the diameter or aperture. Because stars are extremely far away, they appear as point sources of light even with a telescope. Their brightness in the telescope depends **only** on the size of the aperture. The brightness of an extended image such as a planet, the Moon, a galaxy or other deep sky object, however, depends not only on the aperture but also on the *f/ratio*.

$$f/\text{ratio} = \frac{\text{focal length of objective}}{\text{aperture}}$$

This is the same f/ratio found on your camera lens. The smaller f/ratio, the brighter the image is, or the *faster* the camera system is said to be. We will confine our attention to light gathering and not image brightness. For this the light gathering ability is described by:

$$\frac{L_1}{L_2} = \frac{D_1^2}{D_2^2}$$

where L_1 and L_2 = light gathered by telescope 1 and 2
D_1 and D_2 = aperture of telescope 1 and 2

Magnification is the measure of how much larger an object appears when seen through a telescope. When looking at an extended source rather than a star, magnification by the telescope allows more detail to be seen. The objective forms a fixed image size, which is viewed by the eyepiece to produce the final magnification. The magnification of the objective and eyepiece combined is given by:

$$M = \frac{F_o}{F_e}$$

where F_o = objective focal length
F_e = eyepiece focal length

Resolving power α given in seconds of arc is a measure of the ability of an optical system to produce distinct detail within an image. Even though magnification can be increased, there is a fundamental limit on how fine a resolution of detail can be achieved. This limit is given by the *Rayliegh criterion*, and is determined by the aperture of the telescope. According to the Rayleigh criterion it is possible to separate or resolve, two objects if their angular separation is given by:

$$\alpha = (2.52 \times 10^5)\,\lambda / D$$

where: D = telescope aperture
λ = wavelength of light being observed
D and λ **must be in the same units.**

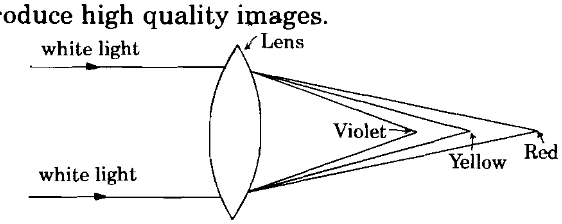
When visible light is used, this reduces to *Dawe's limit* given by:

$$\alpha = 4.56/D(\text{inch}) = 11.6/D(\text{cm})$$

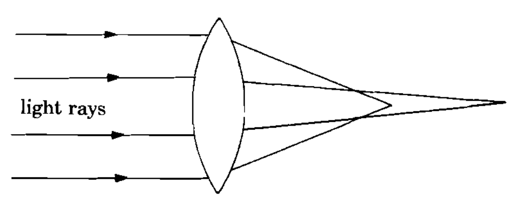
The angle α is in units of seconds of arc and is the resolving power of the telescope. It sets a limit on the smallest amount of detail that can be observed. In practice, this is a theoretical limit and other factors such as atmospheric conditions, brightness of the objects, etc. are generally more important. Until recently the actual resolving power was always worse than the theoretical value. Modern AO technology however has introduced the ability to correct for seeing by using optical elements that change shape in response to a laser beam that monitors the "seeing".

An important consideration in selecting a telescope is the minimization of optical aberrations. *Aberrations* of lenses and mirrors are departures from perfect image formation caused by paths of light not coming to the same focal plane. The aberration that delayed the widespread development of the refracting telescope until the mid-eighteenth century was *chromatic aberration*. This defect results because the amount of bending (refraction) of a light ray depends on its wavelength or color. Blue light is refracted more than red. Thus, a simple convex lens forms an image for each color at a slightly different distance from the lens as illustrated below. This aberration is a property of the glass and can only be corrected by combining lenses of two or more different glasses (different index of refraction). Such a lens system is called an *achromat*, and when high quality achromats became available in 1750, the development of the refracting telescope leaped forward. Mirrors do not involve the transmission of light, so they are free of chromatic aberration.

A second common aberration is found in both refracting and reflecting objectives. Spherical aberration is caused by the failure of a spherically curved surface to bring all parallel rays to the same focal point as illustrated below. For refracting lenses the surfaces are made slightly non-spherical and for mirrors, the curve is made into a parabola. These are referred to as corrected optical surfaces and can produce high quality images.

