Laboratory 2 - Introduction to Lenses & Telescopes

Materials Used: A set of four lenses, an optical bench with a centimeter scale, a white screen, several lens holders, a light source (with crossed arrows), a set of high-intensity lamps (mounted in the front of the room), marking tape, a lens cleaning kit.

Objectives: To understand basic optical system parameters; to relate image and object distances to focal lengths for various lenses; to determine the focal length, image size, brightness, and *f*-number for various lenses; to understand the differences between telescopic systems and astronomical telescopes; to construct a simple refracting telescope and to understand it's performance.

Discussion: First we must distinguish between a *telescopic system* and an *astronomical telescope*. Though both are "telescopic" they are distinguishable. A telescopic system is anything that produces parallel rays of light. An *astronomical telescope* is, in addition to this, a light amplification system. Many objects of interest in the night sky are large enough but not bright enough to be easily viewed (the Andromeda Galaxy is a great example of this - being nearly the size of the full moon but dim and difficult to see). Although astronomical telescopes do, indeed, magnify objects, their main function is to make dim objects brighter.

Most of the light rays that we see, unless they are coming from objects that are *very* close, are approximately parallel to each other as they move through space (left in Figure 1). Optical systems create images by by *focusing* rays of light – generally with lenses and/or mirrors. In order to achieve focus, rays of light they must be redirected so that instead of traveling parallel to each other they converge on a *focal point* as shown in Figure 1. The focal point of an optical system is where images are formed.

Focusing light rays is generally accomplished in one of two ways: by *refraction* through curved glass lenses – which exploits the fact that light rays bend when traveling from one medium to the next, or by *reflection* from curved mirrors – which exploits the fact that light rays reflect at the same angle as they impinge upon a reflecting surface. Although both arrangements are used to focus light we will concentrate on refractory methods of obtaining images.

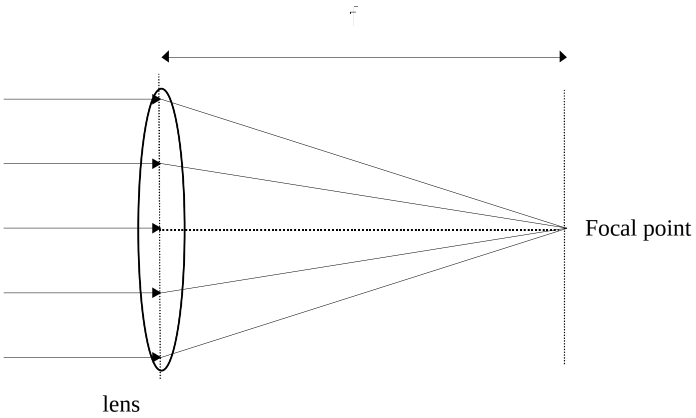

Figure 1. A refractory focusing arrangement.

In this procedure we will explore a simple refracting telescope that employs three lenses to produce an image on the retinal plane of your eye. We'll begin by discovering the properties of lenses and then determining how they may be arranged to form a refracting telescope.

For the purpose of this exercise a *converging lens* is one with two convex surfaces such as the one shown in Figure 2. Our telescope will contain converging lenses.

An *object* is whatever is producing the light that is being viewed through an optical system. When one looks, for instance, at a tree through a camera lens, a telescope, or with the naked eye the tree is the optical object. *The object distance* is the distance from the object to the front end of the optical system.

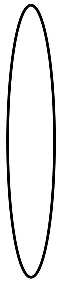

Figure 2. A bi-convex lens.

An *image* is the likeness of an object produced at the focal point of the optical system. The *image distance* is the distance from the optical system to the point of focus where the image is produced. The *focal length* (*f)* of a lens is a principal defining characteristic of the lens. Focal length may be defined as the distance from a lens at which a distant object, one far enough away that the rays intercepted by the lens are parallel, will produce an image. The focal length of a lens is related to a specific physical characteristic of the lens that you will determine in today's procedure.

