DAY LABORATORY
OPTICS AND TELESCOPES

Goals:
- To explore the functions of simple lenses
- To construct and use a refracting telescope
- To understand the concepts of focal length, focal ratio, and magnification.
- To study aberrations in simple telescope systems.
- To explore the concept of angular resolution.

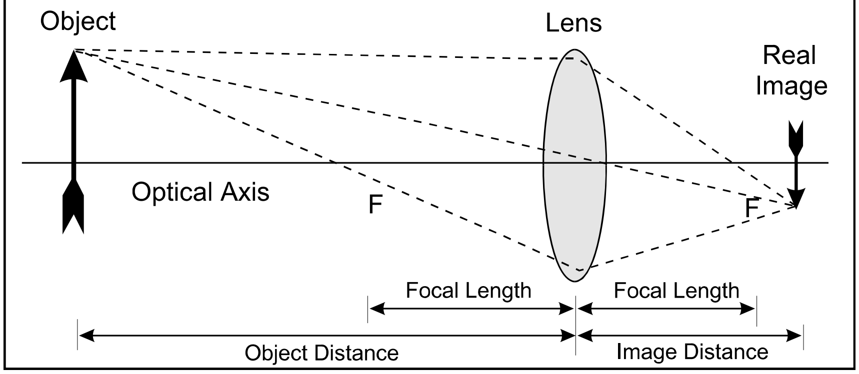
Equipment: Lens kits, optical benches, light sources, rulers, calculators

Methods:
- Measure lens focal lengths by forming images of distant objects
- Focus refracting telescope on distant object - measure lens separations
- Compare optical aberrations of refracting and reflecting telescopes
- Explore optical systems using a multiple lens optics kit and light source
- Measure angular resolution of the eye using distant eye chart

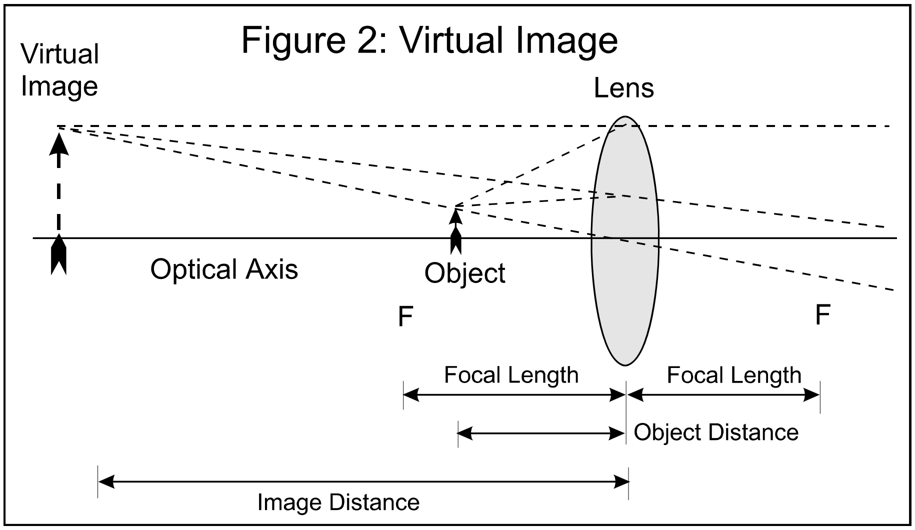
Introduction - Telescopes are the primary instruments for the acquisition of data by astronomers. This exercise investigates the basic principles of geometric optics as applied to telescopes. You will primarily use refracting telescopes for the examples, but what you learn can be applied to any telescope (i.e., reflecting or radio).

Lenses and Mirrors - A **positive lens** has at least one convex surface and is capable of focusing light from a distant **object** into a real **image**, that is, an image which can be seen projected onto a screen (see Figure 1).

Figure 1: Real Image



However, the same lens, when placed *close* to an object, produces a magnified *virtual* image which can be seen through the lens with the eye, but cannot be projected onto a screen (see Figure 2). A **negative lens** has at least one concave surface and always produces a virtual image. All of the lenses in this exercise have convex surfaces (the glass surface bulges outward from the lens center).



