

# Telescopes

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Ch 8 from *The Handbook of Optical Engineering*  
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OPTI 521  
November 19, 2007

## I. Introduction

The term *telescope* encompasses a rather large variety of instruments. There is not one specific thing you can pick up and say, "This is a telescope." They differ in their application, and thus have different designs based on the desired function. Some use lenses (*refractive* or *transmissive* telescopes) while others use mirrors (*reflective* telescopes), and some even use both. Some have 1 mirror, while others use 2 or 3. And though they can be very different in their appearance, design and application, they all serve essentially the same purpose; to collect light (be it visible or not) from a far away object and increase its angular size such that the human eye can see it. This paper discusses the variety of telescopes that exist, how they differ, their specific applications, and a general overview of image quality characteristics of telescopes.

## II. Telescope Images

A telescope would be quite pointless if the images it made weren't useful. For instance, suppose you were using a telescope to image 2 stars that were relatively close together. Well, if you don't design the telescope such that you can tell that there are actually 2 stars there, perhaps it looks like just one big blob, then it really isn't doing what you want. This and other things must be taken into account when choosing and designing a telescope.

Above was an example of the *resolution* of a telescope. Resolution can be defined many ways, but it is essentially the ability to resolve two objects that are close together. This is an issue because of the effects of diffraction. Diffraction causes the image of a point source to be spread out into a bright central disk (called the Airy disk) surrounded by bright rings or much less and gradually decreasing intensity. For an optical system of focal length  $f$  and circular entrance pupil of diameter  $D$ , the radius of the Airy disk for light of wavelength  $\lambda$  is given by,

$$r = 1.22f\lambda/D \quad (1)$$

So the ability to decipher the image of two objects will be limited by how much these images are spread out, namely, the size of the Airy disk. One criterion for resolution is the *Rayleigh resolution criterion*. It states that two point sources may just be distinguishable if the first zero of one diffraction pattern overlaps the central max of the other. This means that the center of their images must be separated by the Airy radius given by (1).

In addition to diffraction, the image formed by a telescope (or any optical system) will be degraded (read, spread out more) by aberrations, fabrication imperfections, and alignment errors. These are all geometric considerations, and opposed to diffraction ones. In this case, all the errors can be determined by modeling light as a ray, always propagating in a straight line. The third order aberrations are spherical aberration, astigmatism and coma. An optical system corrected for spherical is called *aplanatic*, and one corrected for spherical and astigmatism is called *aplanatic and astigmatic*.

No matter how good you design and build your optical system, the effects of diffraction will always be there. And for a very well designed and build system where the effects of aberrations are small compared to the effect of diffraction, your system is said to be *diffraction limited*. (The resolution will be given by (1)). If on the other hand your aberrations are large, such that they determine the size of your image, you are said to have a *geometric image*.

The *Modulation Transfer Function (MTF)* is another means by which to describe the performance of your optical system. It is a way to measure how the system responds to different spatial frequencies. In other words, how well it can image things that have a certain level of detail. For low spatial frequency components of an image, most optical systems have near perfect ( $MTF = 1$ ) resolution. However, even for a perfectly designed and built system, as frequency increases response decreases. The rate at which the MTF drops is a function of the specific system. One with more aberrations will drop off more quickly.

### III. Refractive Telescopes

Like the name implies, refractive telescopes use only refractive elements, ie lenses, to do all of the magnifying. The most simple and common of this variety is the Keplerian telescope, shown in figure 1. It is comprised of two positive lenses separated by the sum of their focal lengths,  $f_1$  and  $f_2$ . Where the angular magnification of the system is,

$$M = -f_1/f_2 \quad (2)$$

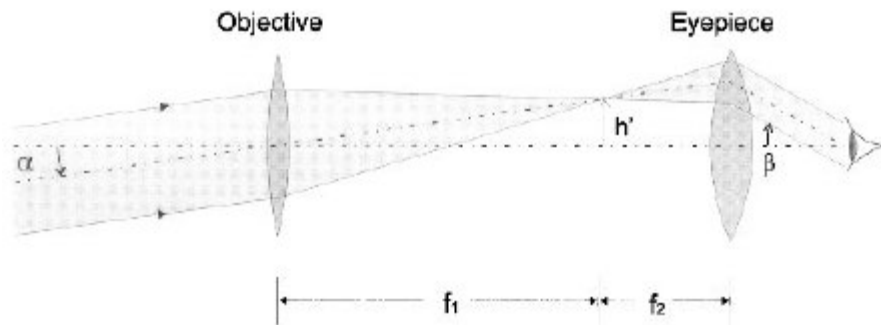


Figure 1. Keplerian Telescope

Because  $f_1$  and  $f_2$  are both positive, this type of telescope will have a negative magnification. From figure 1 you can see that there is an intermediate focal plane between the two lenses. This can be advantageous in some instances, such as adding a pinhole for beam centering and spatial cleaning. But for things such as high power lasers applications, this intermediate focus can cause excessive heating and thus thermal lensing effects, air breakdown, and even second order electric field effects.