The exact manner in which images are formed by lenses is fairly complex and will not be addressed beyond rudimentary insight in this procedure. Figure 3 below shows, in general, how light emanating from a particular point on an object is processed by a thin lens. Imagine the arrow on the left (the object) consisting of an infinite series of such points all producing a similar set of light rays that are intercepted and processed by the lens. These would produce the image of the arrow on the right side of the lens.

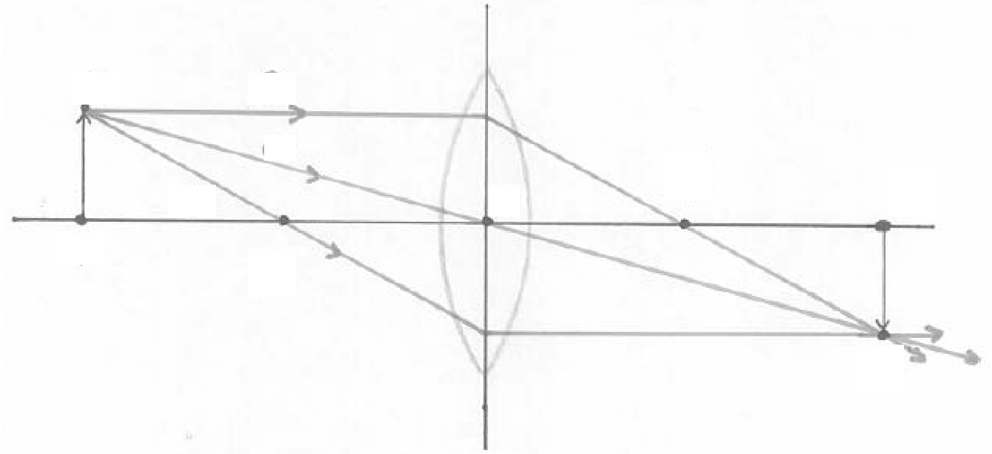

Figure 3. How Thin Lenses Form Images.

Focal length is mathematically related to *object distance* (*p*) and *image distance* (*q*) by the following *thin lens equation*:

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

The *f-number* or *relative aperture* of a lens is a measure of how bright an image a lens will produce:

$$F_n=\frac{f}{diameter}$$

You will determine the optical characteristics of the set of converging lenses that has been provided for you: focal lengths, relative apertures, etc. After this you will choose two of these lenses to construct your refracting telescope.

Determining Lens Characteristics

Notice that if the object distance (*p*) is very *large* in the thin lens equation:

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

the quantity 1/*p* becomes very *small* and the equation reduces to:

$$\frac{1}{q}=\frac{1}{f}\Rightarrow q=f$$

Physically this means that at large object distances the image distance equals the focal length. This suggests a simple method of measuring focal lengths of lenses. What is the relationship for image distance and focal length for a faraway object? How might one exploit this relationship to easily measure focal lengths of lenses?

I – Determining the focal length of a lens by the "distant object" method

You have been provided with a set of four converging lenses, an optical bench and accessories. Your optical bench should be set so that it points at the high-intensity lamps in front of the room. Order your lenses 1 – 4, from largest diameter to smallest, and number them with the aid of a piece of marking tape near the edge of each lens.

- Take the smallest lens and place it in a lens holder; position the holder at the 0 cm mark on the optical bench.
- Place a screen in a holder on the optical bench. Move the screen back and forth along the bench until you have a sharp image of the lights at the front of the room on the screen. The object distance is considered infinity (inf) for this process. Determine the distance from the lens to the screen from the scale on the optical bench. This is the focal length of this lens.
- Each lab partner should try this a few times to determine the point of best focus. Record only the average of all your image distance/focal length measurements. In addition to recording this in the space below mark this value on the marking tape on the lens.
- Make note of the size of the image as compared to the size of the object (magnification), i.e., bigger, smaller or about the same. Is the orientation of the image the same as that of the object or inverted?

