Lab 3: Telescopes

Perhaps no scientific instrument is as closely associated with a field of study as is the telescope to astronomy. And yet arguably the telescope is also the most misunderstood of scientific instruments, so closely associated is the telescope with the word “magnification”.

First and foremost, an astronomical telescope is a “light bucket” designed to collect light. A celestial object, such as a star, emits light in all directions. After traveling for thousands of years across billions of kilometers, a tiny portion of that light rains down on the hemisphere of the Earth facing that star. Almost all of that light does nothing more than be absorbed by the atmosphere or the ground, ever so slightly heating up the Earth. An infinitesimal portion of the star’s light strikes the lens or mirror of a telescope and is directed into an eye, or onto a piece of film, or through a spectrograph. The bigger the diameter of the lens or mirror, the more light that is guided to the detector, and the more knowledge that is gained about the Universe. This is the basic fact that underlies astronomers’ never-ending quest for telescopes of larger diameter.

Considered broadly, telescopes are all around you in optical devices of other names – cameras, eyes, binoculars, eyeglasses, and more. The details of the optics in each of these telescopes dictates how effectively the collected light is used. The goal of this lab is to give you a feel for optics through recreation of that marvelous device of Galileo, the telescope.
Before You Come to Class ...

Read the lab completely. Your time in the lab is best used observing the "sky", not reading this manual.

Complete the pre-lab assignment.

Bring to class this lab manual, your lab book, a pencil or erasable pen, a straight edge, and a scientific calculator.

Schedule

This lab is designed to be completed in two lab sessions.
Section 1 – The Simple Telescope – A Primer

To make a telescope all you need is one lens\(^1\), appropriately curved. This \textit{objective lens} receives light from a distant object – perhaps a student across the classroom, a sailboat on Lake Mendota, the Moon, the planet Jupiter, or a galaxy - and creates an image of that object behind the lens on a flat plane called the "Image Plane".

Before working with celestial objects, let’s consider two headlights on a car on the far side of Lake Mendota at night. The car is far enough away that each headlight appears simply as a point of light. In Figure 1 the headlights are shown as points A and B. To start, Figure 1 shows only the light rays coming from headlight A. There are several important things to notice in this simple picture.

a) The light rays that strike the lens are bent (refracted) in such a way that they all pass through the same point in space. This place is the \textit{focal point} for headlight A. If you were to put a piece of paper here, you would see a point of light on the paper. This point of light is called the \textit{real image} of headlight A.

b) The light rays don’t stop at the focal point.

c) Most of the light from the headlight misses the lens and thus is never sent to the focal point.

---

\(^1\) Either a lens or concave mirror will do, and in fact most astronomical telescopes use a mirror. Since in this lab you will be using lenses, we will continue to talk in terms of lenses.
Of course, light is also arriving at the lens from headlight B. As shown in Figure 2, because the light from B is coming from a different direction, the focal point of B is located at a different place in space.

Figure 2

If you were to hold a piece of paper at the appropriate distance behind the lens, you would see two points of light on the paper, one at the focal point of headlight A and one at the focal point of headlight B.

Now, instead of headlights, imagine a fluorescent Texaco sign on the other side of Lake Mendota. Just like the two headlights, light from every point on the sign comes to a focus at a different place behind the lens. And the ensemble of all these points of light become an image of the Texaco sign! This image behind the objective lens is a two-dimensional reproduction of the object suspended in space, and as before is called a real image. Perhaps this phrasing might now make more sense – optically speaking, the real image of the Texaco sign is no different than the sign itself. The real image can be looked at and examined with no loss of information compared to looking at the sign itself (with the exception of optical imperfections). In a sense, the sign has been “beamed” to the focal point of the lens!