An alternative to the Keplerian that has a more compact design is the Galilean Telescope, figure 2. It too is comprised of two lenses separated by the sum of their focal lengths, but in this case the second element is negative, resulting in a shorter instrument. Without an intermediate focus, this design would be ideal for a high power laser application.

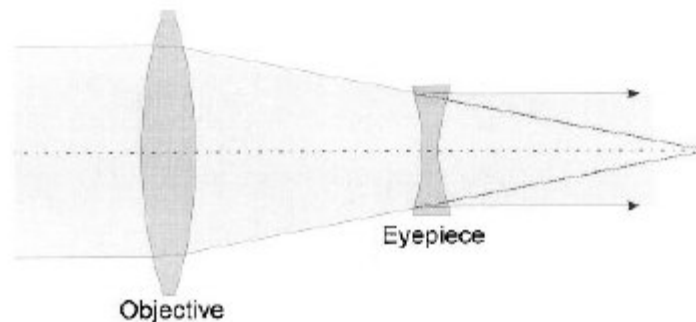


Figure 2. Galilean Telescope

### Terrestrial Telescopes

If categorized by primary application, telescopes can be divided into three categories, terrestrial, astronomical, and space telescopes. While astronomical and space telescope are both used for looking at objects really really far away (eg stars), terrestrial telescopes are used for imaging relatively close objects. That is, ones that are 50 – 1000 meters away, such as hunters would need to do. Important features of such a telescope would be an erect image (positive magnification), color correction, and a large field of view. The former two characteristics both necessary to provide the most correct image of the source, as would be important to a hunter.

### **IV. Reflecting Telescopes**

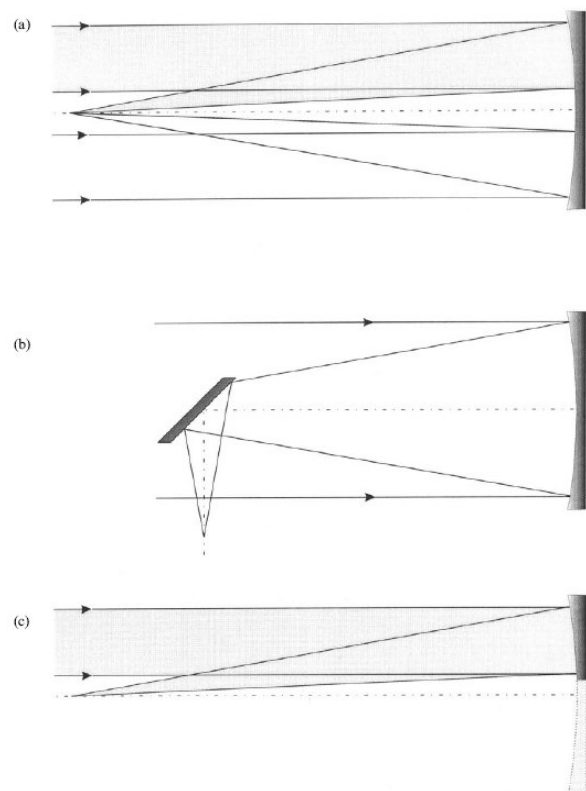
To see an image with a telescope, or any optical system (including your eye) there must be enough light collected from the source. For far away objects, the light is quite faint. Thus to increase the speed at which the required amount of light is gathered, the aperture of a telescope can be increased. However, increasing the size of a refracting telescope can become quite a hassle. For one, fabrication of large lenses, which have two surfaces to figure and polish is difficult. Secondly, mounting a large lens is more cumbersome than a mirror. A lens has to be counted such that light can travel through it. A mirror on the other hand can be essentially mounted on the ground or table of sorts, a much easier task.

And more than just difficulties with large lenses, mirrors have advantages themselves. Because they are reflective, there are no chromatic issues to deal with, and they have less aberrations in general. And a single mirror design can be used for a wide band of wavelengths due to the very good broadband reflective coatings that are available. This is opposed to a lens, whose chromatic issues and more narrow band anti-reflection coatings make them a more specialized design.