Make several measurements of the diameter of your lens and record the average of these values (in cm). Determine the f-number (F_n) for this lens.

Repeat these steps for each of your lenses. Record your observations below.

Lens 1: inf f_{ave} **magnification/orientation** **diameter** F_n

Lens 2: inf f_{ave} **magnification/orientation** **diameter** F_n

Lens 3: inf f_{ave} **magnification/orientataion** **diameter** F_n

Lens 4: inf f_{ave} **magnification/orientation** **diameter** F_n

II – Determining the focal length of a lens with the thin lens equation

- Place the small crossed-arrow light source in a holder on the optical bench and position it at the 0 cm mark. This will serve as the object for this part of the procedure.
- Place the smallest diameter lens in a lens holder and place it on the optical bench around the 50 cm mark.
- Put the screen in a holder; place it on the bench at the 100 cm mark. Move the lens back and forth along the bench until you obtain a sharp image of the light on the screen. Record both the image and object distances from the scale on the optical bench. Each lab partner should try this a few times and only the average value for each measurement should be recorded.
- Use the thin lens equation to compute the focal length of each lens from the values obtained for the image and object distance. Also note the magnification and orientation of the image on the screen.
- Repeat this process for each of your four lenses in the same order as before. For one of the lenses you may be unable to obtain a clear image on the screen. Proceed with the others.
- You will notice that for each lens for which you are able to obtain an image on the screen there are *two* positions of the lens along the optical bench that will produce an image, one closer to the light source and one closer to the screen. Note that in the thin lens equation the object distance (*p*) and the image distance (*q*) are interchangeable. Physically this gives rise to *points of conjunction*. It doesn't matter which of these positions that you use (both will yield the same value for *f)*. This is a property of optical systems known as *reversibility*.
- Note that the orientation of the image on the screen. How does it compare to the image obtained for the same lens in using the previous method? What do you think accounts for this?

Thin Lens Equation Example: Suppose that I compute an average object distance for a lens of 90 cm, and an average image distance of 10 cm. In this case, *p* (the object distance) is 90 and *q* (the image distance) is 10. I wish to solve:

$$\frac{1}{90}+\frac{1}{10}=\frac{1}{f}$$

To solve this equation I would add the terms on the left side of the equation in my calculator (or by finding a common denominator) and take the inverse of their sum (in other words, divide 1 by the sum):

$$\frac{1}{90}+\frac{9}{90}=\frac{10}{90}=\frac{1}{f}\Rightarrow\frac{90}{10}=\frac{9}{1}=f$$

The answer is the focal length of the lens. In this case, *f* = 9 cm. Try this calculation for yourself.

Record your observations below. If you were unable to obtain a clear image for one of your lenses what do you think may have been responsible for this?

Lens 1: p_{ave} q_{ave} **magnification/orientation** f_{ave}

Lens 2: p_{ave} q_{ave} **magnification/orientation** f_{ave}

Lens 3: p_{ave} q_{ave} **magnification/orientation** f_{ave}

Lens 4: p_{ave} q_{ave} **magnification/orientation** f_{ave}

Compare the values obtained for the focal lengths of each lens from the previous method with the values obtained here. Are these methods consistent? Does the focal length of a lens equal the image distance for large object distances?

Examine the data from steps 1 and 2 above to determine any relationship between focal length and image size. State the relationship (if any) below.

Lay out your lenses in front of you in order of increasing focal length. What physical property of each lens determines its focal length? Does the diameter of a lens have any apparent effect on its focal length?

The diameter of a lens determines its light gathering power while the focal length determines how much area the gathered light is focused into. The ratio of these two quantities, the *f*-number, determines the brightness of the image. A large *f-number* means that the image is *not* very bright. You have already recorded the *f-number* for each of your lenses. Which lens of your four will produce the brightest image? Which lens will produce the dimmest? Rank your lenses in order of decreasing brightness. What physical characteristic most determines *f*-number?