Once a real image is created by the objective lens, it can be carefully inspected in a variety of ways. For example, one could project the real image onto a piece of white paper, which in fact is an excellent and safe way to observe the Sun with a telescope. Alternatively, the real image can be examined by eye, perhaps with a magnifying glass. More traditionally the magnifying glass is called an eyepiece, and most likely this is how you have used telescopes. However, it is almost never the way professional astronomers use a telescope, simply because the eye is a very insensitive light detector. One could also record the image by placing photographic film or a light-sensitive silicon chip (called a charge coupled device; CCD) at the position of the image. In this case the telescope is a high-end camera – indeed, your digital camera is simply a single lens and a CCD. Or the spectrum of the light from the object could be measured by placing the entrance of a spectrograph at the position of the image.

- Why do astronomers prefer these latter two uses of the telescope and almost never look at the image with their eye?
Section 2 – Becoming Familiar with Lenses

FINDING IMAGES, OR SEEING SPOTS

Your lab group has been supplied with an assortment of lenses, lens holders, a white screen, and a lens rail onto which the lenses and screen can be mounted. In this section you can explore creating and finding real images. There is no need to write anything in your notebook for this section.

- Place the "blue" lens near one end of the lens rail, tighten the lens holder onto the lens rail, and aim the rail as accurately as you can toward one of the "double stars" located on the far side of the room. To aim up or down, you may need to shim one end of the rail with something, such as a book or block of wood.

Now find the real image of the "double stars". The image will be located 50 cm or so behind the lens along a line from the "stars" through the center of the lens.

Try finding the image in a couple of different ways:

- Place the white screen on the rail behind the lens. Slide the screen back and forth until the image of the two stars appears on the screen. In this situation the light that creates the image hits the white screen and scatters in all directions, making it possible to see the image easily from any direction.

- Stand about 1 m behind the lens and look toward the stars through the lens. Can you see an image of the stars suspended in space just in front of you? (Note: some people can and some people can’t – even professors! This is the result of eyes and brains, not the existence of the real image.)
Section 3 – Focal Lengths and Image Size

When looking at an object very far away, the distance between the lens and the real image of the object is a property of a lens called its focal length. The focal length is a measure of how much the lens bends light. Typically, the greater the curvature of the surface of the lens, the more that light is bent and the shorter is its focal length.

- Q1: The four lenses supplied for this lab have different focal lengths. Observe a “double star” with your screen to measure the focal length of each of your lenses. Record your results in Table 1 (copied to your labbook), listing each lens and its focal length in mm. BE SURE TO OBSERVE THE SAME “DOUBLE STAR” WITH ALL OF YOUR LENSES. Also measure the separation in mm between the two star images. When you make your table be sure to leave room for the extra column for "magnifier distance", which you will fill in later.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>lens</td>
</tr>
<tr>
<td>White</td>
</tr>
<tr>
<td>Yellow</td>
</tr>
<tr>
<td>Blue</td>
</tr>
<tr>
<td>Orange</td>
</tr>
</tbody>
</table>

Q2: Make a graph, plotting separation (distance between the two star images) on the vertical axis and focal length on the horizontal axis. What qualitative relationship do you find between focal length and the separation between the two star images? Show this relationship in a graph.

Q3: Examine the lenses. What physical property of the lenses accounts for their differing focal lengths?

Q4: Suppose you want to take photographs of the sky with pieces of film that are 35 mm square. Which of your lenses would be best for taking a photograph of a large field of view, e.g. a photograph of the entire constellation Orion? Why?

Which of your lenses would be best for taking a photograph that reveals fine detail, e.g. of group of craters on the Moon? Why? The ability to distinguish fine detail is called the resolution of a telescope.

---

2 See Appendix A for more detail on focal lengths of lenses and ray tracing.
Can a telescope provide both a wide field of view and superb resolution? Why or why not?

For a given diameter, telescopes of different focal lengths have very different capabilities. When designing telescopes astronomers must make design decisions very similar to the ones that you have just made, depending on their scientific goals. Of course, astronomers cast those design decisions into multi-million dollar facilities!

Q5: Consider Figure 2 carefully. Recreate it in your lab notebook.

Imagine replacing the lens in Figure 2 with a longer focal length lens. On your figure, redraw the light rays after they pass through this longer focal length lens. It helps to know that the ray that passes through the center of a lens is always unbent, whatever the focal length of the lens.