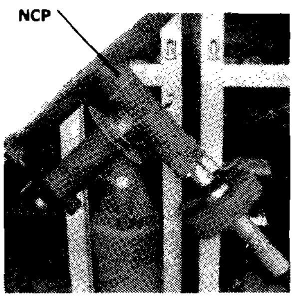


Chromatic Abberration

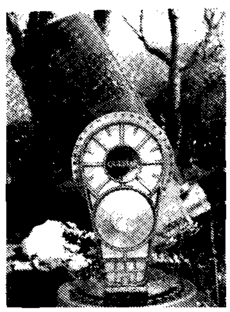


Spherical Abberation

A major problem for observers has been the ability to hold the telescope steady. This is especially necessary at high magnification since the slightest vibration is greatly exaggerated when viewing through the telescope. The mounting and tracking of a telescope to follow the daily motion of the heavens is basically an engineering problem. A movable system of rotation axes is fixed to a tripod mount or for a permanent location, a pier. The two common mounts are the *altazimuth* and *equatorial* types. Both mounts provide two axes of rotation so that any point on the sky can be reached. The equatorial mount has a design that allows one axis, the polar axis, to be pointed toward the North Celestial Pole (NCP). Rotating the telescope around this axis can then easily counter the earth's rotation and maintain the telescope pointing toward the object being observed. The altazimuth design does not have the ability to point one axis at the NCP, but is easier to move because of its simple up-down, left-right movements. The basic telescope mount designs are illustrated below.



Equatorial



Altazimuth

The equatorial mounts make it relatively easy to track celestial objects for viewing and astrophotography and traditionally were the design of choice. However the introduction of computer controlled motors has solved the tracking inconvenience of the altazimuth mount by simultaneously moving both axes automatically to stay fixed on a sky object. Most modern large professional telescopes and many small amateur telescopes use the altazimuth mount design for this reason since it is easier to build than the equatorial design. Today even amateur astronomers can buy fully automated mounts that not only track objects but can find them using coordinates input to a computer based mount. These are usually referred to as *GOTO systems*.

The very large telescopes of today, and even the small telescopes of amateurs are vastly different in appearance from the early telescopes of Galileo and Newton. Many amateurs now have telescopes that make possible views of the heavens that professional astronomers of fifty years ago would envy. The giant telescopes of the professionals will continue to evolve in design. These will look more deeply into the universe and make discoveries yet unanticipated. It is hard to imagine what these telescopes will allow observers to see at **first light**.

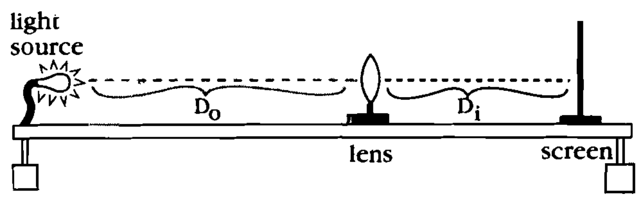
QUESTIONS:

1. Using two simple lenses with known focal lengths, an optical bench and a light source, some simple telescope properties can be investigated. Complete parts a - k of this question about assembling a set of refracting telescope optics.

   a. Which of the two lenses is the best choice for the objective? Explain the basis of your selection and record the focal length and aperture below.

   focal length _______ aperture ________

   b. The diagram below shows the optical bench setup for the telescope measurements. Mark on the light bulb an indicator such as the following (↳). Place the objective lens in its holder as far from the light source as practical, leaving room on the optical bench to project an image on the screen. Move the screen until the image is in focus.



   c. How does the distance D_i between the lens and screen compare to the lens focal length?

   d. Is this a real or virtual image?

   e. All parts of this question below compare the image properties to the source properties.

   Is the image larger or smaller than the source?

   Is the image erect or inverted?

   Is the left/right orientation the same or reversed?

f. Decrease the aperture of the objective by placing a card with a 1/4 to 1/2 inch hole in it directly in front of the objective. Describe any changes in the image projected on the screen.

g. Measure the aperture and calculate the f/ratio of the system with and without the card.

without card ______________

with card ______________

Which f/ratio produces the brightest image?

h. Now remove the screen and use the short focal length lens as an eyepiece (magnifier). That is, place the lens somewhat further away from the objective than the screen was located, and view the source through it. This is a little tricky but move the eyepiece lens until the source is focused. What is happening is that you are using the eyepiece much the way a magnifying glass is used to enlarge something. The difference in this case is the something you are magnifying is the image formed by the objective. Estimate the magnification (m) of the system by alternatively viewing through the "telescope" you have now assembled and then along side it.