Note: The dashed lines in each figure represent a few of the numerous light rays leaving from a single point on the object. The rays that fall upon the lens are bent to form an image. For simplicity, these diagrams show only three rays from one point at the top of each object.

Lenses and Refracting Telescopes - The **focal length**, **f**, of a lens is the distance between the lens and the image formed from originally parallel light rays (i.e., light rays from a very distant object). The focal length of a lens depends on the curvature of the lens surface.

A basic refracting telescope consists of two lenses. The larger, **primary lens** is called the **objective**, while the second lens, the **eyepiece**, is used to view the image produced by the objective. Telescopes whose objectives have long focal lengths are typically physically large in size, though "folded" optical designs, like the catadioptics of our rooftop 8" telescopes, can be small enough to be portable. Long focal length optics are easier to make with high precision and quality, and are thus generally more inexpensive to construct.

The **aperture** of a telescope is the "opening" through which light enters. The names "aperture" and "objective lens" are often used interchangeably. The aperture determines how much light is collected, much as a bucket -- a large bucket collects more rain drops than a small one.

The **field of view** is a measure of the total **angular area** of the sky visible through the telescope. This field size depends on the properties of both the objective and eyepiece lenses.

The **focal ratio**, **f/ratio**, or simply "**f/number**" all describe the ratio of the focal length of a lens to its diameter. A small f/ratio lens (a "fast lens") produces a smaller, brighter image than a large f/ratio lens (a "slow lens"). "Faster" telescopes yield large fields of view with lower magnification, producing bright images at the **focal plane**. "Slower" optical systems exhibit highly magnified fields but with dimmer images.

The **angular magnification** of a telescope is the ratio of the apparent size of an object viewed through a telescope to the apparent size of the object seen with the naked eye. The formula for calculating the angular magnification of a telescope is:

$$M = f_{\text{Objective}} / f_{\text{Eyepiece}}$$

where M is the magnification, $f_{\text{Objective}}$ is the focal length of the objective and f_{Eyepiece} is the focal length of the eyepiece. Selection of a different eyepiece, with a different focal length, is the easiest way to change the magnification of a telescope.

The **angular resolution** of a telescope is a measure of its ability to render separate images of two closely spaced objects. If two point-like objects are rendered as a single point-like image, they are said to be **unresolved**. If the two objects appear as two distinct point-like images, they are **resolved**. Thus, resolution is a measure of the degree of detail a telescope is able to discern. The following formula can be used to estimate the angular resolution expected of an optical system:

$$\theta = (138.4/D)$$

where θ is the angular resolution, in seconds of arc, and D is the diameter of the aperture (or objective lens), in millimeters. The angle θ is also known as the **minimum resolvable angle**. Note that resolution is *inversely* proportional to the size of the lens. Resolution is also dependent on the wavelength of light. A wavelength of 550 nm was assumed in the equation since the human eye is most sensitive to this wavelength.

Imperfections in Lenses and Mirrors - **Aberrations** are defects that prevent formation of a precise, sharp focus of the image in the focal plane.

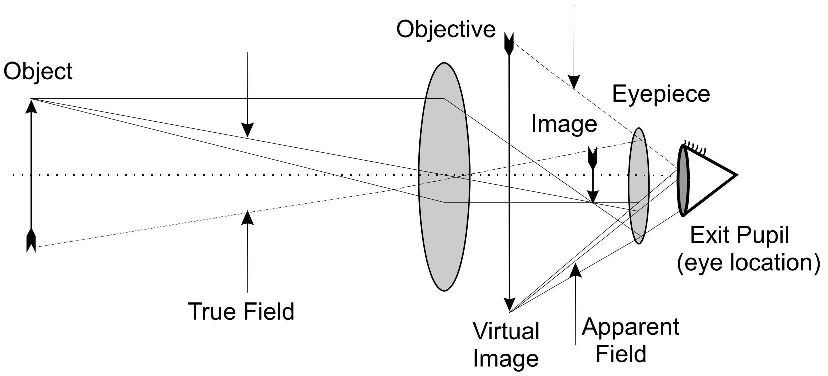
One imperfection intrinsic to refracting telescopes is **chromatic aberration**. The refraction of light through each lens tends to disperse shorter wavelength light through larger angles than for longer wavelength light. This results in blue light bending more than red light, so that each color comes to a focus at a somewhat different point (the focal length of the lens is wavelength dependent). Multiple color images of the same object or image having red- and blue-tinted edges are manifestations of chromatic aberration. Modern **achromatic lenses** sandwich several lenses of different glass compositions together to correct much of this aberration.

