Exercise 6: Optics of telescopes

Optics is the field of physics involved in the study of light. No less a luminary than Isaac Newton is credited with originating the field, though of course humans have been interested in the properties of light since antiquity. Newton, in his book *Opticks* (1704), systematically set out to describe light and its properties; many of the experiments he describes in the book are still the basis of various modern telescopes and spectroscopes.

Fundamentally, diffuse rays of starlight are “collected” by mirrors or lenses, and focussed into a viewable, magnified image. In order to focus, the paths of the starlight rays must be changed. Mirrors accomplish this by reflecting the light rays off of a polished curved surface; lenses accomplish the change by bending (or, technically, refracting) the light rays through a curved piece of glass.

Some terminology: if the curved surface bows outward, it is called convex; if it bows inward, it is called concave. If both sides of a lens bow outward, it is called a double convex lens; this is the type you will be using.

In this exercise, you will first study factors that influence how “good” a telescope is, then draw the paths of starlight through some sample lenses and mirrors, and finally perform various experiments to determine the magnification available through telescopic lenses.

Part 1 — Mostly about refractors

*Aperture size*

Basically, the primary mirror or lens (also called the objective lens) of a telescope or spectroscope is the surface that will gather the rays of light from distant objects. Clearly, the larger the surface, the more light rays it can gather and thus the more light intensity will be available to view. For this reason, the primary is often called “the light bucket”.

On the next page is a figure from an anatomy and physiology textbook that shows the changes in the human eye’s pupil size at varying light conditions. The pupil is the round spot in the middle of the eye. Though the pictures enlarge the size of the eye, by taking a ratio of the dim light pupil to the bright light pupil, we can determine the change in light gathering capability of the eye.

1. Using a ruler, measure the diameter of the dim light and bright light pupil; enter the information in the table on the next page. Calculate the ratio of dim to bright diameter.

Assuming that pupils are circular (reasonably good assumption), calculate the area of the dim light and bright light pupils, and enter the data in the table. Hint: $A = \pi r^2$. Calculate the ratio of dim to bright area.
Responses of the pupil to light of varying brightness.

Contraction of the circular muscles causes constriction of the pupil; contraction of the radial muscles causes dilation of the pupil.

<table>
<thead>
<tr>
<th>Pupil</th>
<th>Dim light</th>
<th>Bright light</th>
<th>Dim/bright ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area (mm²)</td>
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<td></td>
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</table>

2. a. The area of a light-gathering surface is proportional to its light-gathering capability; what is the mathematical relationship between the linear diameter of a light-gathering surface and its light-gathering capability?

b. So what’s one reason that a 6-inch primary lens telescope costs more than twice a 3-inch primary lens telescope?

Magnification and focus

Another characteristic you should look for in a telescope, besides its primary lens or mirror size, is its ability to have a well-defined focus. Clearly, a badly-defined focus will not allow you to examine a distant object very well.

For the refractor telescopes...

• Light rays go straight unless...

• Light rays refract at a glass/air or air/glass transition (i.e., the surface of a lens). A light ray travelling from air into glass will bend towards a line
perpendicular to the surface of the lens. A light ray travelling from glass into air will bend away from a line perpendicular to the surface of the lens. If you define the “angle of incidence” as the angle between the incoming light ray and the perpendicular to the surface, and the “angle of refraction” as the angle between the outgoing light ray and the perpendicular to the surface, then the law of refraction says that the angle of refraction is less than the angle of incidence if the light travels from a less dense to a more dense medium, such as when light travels from air to water. The opposite is true when light goes from a more dense to a less dense medium.

- A light ray whose path is along the perpendicular line will not bend, because this ray is already going along a line perpendicular to the surface.

Note that this means a lens will bend the light twice. On the previous page is a cross-section of a double convex lens. I have drawn a beam of incident light, and two lines representing the tangent (or perpendicular) to the surface of both sides of the lens.

3. a. The diagram on the next page shows a cross-section of a lens and some incident light rays. It also shows a line called the principal axis (dotted) on which is a point marked "F", which is the focus of the back side of the lens. Draw the continuation of the light rays as they enter the lens and converge on the focus.
There is some distortion associated with gathering light rays through a lens; the most important effect is inversion, which results in an upside-down and backwards image. In the diagram below, an object (a nail) is shown on one side of a lens and its image is shown on the other side.

b. **Draw a set of light rays** which demonstrates why the image of the nail shows up where it does. Note that the image is ultimately inverted. Hints: First, draw a light ray horizontal from the top of the object to the lens; where must this light ray end up? Next, draw a light ray from the top of the object diagonally through the center of the lens; where must this light ray end up. Finally, draw a light ray from the bottom of the object along the principal axis; where must this light ray end up?

Characteristics such as **field of view** (how much sky you can see through the eyepiece), **resolving power** (the ability to distinguish two closely-spaced objects, see previous section) and **chromatic and spherical aberration** (distortions due to the shape of the objective lens) are important, and depend on the focus.