Estimated M ______________

Now calculate M using the magnification equation in the introduction.

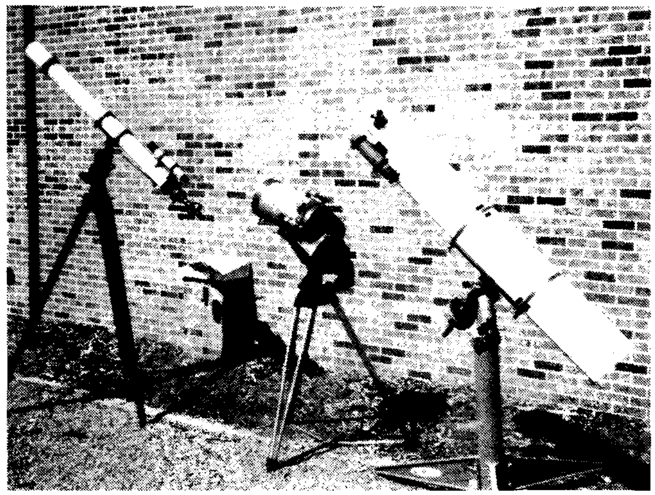
Calculated M ______________

i. When viewing with the eye, a virtual image is usually seen in the eyepiece as it is with the magnifying glass. With the magnifying glass this virtual image is usually seen right-side-up, while the telescope image is seen inverted. Why is the telescope image inverted?

j. Is it possible to use the eyepiece to obtain a real image and if so, what adjustment must be done?

k. When might it be desirable to complete the telescope optics to produce a real image rather than a virtual image?

2. The photograph below illustrates a refractor, Newtonian reflector and Schmidt-Cassegrain system. Complete parts a - f of this question using the photograph below.



a. Under each telescope label the type of telescope it is.

b. Label the location of the objective (obj.) and eyepiece (ep.) of each telescope. (Hint: Check the ray diagrams in the introduction.)

c. Label the location of the corrector plate on the Schmidt-Cassegrain.

d. What is the purpose of the small telescope mounted on each tube?

e. Judging from the photographs with what type of mounts are these telescopes equipped?

f. Notice that the refractor is equiped with a turret eyepiece unit. What is the advantage for using the turret accessary?

3. The figures below show pictures of Jupiter taken with telescopes of different magnification. Complete parts a – e.

a. Place a number, 1 to 4, below each photograph starting with 1 for the least magnification.

A. ______________

B. ______________

C. ______________

D. ______________

b. Small telescopes are usually used with a selection of eyepieces that provide different magnifications. For a 125 cm focal length telescope a typical selection of removable eyepieces might be: 25 mm, 12.5 mm and 5 mm. Calculate the magnifications available with this set of eyepieces.

25 mm_____ 12.5 mm _____ 5 mm _____

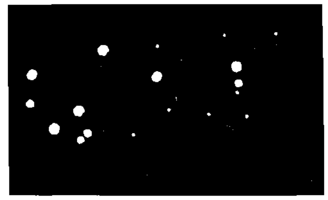
c. If the focal length of the objective is the same for each telescope, then which image, A - D, was produced using the **shortest** focal length eyepiece?

d. If the eyepiece being used in each image is the same, which telescope has the **longest** focal length objective?

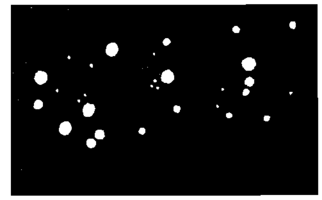
e. If the size of Jupiter was 45 seconds of arc without a telescope, and it appeared as seen in A to be 1 degree in size through a telescope, what was the magnification of the telescope?

4. All the star field images below were acquired with telescopes of different apertures, with equal time exposures. Complete parts a – e.