We can divide mirror based (catoptric) telescopes into categories based on number of mirrors, here I will summarize the different varieties.

### One-Mirror Telescopes

The one-mirror telescope can take on 3 general forms, see figure 3. The simplest is a parabolic mirror, which has no spherical aberration or astigmatism when the stop is at the front focal point and the image is on a spherical surface. One inconvenience of this design is the fact that the image plane lies in the beam path. An modification to alleviate this issue is the Newtonian telescope. As you can see, this design uses a fold mirror to shoot the image off at 90 degrees outside of the incoming rays. This solves the problem of access to the image plane, but it still leaves an obstruction in the way of the primary mirror. A solution to this is to use an off-axis configuration as shown in 3(c). This design is known as a Herschelian telescope. It still uses a parabolic primary, but only the segment above the focal plane. This eliminates the need for the turning mirror, and there is no central obstruction.



**Figure 3. One-Mirror Telescopes**

(a) Parabolic Mirror, (b) Newtonian, same as above with fold mirror, (c) Herschelian, off-axis configuration without central obstruction.

### Effects of a Central Obstruction

Not only does a central obstruction decrease the effective area of the primary mirror, and thus the light collecting ability of the telescope, but it also degrades the diffraction limited performance. The central obstruction ratio  $\epsilon$  is the ratio of the obstruction radius to the primary mirror radius,  $\epsilon = r/R$ . As this value increases, the intensity of the Airy disk drops, with the difference being thrown into the “wings”, or rings, around this central bright spot. Figure 4 shows a logarithmic plot of the intensity of the diffraction spot for various values of the obscuration ratio.

The MTF is also negatively effected. Figure 5 shows how it decreases as  $\epsilon$  is increased. This means that no matter how well you design and build your telescope, it can never do better than the corresponding diffraction limited performance.