With your drawing, explain the relationship that you have discovered between focal length and separation.

Section 4 – A Better Light Bucket

When used for astronomy, one of the telescope's most important characteristics is the size of its objective lens.

- While projecting the double star onto the white screen, have one of your lab partners
decrease the usable area of the objective lens.

A piece of paper with a hole in it (a "mask") can be held just in front of the lens, for example. Start with a mask that has a hole about 1/2 the diameter of the objective lens. Try another with about 1/10 the diameter.

Q6: In a few sentences, explain why the brightnesses of the images depends upon the diameter of the objective lens.

Q7: Suppose an astronomer has used the UW 3.5m-diameter telescope (located in Arizona!) to just barely detect brown dwarf stars in a nearby star cluster. She believes that if she could detect objects 10 times fainter, she could discover Jupiter-like planets in the star cluster. If she submits a proposal to use the Keck Observatory 10m-diameter telescope for this project, would you award her observing time?

Note: Justify your decision with sound arguments. This is an obligation of every Time Assignment Committee Member, and a pillar supporting the peer-review system of science.
Section 5 – The Simple Magnifier

Hopefully by now you are convinced that the critical component of a telescope is the objective lens (or mirror). The diameter of the lens determines the brightness of images, or equivalently the faintest celestial objects that you can observe. The focal length of the lens determines the field of view that can be observed with the telescope and the ability of the telescope to resolve fine detail. From the point of view of a professional astronomer, this largely completes the story.

But for the rest of the human race who will be observing through a telescope by eye, there is more to be said. In principle you can simply look at the real image of an objective lens with your eye, as you have already done. But more typically the view of the real image is enhanced by using a magnifying glass. Which ultimately will bring us to the subject of magnification.

Your four lenses can also be used as magnifiers. Hold each of the lenses (one at a time) close to your eye and then examine your finger tip, the page of your notebook, or the graduations on a ruler. How close to the lens do you have to bring the object in order to see a clear, magnified image of the object?

Q8: Measure this distance for each lens and record it in your Table 1 under "magnifier distance."

How does this distance compare to the focal length of the lens listed in Table 1?

Do you find a relationship between the focal length and the magnification? That is, if lens A has a focal length smaller than that of lens B, do objects look bigger when viewed through lens B or through lens A?

To better understand how the magnifier works, see Appendix B.

Section 6 – Making a Visual Refracting Telescope

Now you are ready to use what you have learned about lenses to make a visual refracting telescope. (That is, a telescope comprised of lenses for use by eye.) Simply use one of the lenses as a magnifier to examine the real image formed by an objective lens.

• Try it!

Usually the trickiest part of making a telescope is simply getting the objective lens and the magnifier lens (or "eyepiece") properly aligned with each other. If you are having trouble, here’s a trick:

Place one of the short focal length lenses on the lens rail behind the real image formed by one of the long focal length lenses (in this case, the objective lens). Place the white screen at the position of the real image of the objective lens. Now look at the back of the screen through the short focal length lens (in this case, the eyepiece). Move the eyepiece back and forth along the rail until a clear, magnified view of the back of the screen appears. At this point the eyepiece is acting as a simple magnifier for objects located at the position of the screen. Since the real image from the objective lens is also at the position of the screen, you need only remove the screen to see a magnified image of the real image of the "stars". The two lenses are now operating as a telescope. (Be sure the
centers of the lenses are at the same height above the rail and that the telescope is pointed
directly at the stars.)

Q9: Sketch your telescope in your labbook, indicating distances between lenses, focal lengths of the
lenses, and the distance of each lens to the real image. Be sure to label which lens is the objective lens
and which is the eyepiece.

Section 7 – Measuring the Magnification of a Telescope

Magnification has many definitions, but for our purpose we will define it as the ratio of the size of an
object as seen with a telescope to the size of the object as seen with the unaided eye.

• With one eye looking through the telescope at a double star and the other looking
at the double star directly, estimate the magnification of the telescope.