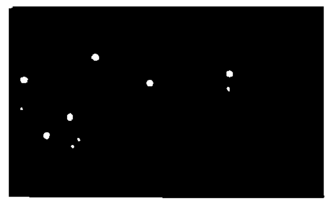
a. Place a number 1 to 4 under each image starting with 1 for the poorest light gathering power.



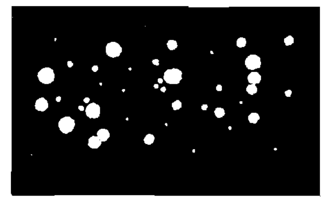
A. ______________



B. ______________



C. ______________



D. ______________

b. Which telescope has the largest aperture? Explain.

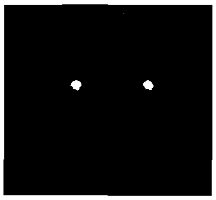
c. If the comparative brightness of the stars of image A and D differ by a factor of 4X, then how many times larger is the aperature of D compared to the aperature of A?

d. The Hale Telescope has a 5 m aperture and each Keck Telescope has a 10 m aperature. How many times more light is collected by a Keck Telescope than the Hale Telescope?

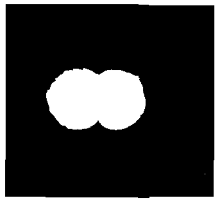
e. If the Extremely Large Telescope will have a 42 m aperture, how many times more light will be collected by the ELT than a Keck telescope?

5. The resolving power of a telescope allows the viewer to see closely spaced objects as separate objects. Complete parts a - c.

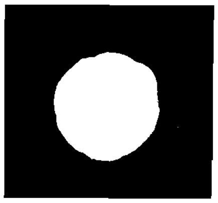
a. The images below represent a pair of closely spaced stars referred to as a double star. Users of small telescopes frequently test their telescopes by seeing if they can resolve this type of object into separate points of light. Place a number 1 to 4, below each image starting with 1 to indicate the poorest resolving power.



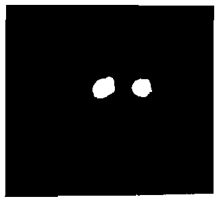
A. ________



B. ________

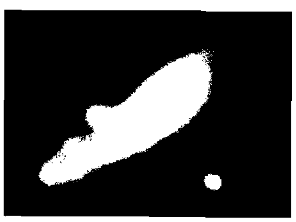


C. ________

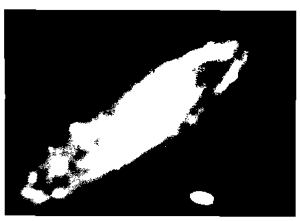


D. ________

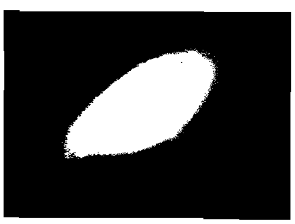
b. The resolving power when looking at an extended object such as the galaxy below is usually ranked in terms of the detailed structure that can be identified. In these pictures we have separate spiral arms and two small nearby galaxies. Place a number 1 to 4, below each image starting with 1 to indicate the poorest resolving power.



A. ~~B~~ ~~4~~ 2



B. ~~2~~ 3

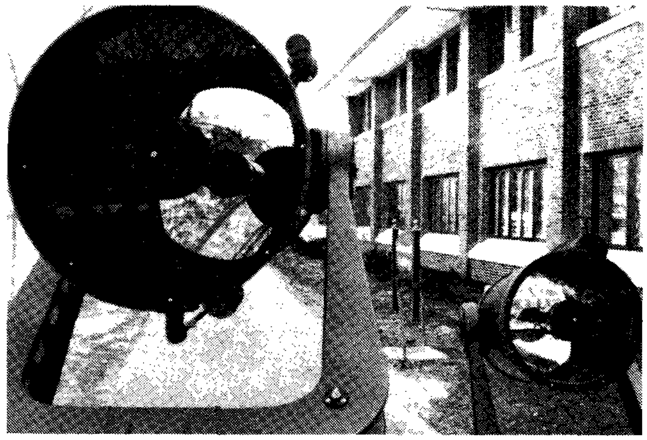


C. ~~4~~ 1

D. 4

c. If the two stars in part a are separated by 0.8 seconds of arc, what is the theoretical aperture of the telescope that resolves them in visible light? (Hint: Use Dawe's limit.)

