Optics 101 - How Our Telescopes Work

Part 1: The Basics

By Dan Lessmann

Part of what we need to know as astronomers is how our telescopes work. This allows us to take full advantage of the capabilities they provide and that's what I'm going to be discussing in this series of articles.

This first part will deal with how our telescopes' characteristics are defined and what they do for us.

Some Definitions

These definitions are mainly for those of us just entering into the hobby so feel free to skim as you please.

Optical Element

Any optical component that light passes through or reflects from within the telescope.

Optical System

All optical elements within the telescope.

Optical Path or Light Path

The path that light takes through the optical system.

Optical Tube or simply, Tube

The tube to which the optical elements are mounted.

Optical Tube Assembly or OTA

The optical tube with the assembled optical elements.

Objective Lens

The first lens in the light path of a refracting telescope.

Primary Mirror or Objective Mirror

The main mirror of a reflecting telescope.

Secondary Mirror

The second and subsequent mirrors in a reflecting telescope. Most have one secondary mirror.

Corrector Plate

A lens on catadioptric telescopes (Schmidt-Cassegrains, Maksutov-Cassegrains, etc.) that corrects the light path prior to reflecting off the primary mirror.

Aperture

The diameter of the objective lens or primary mirror. Aperture determines the amount of light that can be gathered by the optical system.

Prime Focus

The point along the light path where the image comes to focus. More on this later.

Focal Length

The distance traveled by the light path within the optical system. Focal length determines magnification. Longer lengths have a greater magnification than shorter lengths.

For reflectors, the focal length is the distance light travels from the primary mirror to prime focus. For refractors it's the distance from the objective lens to prime focus.

Focal Ratio

The ratio of focal length versus aperture. The focal ratio determines the *speed* of the optical system. Lower ratios are *faster* and higher ratios are *slower*. Focal ratios are designated as f/ and the ratio number, an f/stop number. This is a carryover from the photography world. Faster f/stops expose film faster because there's more light being focused on the film.

My 10" Schmidt has an aperture of 10 inches or 254mm (there are 25.4 mm in an inch) and a focal length of 2,500mm. So the focal ratio is:

$$2500 \div 254 = 9.8$$

Around 10, thus, my scope is designated as a 2500 mm, f/10 telescope.

Aberration

Any distortion of the light path that takes place within the optical system. There are many different kinds.

Focal Plane

The plane perpendicular to the optical path that passes through prime focus.

Field of View or FOV

The diameter of the field visible through the optical system. This is usually expressed in arc-degrees, minutes and seconds.

Collimation Error

The angular error between either the primary and secondary mirrors of a reflecting telescope or between the objective and secondary lenses of a refractor telescope.

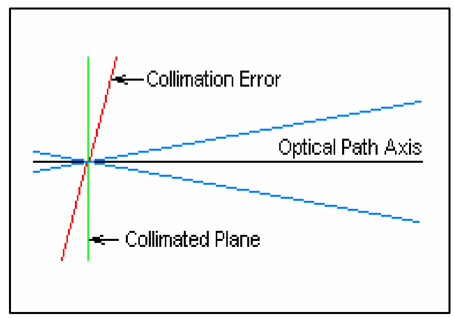

Figure 1: Collimation Error

Figure 1 illustrates collimation error. The planes shown are seen edge on.

The collimated plane is the focal plane that is properly collimated. Because this plane is perpendicular to the optical axis the entire plane can be positioned equidistantly along the optical axis.

The collimation error plane is a gross collimation error. Because this plane is not perpendicular to the axis, it's impossible to bring the entire plane to focus along the axis. The image will be out of focus across the entire FOV.

Diffraction

Diffraction is the bending of a wave of light when it travels around an obstacle.

Refraction

The bending of a wave of light inward towards the optical axis. This is done by any boundary the light passes through that is angled to the axis. This angle is the *angle of incidence*.

Point Source of Light

A light source that is so small, or so far away that the visible size of the light source is an infinitesimally small point. Light waves from such objects are parallel as they enter our telescopes.

Types of Telescopes

Most telescopes fall into one of two categories, refractors and reflectors. I'll describe the more common ones here. Please refer to the diagrams in Figure 2.

Refractors

Refractors have a straight-through light path. Light passes through an objective lens where it is refracted towards a focal point, noted as F.

At the same focal length, refractor tubes are longer than reflectors as the light path is not reflected within the tube so high power refractors are not terribly portable.

However, most spotting scopes and just about all view finders are refractors and medium sized refractors are often mounted on larger scopes for astrophotography saving the cost of a second mount.

Medium to large refractors are some of the most expensive telescopes because of the number of optical elements required but they provide some of the highest quality images. Apochromatic designs are especially popular for astrophotography.