A Simple Refracting Telescope

A refracting telescope is composed of an *objective lens* and an *eyepiece*. The objective lens is a converging lens in the front end of the telescope - the end you point at whatever you are looking at. The diameter of the objective determines the light gathering ability of the telescope. The eyepiece is a converging lens that processes the rays from the objective and produces a smaller diameter bundle of parallel rays bunched closely together so that they may enter the pupil of the eye. The eye processes this bundle of rays by focusing them onto the retinal plane.

The *f*-number of a telescope is the *f*-number of the objective lens (since this limits its light gathering ability). The *magnification* of the refracting telescope is the ratio of the focal length of the objective lens to the focal length of the eyepiece.

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

A diagram of a simple refracting telescope like the one that you are to construct is shown below. The object is to the left of the diagram. Notice that the distance between the two lenses is equal to the sum of their individual focal lengths. Note that the output of this system is parallel rays. What else is required to focus these rays and produce an image?

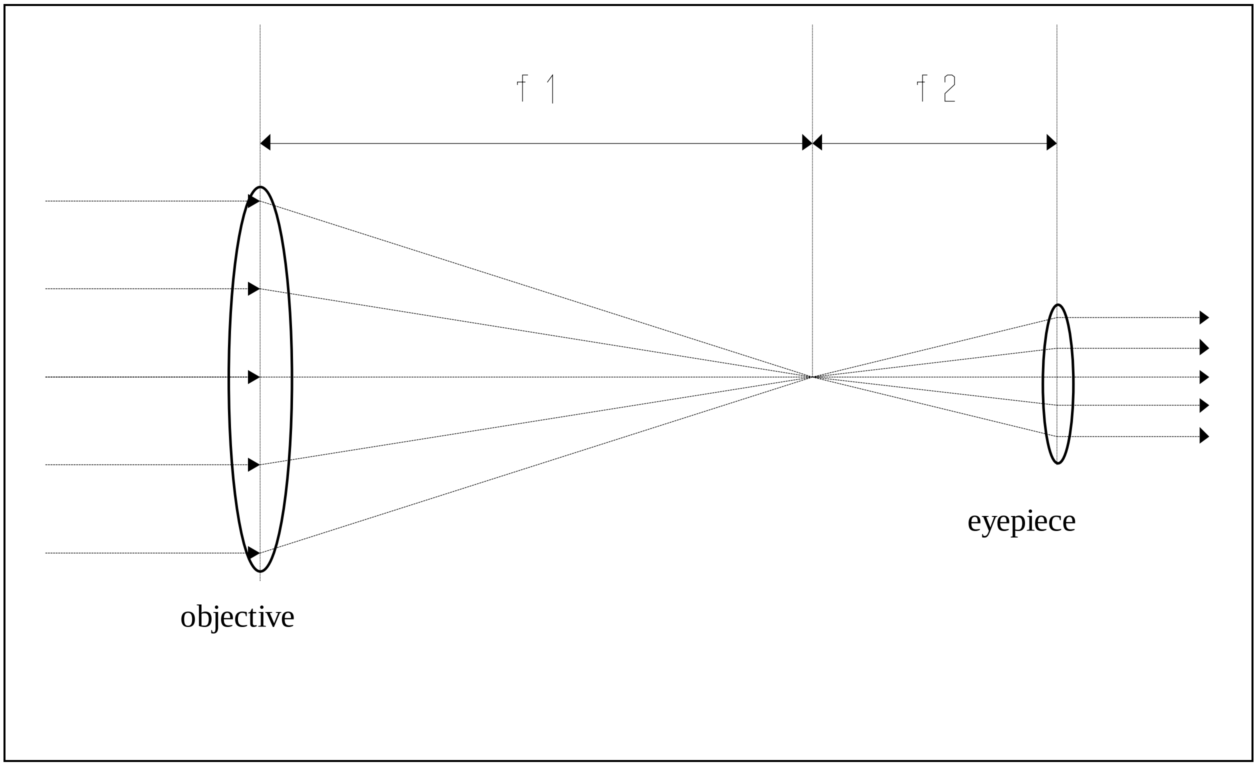

Figure 4. A simple refracting telescope.