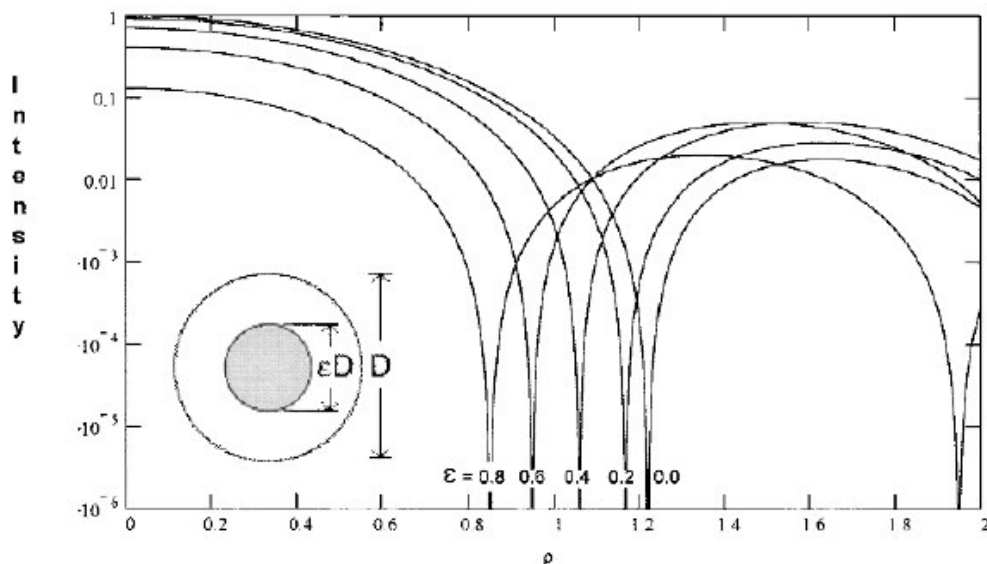


Figure 4. Diffraction Spot as a function of obscuration ratio

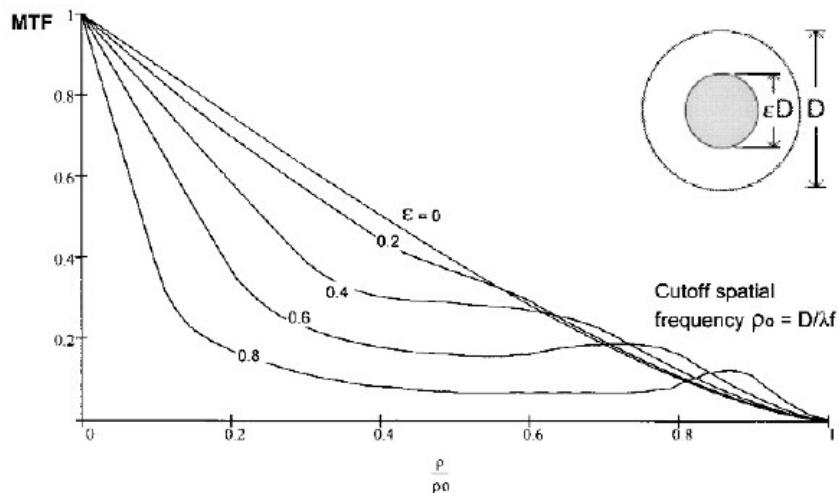
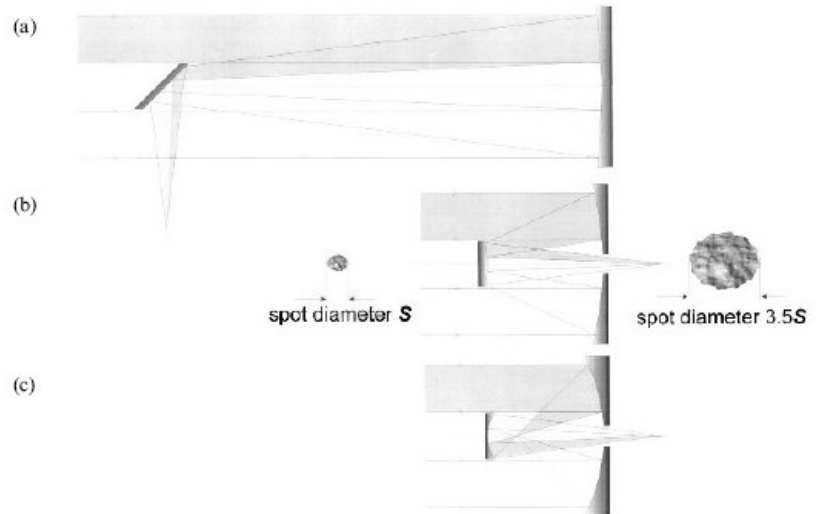


Figure 5. MTF as a function of obscuration ratio

### Two-Mirror Telescopes

Some varieties of two-mirror telescopes are shown in figure 6. The Newtonian is probably the simplest, having on a flat secondary mirror as shown before. Then you have the Cassegrain telescope, similar to the Galilean refractive design, in that the first element is positive and the second is negative, resulting in a design without an intermediate image plane. The primary mirror is a paraboloid, while the secondary is a hyperboloid.

This is opposed to the Gregorian design, which has two positive elements (similar to a Keplerian) that does have an intermediate focus. In this case, the primary is a parabola and the secondary an ellipse. The advantage of this design is that the image has positive magnification, making it useful for terrestrial applications.



**Figure 6. Two Mirror Telescopes** (a) Newtonian, (b) Cassegrain, (c) Gregorian

Purely reflective telescopes are *catoptric* systems, while refractive ones are *dioptric*. Systems employing both reflective and refractive elements are called *catadioptric*. An example of such a configuration is a telescope with a reflective primary and secondary, but also including a refractive correcting lens. A popular variety of the latter is called a *Schmidt Plate*.

Cassegrain telescopes come in different forms. Table 1 shows three such designs, including the third order aberrations that are left. A corrector lens such as a Schmidt plate could then be added to the system to help reduce or eliminate these image errors.

**Table 1. Cassegrain Telescope Varieties**

	Primary mirror	Secondary mirror	Limiting aberrations
Classical	Parabolic	Hyperbolic	Coma Astigmatism Field curvature
Ritchey–Chretien	Hyperbolic	Hyperbolic	Astigmatism Field curvature
Dall–Kirkham	Elliptical	Spherical	Coma Astigmatism Field curvature

### Three-Mirror Telescope

Figure 7 shows a three mirror telescope. As you can see, the hole in the primary mirror that was present in the two-mirror design has now been replaced by a tertiary mirror. In the configuration shown, the image plane lies in the center of the telescope, leaving very little room for cameras and other instruments. For this fact, this design favors the uses of an off-axis configuration, such as adding a flat fold mirror as in a Newtonian telescope.