For **reflector** telescopes...
- Light rays **reflect** off a surface at the same angle as the angle of incidence, except that the reflected rays are directed outward on the other side of the perpendicular.
4. a. The diagram below shows a cross-section of a mirror (the curved line) and some incident light rays (the arrows coming from the left). It also shows a point marked “F”, which is the focus of the mirror and a point marked “C”, which is the center of curvature of the mirror. Draw the continuation of the light rays as they enter the lens and converge on the focus.

b. Obtain the large concave mirror and determine its focal length. How did you do it? Give enough detail that someone else could reconstruct your measurement just from your instructions. Pay special attention to the placement of the source of the image.
Once the various focal issues are resolved, **magnification** of a small image is a significant consideration for a telescope. Though a planet is quite large, its image in the eyepiece is quite small; in order to see detail, the image must be magnified. Consider the *angular* size of a planet; the disk of Mars is virtually impossible to distinguish with the unaided eye. However, a telescope will magnify the apparent *angular* size of any object; you will be able to see the disk of Mars. The diagram below, from Hewitt’s *Conceptual Physics*, shows the light rays and lenses of a telescope:

![Diagram showing light rays and lenses of a telescope.]

The equation for the **magnification** is simple:

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

where $M$ is the magnification (usually expressed with an "X" at the end, such as "10X"), and the $f$'s are the focal lengths of the objective and eyepiece lenses.

Obtain an optical "bench" setup (there should be three sliding mounts on the calibrated horizontal bar. The setup is shown in the diagram below.

![Diagram of optical bench setup.]

Find the centimeter markings on the horizontal bar. Place the light source (on its holder) at 0 cm. Place the screen with the arrows at 5 cm. This exercise will probably work better with all room lighting off.

The **objective** lens (AKA the primary lens) should be placed in the spring-loaded holder, and the **eyepiece** lens (the smaller ones) should be placed in the screw-down holders. You will be switching eyepiece lenses, so practice removing and installing lenses in that holder; don’t tighten the screw so much that the lenses crack!

Begin by placing the objective lens at the 50 cm marker on the horizontal bar, and removing the eyepiece lens holder entirely. Place the frosted glass viewscreen (with
(cross-hairs) on the other side of the objective lens from the light source. Make sure that an image of the arrows is visible on the viewscreen.

Move the mount with the frosted glass screen along the calibrated bar to obtain a **focused** image (upside down and reversed) of the arrows. Do not move the **objective lens mount**! Determine the **focal length** of the objective lens, and enter it in the appropriate square of the table below.

Remove the objective lens and its holder and replace it with one of the smaller eyepiece lenses (record the letter associated with the lens) in its holder. Mount it at 50 cm. Determine the focal length of the eyepiece lens, and enter it into the table below. Calculate the magnification using the equation above.

Replace the objective lens (don’t remove the eyepiece lens) at 50 cm. Move the eyepiece lens so that it is at a distance from the objective lens which is exactly the sum of the objective lens focal length and the eyepiece length focal length (in other words, the sum of columns two and three).

Does the image of the arrows change much as you look through the two lenses and vary the distance your eye is away from the eyepiece lens? If so, move the eyepiece lens a little closer to the objective lens until the image of the arrows doesn’t change.

5. The image of the arrows should be in **focus**. Is it right side up or upside down and backwards? Is the arrow image **magnified** from what it looks like at the same distance without the lenses?

6. Calculate the magnification for various telescopes to compare and contrast magnification abilities. Under “type of telescope”, state whether the telescope is a “refractor” or “reflector” type of telescope.

<table>
<thead>
<tr>
<th>Name of device – type of telescope</th>
<th>Focal length of objective ((f_{\text{objective}})) in centimeters</th>
<th>Focal length of eyepiece ((f_{\text{eyepiece}})) in centimeters</th>
<th>Magnification power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical bench telescope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meade 125 mm telescope</td>
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7. a. What general rule(s) can you formulate about the focal length of the objective lens, the focal length of the eyepiece lens and higher magnification?

b. Examine the eyepiece lenses from actual telescopes; what do you notice is the drawback to the simple rule of “get a smaller focal length eyepiece”?

**Resolution**
Resolution is simply the angular size of the smallest object you can distinguish in a telescope’s field of view. A simple equation to determine the resolution of a telescope is:

\[
\theta = 250,000 \times \left( \frac{\lambda}{D} \right)
\]

where \(\lambda\) is the **wavelength** of incident light in meters, \(D\) is the **diameter** of the objective lens or mirror of the telescope in meters, and \(\theta\) is the **angular resolution** in arcseconds.

8. a. For the telescope you will set up in the last part, assume we are viewing a green light \((\lambda = 550\, \text{nm})\). Measure the diameter of the primary lens and determine the angular resolution of your “telescope”.

b. Will you be able to see individual **lunar craters** (about 5 arcseconds wide) with this telescope?

9. Give **two** ways in which you could make the angular resolution better. Hint: one of the ways is impossible using glass lenses.
10. Why don't telescope makers simply fabricate huge objective lenses, instead of trying to make huge polished mirrors? In fact, this is the reason that all the big telescopes in the world are reflectors and not refractors. (Hint: Consider the material lenses are generally made from and the deformation properties of such material)

11. What is the difference between magnification and resolution in a telescope? (Hint: magnification is a unitless number and resolution is measured in degrees, arcminutes or arcseconds)