

3. Slide the spacer into the foam holder so that it pushes against the flat part of the lens. Push the spacer into the holder just far enough so that the end of the spacer is flat with the end of the foam holder.

4. With the curved side of the lens facing toward the large lens, slide the foam holder into the end of the smaller of the sliding tubes. The foam holder should be flat with the end of the tube.

Determining the Properties that Affect the Telescope's Length

As previously mentioned, the telescope will be in focus when the eyepiece lens is placed approximately one (eyepiece) focal length away from the objective's inverted image. If the object that you're looking at is very far away, the objective lens's image is one (objective) focal length from the objective lens. The eyepiece-to-objective lens separation (L) is thus the sum of these two focal lengths[2]:

$$L = f_{eyepiece} + f_{objective}$$

5. Go out into the hall and focus your telescope on an object that's far away. After doing this, measure the length of the telescope.

Measured length of telescope _____

Do your results agree with the theory? If not, why? (Identify specific sources of error that would result in this inconsistency.) Explain below:

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[2]This is true only when viewing an object that's far away. For nearby objects, you must determine d_i from the thin lens equation, and then add $f_{eyepiece}$ to find the telescope's length.

Investigating the Magnification of a Telescope

In this two-lens system, the magnification of the telescope is equal to the ratio of the objective lens's focal length to that of the eyepiece lens. You have already measured both of these.

$$M = \frac{f_{objective}}{f_{eyepiece}} \tag{8.2}$$

Directly measuring a telescope's magnification can be a tricky task. Fortunately, we have a clever way to do it.
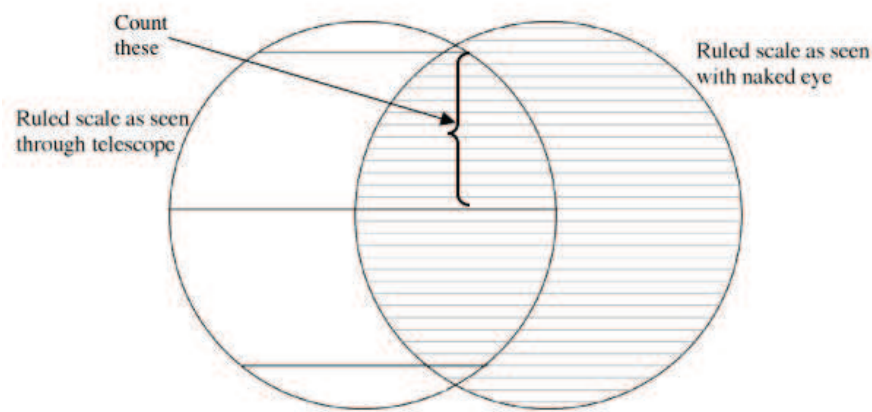

Figure 8.7: Count the number of divisions that lie within one of the magnified spaces.

6. Aim the telescope towards the ruled scale mounted on the lab wall. Use one eye to look through the telescope, and the other eye to simultaneously look at the wall scale. This method will take some time to perfect. You'll have to steady the telescope by leaning against a lab table or something.

   The magnified image of the scale as scene through the telescope will be visually superimposed on the unmagnified scale, as depicted in Figure 8.7.

7. Count the number of divisions on the *unmagnified* scale that overlap one division on the *magnified* scale. This number is the telescope's magnification. Record the magnification below.

   Measured telescope magnification _____

8. Calculate the theoretical magnification predicted by Equation 8.2.

9. Calculate the percentage difference between the theoretical magnification and the measured value.

   Percentage difference _____

8.3.5 Questions

1. Discuss why error is expected to be introduced in the measurement of the focal length of the objective lens using the *Simple Method*. Why is this less of a problem for the eyepiece lens? Refer to any relevant equations as necessary.

2. The Keck telescopes in Hawaii have objective lenses 10 meters in diameter. If the diameter of your eye is 4 mm, how many times more light is received by one of these telescopes than by your eye?

3. Explain briefly why a two-lens system is needed to make a telescope. Make sure to refer to the object distance and the focal length of the objective lens. Explain the function of the eyepiece with regard to the image formed by the objective lens. Where is the image of the objective lens formed?

4. Using the lens equation, explain why the length of the telescope must be adjusted when you move from viewing an object close by to one far away.

5. Calculate the magnification of a telescope and explain what a minus sign means. Explain why we can get a better magnification by switching eyepiece lenses.

8.4 Conclusion

Write a conclusion about what you have learned. Include all relevant numbers you have measure with errors. Sources of error should also be included.