Spherical aberration is produced when the parallel light paths incident on a lens are focused at different distances from the lens, with the focal length dependent on the distance of the light ray from the lens center. Lenses with spherical aberration cannot focus parallel light rays into a point image, but instead produce a blurred disk at the image plane. The primary mirror of the Hubble Space Telescope was found to have a large degree of spherical aberration, after it was launched into Earth orbit. Spherical aberration can be largely overcome by the addition of more lenses or mirrors, designed to equilibrate the different light paths.

Seeing is the distortion of an image caused by the earth's atmosphere. Small-scale turbulence in the atmosphere causes an image to move around, or "twinkle." This effect limits resolution to a few arcseconds at most observing sites.

Telescopes Types - A **refracting telescope** is shown schematically in Figure 3. In 1609, Galileo Galilei heard of a Dutchman who had constructed a spyglass that made distant objects appear closer. Though he was not an expert at optics, Galileo succeeded in constructing his own telescope. His best telescope magnified images thirty-two times. With it, he made numerous discoveries concerning the Moon, the Sun, and the planets. In 1611, Johannes Kepler invented another type of refracting telescope which is the standard arrangement for most modern refractors. In its simplest form, the refractor consists of two positive lenses: the objective lens, which forms the image of the field of view, and the eyepiece, which is used to magnify the image to permit viewing by the eye. The eye is placed at the **exit pupil**.

Figure 3: Refracting Keplerian Telescope



Most modern refractors combine an achromatic objective with multi-element eyepieces. These optimal designs become very expensive when the aperture is greater than three inches. In refracting telescopes, the image is inverted. Another lens could be added to re-invert the image, but such extra lenses add to the cost and become another source of aberrations.

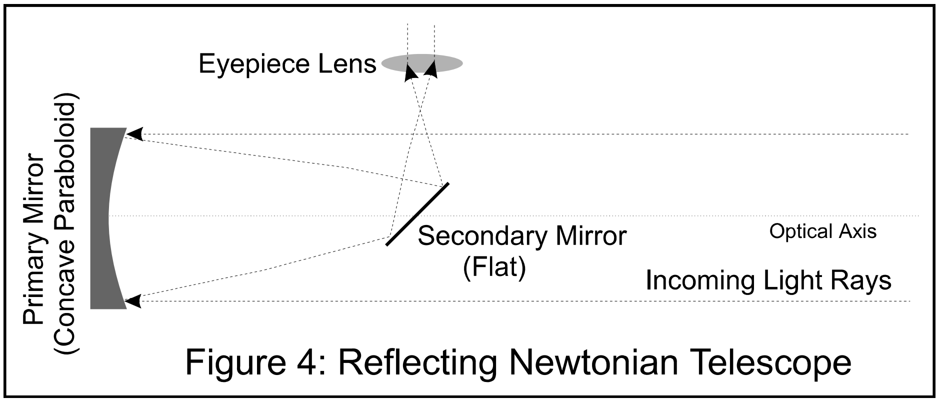


Figure 4: Reflecting Newtonian Telescope

The first telescope design that used mirrors instead of lenses was invented by Isaac Newton in 1680. The objective in this design (see Figure 4) is a **concave parabolic mirror**, which reflects light onto a flat secondary mirror, moving the focus of the primary outside of the path of the light rays entering the aperture. Use of an objective mirror, instead of a lens, eliminates chromatic aberration.

The eyepiece is near the front of the telescope tube and is set at a right angle to the optical axis (where the telescope points). This optical design is still much used today and is popular with amateur telescope makers.