Reflectors

All of the other telescopes in the figure are reflectors. Their greatest advantage is that they reflect the light within the tube resulting in a longer focal length than from a refractor of the same tube size.

Newtonian Reflector

These are by far the most common. In a "Newt", light is reflected off a primary mirror to a secondary oriented at 45° to the primary mirror which redirects the light path out through the side of the OTA to the focuser and eyepeice.

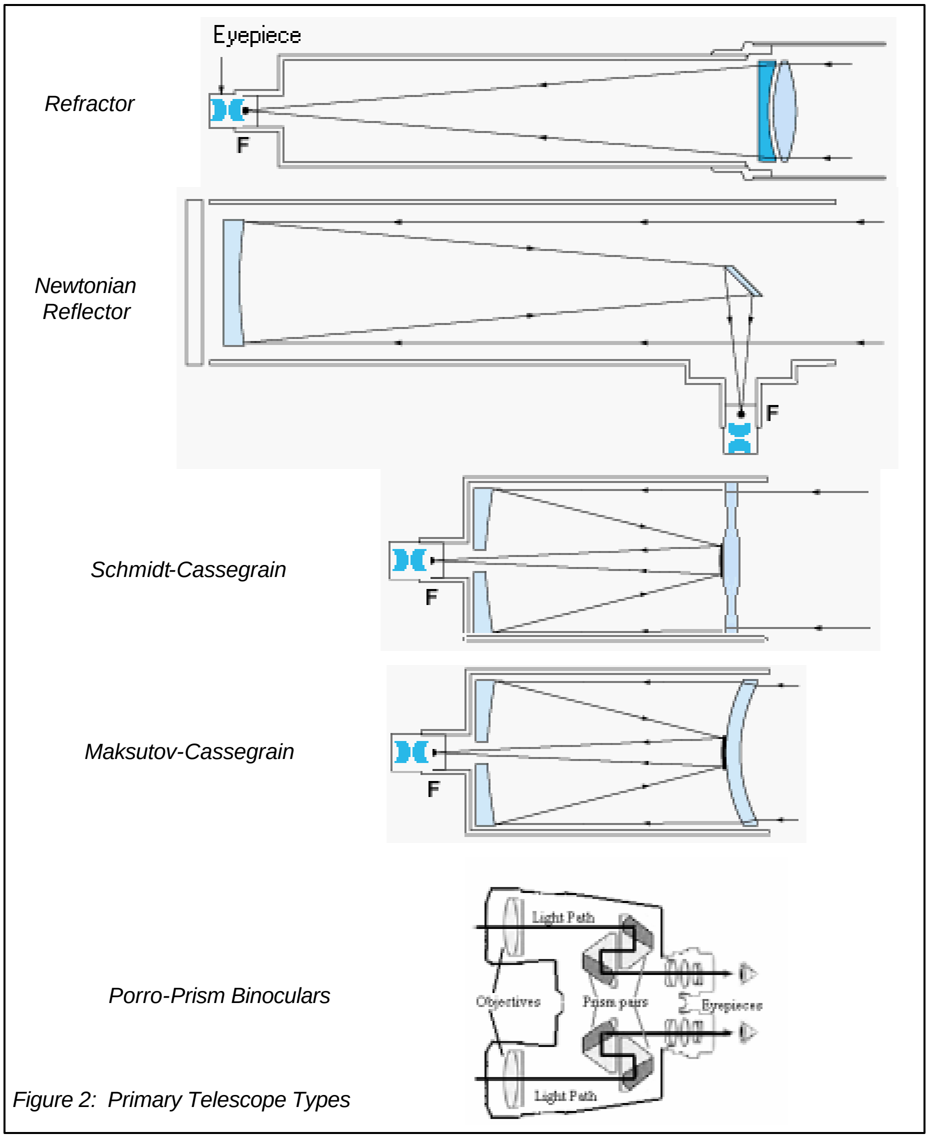

Figure 2: Primary Telescope Types

The greatest advantage of Newts is their low cost. You can buy more aperture and focal length for less money in this design than any other.

Schmidt or Maksutov-Cassegrain

In these designs, light passes first through a corrector plate. The only major difference in these is the shape of the corrector plate. The "Mak" has a meniscus corrector plate. The Schmidt or "SCT" has a flatter shape. The corrector plate corrects spherical aberration.

Light enters through the corrector plate, reflects off a primary and then a secondary mirror through a hole in the primary to prime focus. This allows for a longer focal length than Newts and refractors in a shorter optical tube.

These designs are more expensive than Newts. But, inch for inch, these OTAs are the biggest focal length bang for the tube size.