To begin constructing your refracting telescope, remove the screen and mountable light from the optical bench and replace them with a second lens holder. Your optical bench should now have just two lens holders.

Examine the lens data you accumulated. Select the lens with the smallest *f*-number for the objective and the lens with the shortest focal length for the eyepiece. Arrange them on the optical bench as shown in the diagram above.

The characteristics of your telescope

Record the focal length of the lenses (f_o, f_e) used, the *f*-number (F_n) of your telescope and the magnification (M) of your telescope.

Point your telescope at the lamps in the front of the room. Align your two lenses so that a straight line runs between the object (the lamps in front of the room) and the two lenses. Look through the eyepiece of your telescope and adjust the length between the two lenses to produce the sharpest image. What is the distance between the lenses? Is the image upright or inverted? Is the image larger or smaller than the object? Is the image brighter or dimmer than the object?

Remove any marking tape from your lenses, carefully clean them and replace them in the foam container and remove all holders from the optical bench.

Exercises

1. What is the magnification of a telescope with an objective of 4000mm and an eyepiece of 26mm?

2. What do all telescopic systems do?

3. A converging lens produces an image at 20 cm for an object 50 cm from the lens. What is the focal length of this lens?

4. The curvature of a lens affects its ______________________ while its diameter affects its _________________________.

5. A refracting telescope consists of two lenses, the _____________________ and the _____________________, located the sum of their ________________________ apart.

6. It was stated in the notes that a simple refracting telescope has *three* lenses. What is the third lens in a simple refracting telescope like the one that you built?

7. Examine Figure 3 and produce a sketch that shows the path that a bundle of light rays takes through your refracting telescope to the retinal plane of your eye.

8. The lens in your eye is a converging lens. Since converging lenses produce inverted images why do you see everything right side up?

Common Focusing Arrangements for Astronomical Telescopes

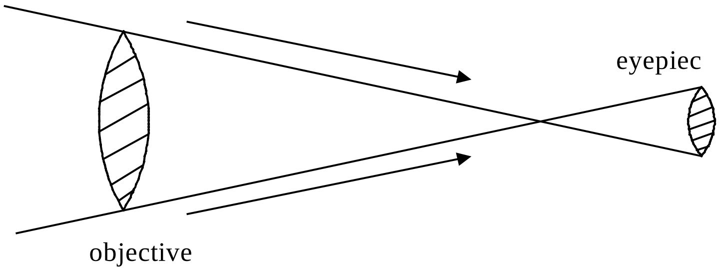

Figure 5. Refracting Telescope.

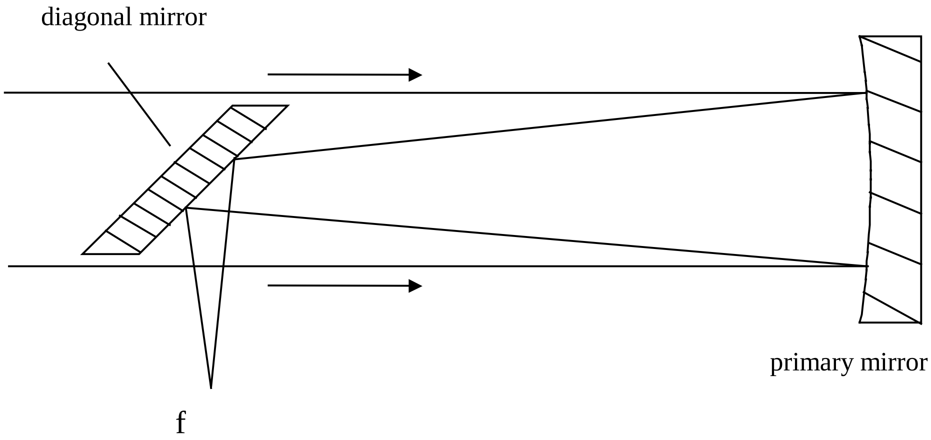

Figure 6. Newtonian Telescope.