DAY LABORATORY EXERCISE #3:
OPTICS AND TELESCOPES

Name/ID\#_____________________________ TA's Initials:________

Class/Section: AS102/ ______ Date due:___________

Procedure:

This laboratory exercise consists of five "stations," each of which is designed to explore one or more distinct aspects of lenses, telescopes, and optics. Proceed to each station and use the following questions to guide your study.

Station 1: Refracting Telescope Viewing A Distant Object

The optical configuration at this station is a simple refracting telescope, such as the one illustrated in Figure 3. This telescope has been aligned to point to an object which is effectively at an infinite distance. The light rays coming from such a distant object are almost perfectly parallel as they enter the optical system.

1. Measure the focal lengths of the objective and eyepiece lenses. To do so, place a white piece of paper behind the lens whose focal length you are measuring. Move the paper back and forth along the optical path until a sharp image of the object is projected on the paper. *(Note - make sure the image in focus is the distant object and not the much closer window frame.)* Measure the distance between the lens and the projected image. This is the focal length of the lens.

   Measured focal length of objective lens = _________________ [cm].

   Repeat the procedure for the eyepiece lens. (Remember to remove the objective lens from the eyepiece's light path!)

   Measured focal length of eyepiece lens = _________________ [cm].

   Now, compute the sum of the focal lengths for the two lenses.

   Sum of lens focal lengths = _________________ [cm].

Based on your reading about refracting telescopes, how should the distance between the objective and eyepiece lenses be related to their focal lengths when the telescope is focused on a distant object?

I predict that the lens separation should be ______________ the focal length sum for the two lenses. (Fill in the blank with "less than", "equal to", or "greater than".) Why?

2. Look through the telescope and focus on the object by moving the eyepiece holder back and forth on the optical bench. Measure the distance between the objective and the eyepiece lenses.

Measured lens separation = ___________________ [cm].

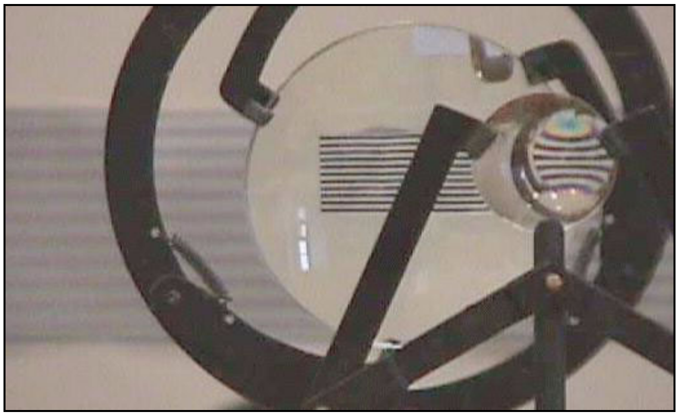
How well was your lens separation prediction met? ____________________________

Describe the <u>orientation</u> of the object seen through the telescope. _________________________

3. Examine the object's image carefully. Comment on the clarity and steadiness of the image.

4. What aberrations seem to be present?

Station 2: Refracting Telescope Viewing A Nearby Object



This optical configuration is *identical* to that of Station 1, but it has been directed at a nearby object, here a paper attached to the lab wall and containing several black and white stripes. Position your eye about one inch away from the eyepiece lens when viewing. In order to bring this nearby object into focus, you will have to change the separation between the objective and eyepiece lenses.

Relative to the separation between the lenses used in Station 1 to view the distant object, what do you predict you will need to do to focus on the nearby object? (**reduce** or **increase** the separation?) ______________________________

1. Set the lens separation to the value you found for Station 1.

2. Next, change the lens separation to focus the black and white stripes in your telescope. Measure the distance separating the objective and the eyepiece.

   Measured lens separation for B/W stripes = _______________________ [cm].