• A more accurate measure of the magnification can be made by looking at the large
numbered illuminated boards positioned around the room. With one eye
looking through the telescope and the other looking directly at the board, you
should see something like that displayed below. In this example, the
magnification of the telescope is about 4.

Inverted image as seen through the telescope.

White board as seen directly with the other eye.

Figure 4
Q10: Make telescopes using different objective lenses and eyepieces. Record your results in Table 2 (copied to your labbook).

Can you find a relationship between magnification and the focal lengths of your lenses? Think of a systematic way to explore this question.

Table 2

<table>
<thead>
<tr>
<th>Focal length objective</th>
<th>Focal length eyepiece</th>
<th>Magnification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Q11: Explain your findings.

Hint: Consider the objective lens and the eyepiece lens separately. What is each lens doing, independent of the other?

Section 8 – Astronomical Seeing

Despite the advertising for WalMart telescopes, magnification is a vastly overrated property of telescopes. It turns out that when looking at stars and planets through a telescope, after a certain point, more and more magnification does not result in seeing the object in better and better detail. For example, no matter how much magnification your telescope has, it will never allow you to see individual grains of sand on the surface of Mars.

The blurring by the earth's atmosphere, called "atmospheric seeing" by astronomers, is one of the limiting factors.

- While looking at a "double star" with your highest magnification telescope, take a heat gun and blow hot air across the light path in front of the objective.

Notice that the stars become noticeably blurry due to the churning hot and cool air through which the light must pass. Ground based telescopes must also look through such a churning atmosphere, although the effect is not so dramatic as with a heat gun. This churning of the air is what makes the stars twinkle in the night sky.

Remember that stars (except the Sun) are much too distant to be able to visually resolve them. Thus effectively stars appear as perfect points of light. However, if one takes a photograph of a star its IMAGES will have a measurable size because of the atmosphere moving the point of light around during the exposure. This is also true for your eye, which also has an exposure time, albeit brief.

The measure of such image sizes are called astronomical seeing, and is the limit of detail that can be resolved on any celestial object. The best seeing is typically about 1 arc second (1" = 1/3600 degree). High magnification simply allows one to see a magnified view of these blurred images. This means that a ground-based telescope cannot see detail on Mars (when it is 8x10^7 km from Earth) any smaller than 390 km across -- no matter how much magnification the telescope has.
If your telescope were placed above the atmosphere, and if the objective lens (or mirror) were very accurately made, then the amount of detail that the telescope could reveal might improve dramatically. However, even in space there is a limit to the clarity of the image, set by the fact that light behaves as a wave. If you reach the point where the image quality is being degraded by the wave nature of light, then your telescope is said to be working at its "diffraction limit." That is the sharpest image that it can have. The larger the telescope's objective, the smaller (better) is its diffraction limit. For example, the Hubble Telescope (2.4 m diameter objective) is working at its diffraction limit, corresponding to 0.05 arc seconds of smearing in the real image formed at its focal plane. This means Hubble can resolve objects as small as 12 miles across on Mars --very good, but still a long way from seeing that grain of sand!

The diffraction limit of a telescope is given approximately by the formula

\[ \theta = 1.2 \frac{\lambda}{D} \]

where \( \theta \) is the angular size of the blurring due to the wave nature of light, \( \lambda \) is the wavelength of the light (about 0.5 \( \mu \)m for visible light) and \( D \) is the diameter of the objective lens. (1 \( \mu \)m = \( 10^{-6} \) m; 1 mm = \( 10^{-3} \) m).

Note: the angle \( \theta \) is measured in radians (see the hand-out on scientific calculators for a brief discussion of degrees and radians). Astronomers like to express angles in arc seconds. For future reference, note that there are 57.3 degrees or 206,000 arc seconds in a radian and that there are \( 4.85 \times 10^{-6} \) radians in an arc second.

Q12:

a) Using the equation above, what is the diffraction limit of your eye in arc seconds (your pupil diameter is about 3 mm)?

b) For what size telescope (objective diameter) is the smearing by the Earth's atmosphere (1 arc second) and the smearing due to diffraction about equal?