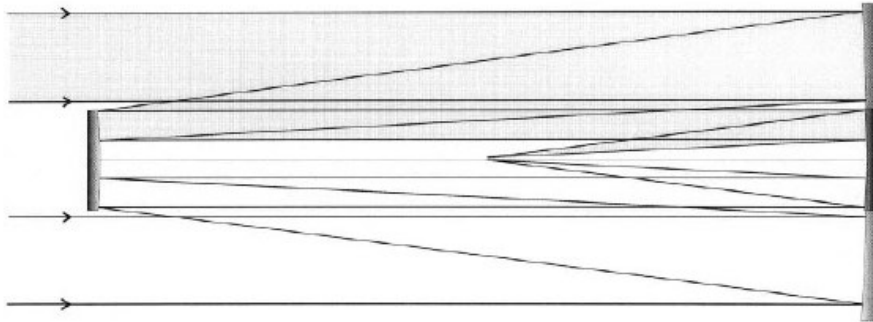


Figure 7. A three-mirror telescope

### V. Atmospheric Effects

Telescope design and manufacture are not the only sources of image degradation that can (and do) occur. There are also variables that are not controllable that must be dealt with. One is *seeing*. Turbulence in the upper layers of the atmosphere limit the resolution of earth-based astronomical telescopes. They have to “look” through a mess of moving air that distorts the image. The resolution at any one specific site caused by the atmosphere is called seeing.

*Air Mass* is another uncontrollable effect. It is due to the increasing thickness of atmosphere that light must traverse as you look farther down from zenith to the horizon. It is measured in units of “air masses”, where one air mass is the thickness of atmosphere at zenith. Thus, if you are looking at an angle  $\theta$  from zenith, the distance  $d$  that light must travel through the atmosphere is,  $d = h/\cos \theta$ , where  $h$  is the thickness at zenith. Figure 8 illustrates this.

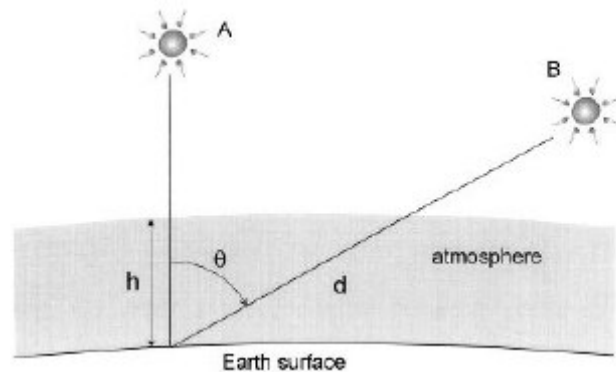


Figure 8. Air Mass Illustration

The effect of air mass is seen when taking looking at an object for a prolonged period of time, such that the telescope must rotate to keep it in place. As the telescope moves, it will be looking through varying amounts of atmosphere, and the atmosphere causes the light to refract and diffuse, changing the image you see over time.

To correct the effects of the atmosphere, *active optics* is often employed. In this system, an active component of the optical system is adjusted such to oppose what the atmosphere has done to the light. Most commonly, the primary mirror is made deformable by placing little actuators behind the mirror to move it just slightly.

## VI. Space Telescopes

The final variety of telescope discussed here is the one located in space. Obviously, this has the advantage of avoiding all atmospheric effects. This disadvantages are obvious though too. Placing a telescope in space is not the easiest of tasks, and once it is up there any routine maintenance or repairs are no longer routine. The Hubble Space telescope is one excellent example. The primary mirror had 0.5 waves of spherical aberration that was not discovered until it was producing horrible images in space.

## VII. Filled Aperture Telescope

Though it is easier to fabricate large mirrors than large lenses, larger and larger mirrors do become harder and harder to make. To get a very large telescope then, another technique has come about: putting together many smaller mirrors in segments to make one large mirror. It does not perform as though it was one monolithic piece though. The diffraction limit is characterized by the individual segment size. But the obvious advantage of such a system is the enormous light collecting area possible, making it possible to observe fainter objects.

Figure 9 shows the Keck telescope with 36 segments, the Hubble primary is shown for comparison.

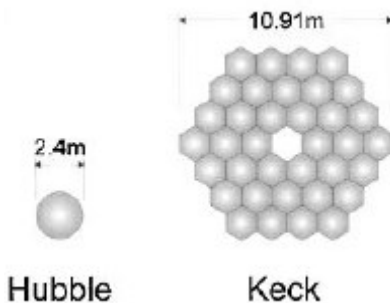


Figure 9. Segmented Telescope

## VIII. Conclusion

This paper is a very good overview of telescopes. It provides a straight forward explanation of the uses of them, how to evaluate their images, and the different types that are available. It is a good reference for those unfamiliar with the field, and even good for those who are, given that you are usually focused on a specific subtopic, and may be unaware of the different applications and designs out there.