   Was your lens separation prediction met? __________________________________

3. Estimate the angular magnification of the image in the telescope by comparing the **true field** to **apparent field** angles (see Figure 3). To estimate the magnification, alternately look through the telescope with one eye while keeping your other eye (which has an unobstructed view of the object) closed, then reverse which eye is open and which is closed. Switch observing back and forth several times so that you can superpose the magnified view of the black and white stripes over the unmagnified view. Estimate how many unmagnified stripes fit into a single magnified stripe. For example: you see 3 stripes next to 1 stripe, which makes the angular magnification of the telescope equal to three.

   Your best estimate of the angular magnification = ___________________________

   Calculated angular magnification, ($M = f_{\text{Objective}} / f_{\text{Eyepiece}}$) = __________________

4. Replace eyepiece #1 with eyepiece #2 in the telescope. Using the same technique as before, measure the focal length of eyepiece #2.

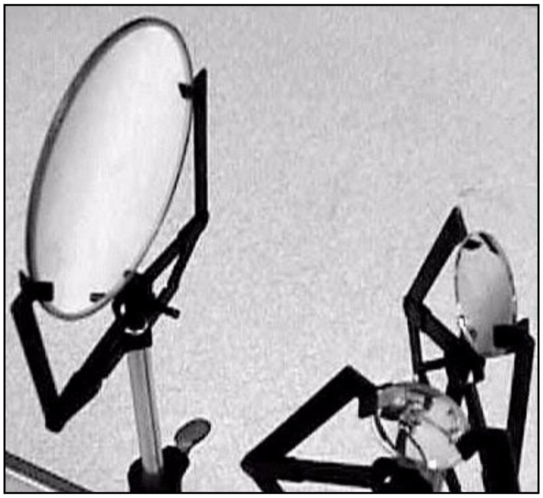
   Measured focal length of eyepiece #2 = ____________________________ [cm].

5. Refocus the telescope on the object and repeat step 3.

   Your best estimate of the angular magnification = ___________________________

   Calculated angular magnification = ________________________________

Station 3: A Newtonian Telescope



At this station, a reflecting telescope is set up. The picture shows an oblique view of the telescope. The primary mirror is in the upper left. The diagonal secondary mirror is in the middle right and the eyepiece lens is in the lower right.

1. Measure and compute the characteristics of the mirrors and lenses in this system.

Measure the diameter of the primary mirror.

Primary mirror diameter = ____________ [mm].

With the eyepiece lens removed, but the secondary mirror in place, measure the focal length of the primary mirror by projecting an image onto a piece of paper held to the side, near the secondary mirror, and moving the paper until the image is in focus. Measure the distance from the paper to the center of the secondary mirror and add the distance from the secondary to the primary.

Measured distance from image focus to secondary mirror center = ____________ [mm].

Measured distance from secondary mirror center to primary mirror center = ____________ [mm].

Computed focal length of primary mirror = ______________ [mm].

Computed focal ratio (f/#) of primary mirror = ______________.

Check your primary focal length by measuring it directly (that is, without the use of the secondary mirror). Measured focal length of primary mirror = ______________ [mm].

Next, measure the focal length of the eyepiece lens, as you did for the first station.

Measured focal length of eyepiece lens = ___________ [mm].

Predicted angular magnification of telescope = __________________.

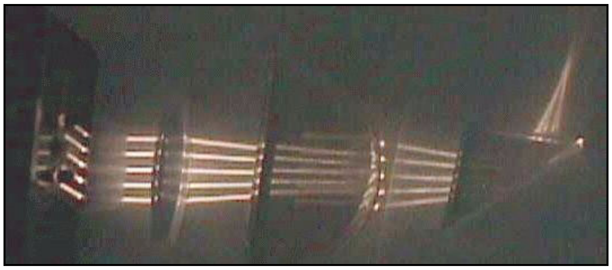
2. Examine a distant object with this telescope. Which aspects of the view through this telescope are superior to those of the view through the station 1 telescope?

Are there any aberrations similar to those seen through the refracting telescope? ______________________________________

Are there any new aberrations? ____

Station 4: Optical Configurations

At this station is a blackboard optics kit, which consists of enlarged cross-sections of various sorts of lenses and mirrors, and a light source to show the path of light through an optical arrangement.