For ground based telescopes that are larger in diameter than that calculated in b), the image does not get any sharper. Is there any advantage to having a telescope larger that this?
Section 9 – For Life Closer to Home … The Lens Formula (Extra Credit)

Considered broadly, telescopes are all around you in optical devices of other names – eyes, cameras, binoculars, eyeglasses, and more. In practice, astronomical telescopes are the simplest of all optical devices, since celestial objects are so far away that for the purposes of optical design they can all be considered to be at the same distance – infinity! The engineering of your eyes does not have that luxury. Your eyes must be able to place a real image on your retina whether you are reading your lab manual or looking at a distant star.

In the first part of this lab in which you constructed a telescope, the object being looked at (the “binary star”) was far away and you found that the real image was located at the focal length of the lens. But for objects closer to the lens, the distance to the real image will be located at a greater distance from the lens than the focal length.

Specifically, the distance I from the lens to the real image is related to the distance S from the lens to the object by the lens formula,

\[
\frac{1}{I} + \frac{1}{S} = \frac{1}{F},
\]

where F is the focal length of the lens.

Q13: Earlier in the lab you found that for light sources at very large distances (e.g., across the room, or at cosmic distances), the real image of the object is located behind the lens at the distance of one focal length. Show that this equation is consistent with that finding.

Q14: The focal length of the orange lens is 100 mm. Use the bright lamp on your optical bench as the object for the lens. (Make sure that the lamp is at the same height as the center of your lens.) Place the lamp at a few positions and verify the lens formula.

NOTE WELL: Unless S is very large, the distance I to the real image is NOT the same as the focal length of the lens. The real image lies more distant than the focal length.
Q15: Place the lamp in front of the lens at the distance of one focal length. Describe what you observe. If you have done this accurately, you have created a searchlight!

Use the figure below to show what is happening.

Guide

Key Words

Astronomical seeing
Field of view
Focal length
Lens formula (extra credit)
Magnification
Objective lens
Real image
Refracting telescope
Resolution

Key Concepts

Light collection and telescope diameter
Formation of a real image
Focal length, field of view, and resolution
Eyepieces and magnification
Visual refracting telescopes
Lens formula (extra credit)
Appendix A - Ray Tracing

Figure A shows photons traveling radially away from a star. Some photons will travel toward the objective lens of a telescope. You know from experience that light travels on straight lines (called rays) through air or vacuum. It turns out that there are some simple rules governing this light-deflection that make it easy to draw a diagram of how lenses produce images.

The concept is simple: follow individual light rays on their straight lines until they hit the lens. Then bend them according to the rules of light-ray bending. This process is called ray tracing. These are the rules and regulations regarding ray tracing:

- Light paths can only change direction where they pass through a lens; everywhere else they are just straight lines (see in the figure below how light travels on straight lines until it gets bent by the lens). Use a ruler or straightedge to draw the rays. It is obvious that light rays missing the lens do not get bent and do not contribute to the image (ray 4 in Figure A is an example of that).
- A ray passing through the very center of a lens does not bend (ray number 1 in the figure below)
- Any ray entering (or exiting) the lens parallel to the lens axis (the lens axis goes through the center of the lens and is perpendicular to the lens surface – see figure) will go through the focus on the opposite side of the lens (rays 2 and 3).

Additional helpful rules:

- All other rays coming from the object point and going through the lens must also go through the image of the point (ray 5 is an example of that). These rays do not help in finding the location of the image through ray tracing.
- Note that the two focal points of a lens are at the same distance F from either side of the lens (see the two points marked F in the figure).
Appendix B – A Magnifying Glass

The magnified image of the object that you see when looking through a magnifying lens is not a real image. There is no actual point in space onto which light rays are being focused. Rather the light appears as if its coming from a much larger object located behind the object being examined. Thus images seen through a magnifying lens are called virtual images.

Of course, all the eye knows is the direction of light rays entering it. Thus the light enters the eye as if it were originating in the virtual image. Then the lens of the eye forms a real image of the virtual image on the surface of the retina --which is what allows the brain to "see" a magnified image.

![Diagram of magnifying glass and light paths](image-url)