6. The photo below shows two Schmidt-Cassegrain telescopes presented looking down the barrel. The larger telescope has an aperture of 14″ and the smaller 8″. Complete parts a - d.



14″ 8″

a. Which telescope will resolve objects that are closer together?

b. How much closer together can the objects be that are resolved by the telescope with the better resolving power?

c. Calculate the Dawes limit for the 14″ telescope.

d. This ideal separation is closer than this telescope can actually separate in practice. Why is the ideal separation never achieved?

7. A simple 15.2 cm reflecting telescope can achieve 1 second of arc resolution for visible light. Many radio telescopes study a particular radio wavelength of 21 cm. Complete parts a - d using the above information.

a. Use the Raleigh criteron to determine how large a radio telescope aperature must be to achieve this resolution at 21 cm.

b. Why must the aperture of a radio telescope be much larger than that of an optical telescope?

c. Why is it possible to resolve two predominantly blue stars when the same telescope can not resolve two simarily separated red stars?

d. In the galaxy pictures of 5b, which photograph corresponds to the largest aperture?

8. The table at the bottom of the page indicates some properties of four small telescopes similar to those readily available to the amateur astronomer. Complete parts a - e of this question based on the table.

a. Complete the missing entries in the table based on the information for each given telescope.

b. Which telescope has the best light gathering ability?

c. Which telescope is capable of the greatest magnification?

d. Which telescope has the fastest speed for camera use?

e. Two stars are 0.71 seconds of arc apart as seen from Earth. Which telescope(s) is(are) ideally capable of producing separated images of the two stars?

9. Shown to the right are some of the present and future primary mirrors to be built in ground based telescopes. The diagrams of the primary telescopes are drawn to scale. Complete the following parts a - f based on the diagram.

a. What are **two** observational advantages to be gained by making the aperatures of these primary mirrors large?

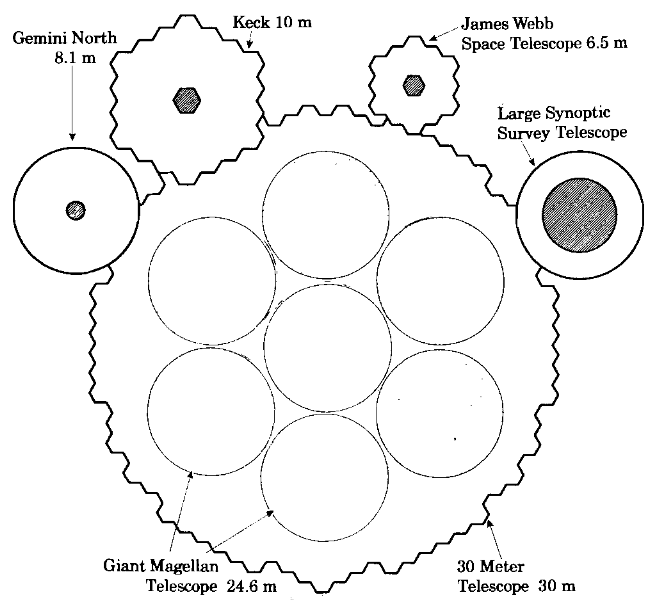
b. What are **two** technological advances in mirror production that have enabled the design of these primary mirrors to be so large?

c. On the front surface of the Keck mirror draw a vertical line representing the height of a 6 foot tall human being. Label the line **human**.

d. The Hubble Space Telescope primary mirror is 2.4 m. What is the LGA increase of the Thirty Meter Telescope?

e. Although the Hubble Space Telescope does not gather as much light as the Thirty Meter Telescope, what is the advantage of the Hubble Space Telescope?

f. How does the Thirty Meter Telescope compare to the length of a football field?



Telescope	Magnifying Power	Resolving Power arc sec	Aperture cm	F_o cm	F_e mm	f/ratio
Schmidt Cassegrain	180X	0.57		230		
Newtonian	192X			122		f/8
Refractor			10		19	f/15
Rich Field	50X		12.5			f/4

Refer to the LSW web site (http://www.lswpub.com) for useful ideas when selecting a telescope.