1. Create a simple refracting telescope from a long focal length lens and a short focal length lens. Your system should have an angular magnification *greater than* unity.

2. Measure the focal lengths of the objective and eyepiece lenses.

   Measured focal length of objective lens = _______________________ [cm].

   Measured focal length of eyepiece lens = _______________________ [cm].

3. Create a scale drawing of your telescope. Label all lenses with their focal lengths. Show all separation distances.

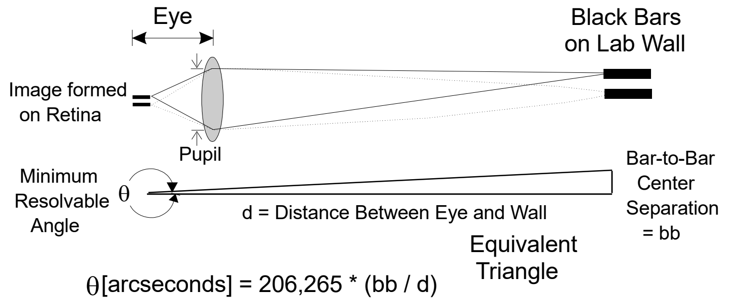
4. Calculate the magnification of your model telescope.

   Calculated magnification = _________________________________

Station 5: Angular Resolution of the eye.

At this station, you will measure the angular resolution of your own eyes. Figure 5 shows both the experimental setup (including your eye) and the equivalent trigonometric angle used to interpret the measurements.

Figure 5: Angular Resolution of the Eye



1. First, compute the angular resolution your eye should be capable of providing. Have your partner measure the diameter of the black part of your eye's pupil (this is the entrance aperture for the telescope consisting of your eye), but <u>not</u> the colored part (the iris).

   Measured diameter of eye pupil = ___________________ [mm].

2. Using the formula for angular resolution, compute the expected angular resolution (the "minimum resolvable angle").

   Calculated angle θ = ____________________ [arcseconds].

3. Detach this page and tape it to one wall in the laboratory (or use the one provided, if it is present). Close one eye and look at the pair of black bars at the bottom of the page. Move back from the wall until the two bars just appear to merge into one bar. Measure the distance from your eye to the wall.

   Measured distance from eye to wall = _________________________ [mm].

4. Next, measure the center-to-center separation of the black bars in the figure below.

   Measured center-to-center bar separation = _____________________ [mm].

5. Using the equivalent triangle shown in Figure 5, compute the minimum resolvable angle you were able to discern with your eye.

   Experimentally determined angle θ = ____________________ [arcseconds].

   How well was your theoretical prediction met? __________________________________

Black bars for measuring the angular resolution of your eye. Tape this page to the lab wall and move back until the bars just merge into one.

Summary Questions *(remember to include units and to check reality!)*

1. The atmosphere limits resolution in the visible portion of the electromagnetic spectrum to 1 arcsecond at the best observing sites. How large an optical telescope does one need to achieve this resolution? ____________________________

2. Calculate the angular resolution for the Hubble Space Telescope (whose mirror diameter is 2.4 meters) and one of the Keck telescopes in Hawaii (with mirror diameter of 10 meters).

   HST angular resolution = _______________________ [arcseconds].

   Keck angular resolution = _______________________ [arcseconds].

   Why is the Hubble Space Telescope's angular resolution better in practice than any ground-based terrestrial telescope?

3. At which of the Stations in this lab exercise would you expect to see chromatic aberrations?

____

   Why?

4. At which Stations would you *not* expect to observe chromatic aberrations?

____

5. Design a refracting telescope capable of resolving 5 arcsecond features on a planet or separating a 5 arcsecond double star pair, given the angular resolution you measured for your eye

   Angular resolution you measured for your eye (from Station 6) = _______________ [arcseconds]

   Minimum angular magnification of the telescope needed ______________________________ to aid your eye to resolve an angle of 5 arcseconds.

If you have an eyepiece with a focal length of 12 mm, what objective lens focal length is needed to produce the required magnification? ________________________[mm]

How far apart should the objective and eyepiece lenses be separated ? ________________ [mm]

Make a scale diagram showing your telescope design.