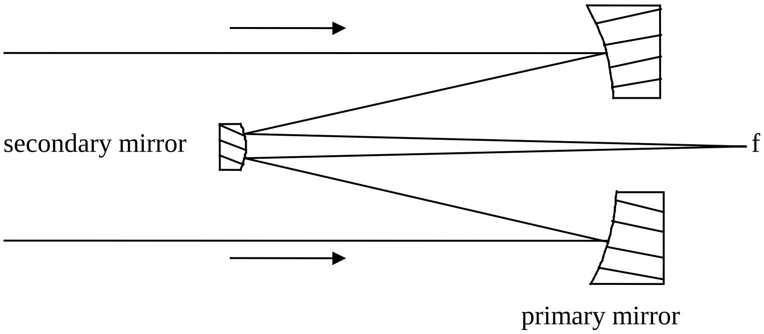

Figure 7. Cassegrain Telescope.

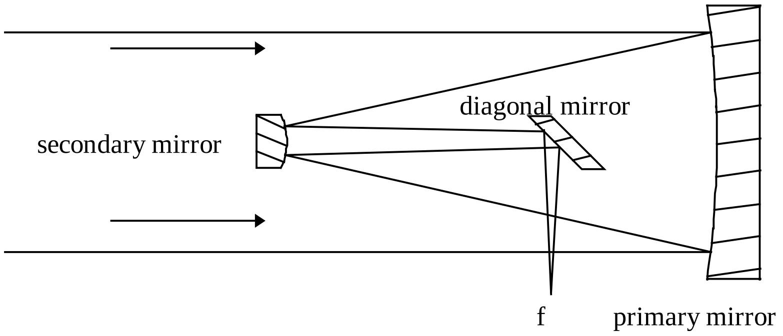

Figure 8. Cassegrain-coud'e Telescope.

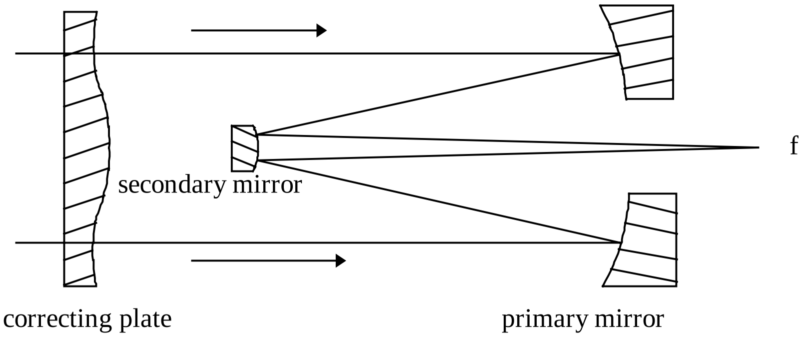

Figure 9. Schmidt-Cassegrain Telescope.

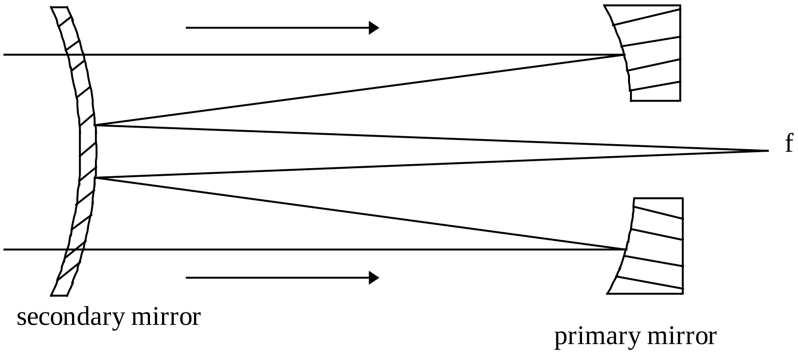

Figure 10. Maksutov-Cassegrain Telescope.