Binoculars

Every amateur astronomer ought to have a good pair of binoculars and the most common is that shown or the Porro-Prism binocular.

Light entering through the objective is directed through a set of prisms that act as mirrors bending the light path and increasing the focal length.

Binoculars are rated by their magnification and the size of their objective lenses. For instance, a pair of 7x35 sport glasses has 7X magnification with a 35mm objective lens size.

Keep in mind that there are *two* objective lenses and we gather light through both eyes with binoculars. Thus the resolving power of 7x35 binoculars is far better than that obtained from a 35mm refractor at the same focal length.

How Telescopes Focus

All optical systems are made up of a primary and secondary system. The primary system is all elements that are forward of the primary focus and the secondary system is all elements behind the primary focus. The primary and secondary can be thought of as two separate OTAs.

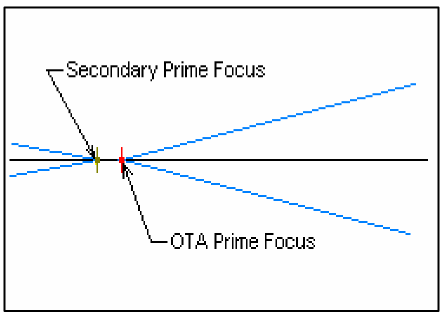

Figure 3: Out of Focus Optical System

Figure 3 shows an optical system that is out of focus.

The OTA prime focus is that of the scope itself and the secondary prime focus is for the eyepiece and other elements of the secondary system.

We can see that the focal planes of these two systems are not aligned so the resulting image is out of focus.

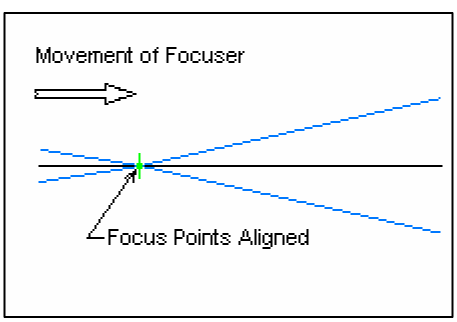

Figure 4: In Focus Optical System

Figure 4 shows the correction necessary to bring the image into focus.

The focuser moved the secondary forward some distance to align the primary and secondary focal planes.

Note that these figures are simplified. In reality, prime focus *is not* located at the point where the light paths cross the optical axis. This point is called the *locus* and the image at this point would be a single point of light.

There are actually *two* locations along the axis where prime focus can be achieved; one in front of the locus, one behind and both equidistant from the locus. The one used by most telescopes is the one behind. Incidentally, this is why our telescopes flip the image.

Prime focus is also not located at a discrete point along the axis. It's actually a range of points known as the *critical focus zone* or *CFZ*.

Focusing mechanisms vary in design. Most Newts and refractors move the secondary system with a rack and pinion focuser. Most catadioptrics move the primary mirror forward and back within the optical tube. This moves the primary system's prime focus. Regardless, both methods do the same thing. They align the focal planes of the primary and secondary systems.

Typically photography is done at prime focus meaning that the only element in the secondary system is the film or CCD chip itself. So the goal is to position the plane of the film or chip at the prime focus (within the CFZ) of the primary system.

Changing the Aperture

An increase in aperture increases light gathering exponentially. This is because we're dealing with the area of the circle defined by the aperture.

The area of a circle is defined as:

$$A = p r^2$$

Okay, back to my 10" scope. It's area is:

$$A = 3.14 * (10 \div 2)^2$$

Or around 78.5 in^2

What's the area of a 12" scope?

$$A = 3.14 * (12 \div 2)^2$$

Or around 113 in^2

That's an increase of 44% for an increase in aperture of only 20%. So, barring practical matters of portability and price, aperture is king when selecting a scope.

Let's see what the change in speed would be. Assuming the same focal length of 2,500mm, the speed of this 12" scope would be…

$$2500 \div (12 * 25.4) = f/8.2$$

About 20% faster than my f/10 scope which means brighter, higher resolution images for our peepers to see.

Now suppose I cut a 2" hole in cardboard and tape it to the front of my 10" telescope. What have I done? I've reduced the aperture from 10" to 2". Changing aperture means I've changed the focal ratio from f/10 to f/49 or slowed the scope *way* down.

This is what most large scope solar filters do. When viewing the sun, brightness is not a problem. No, it's a *huge* problem. The sun is *too* bright. By reducing the aperture and slowing down the scope, *and using a solar filter over the smaller aperture*, I can safely view the sun.

Please! If you choose to view the sun, *you MUST use a high quality solar filter designed for your scope!* Also remove any finder scopes mounted to your scope or you may burn a hole through your forehead while enjoying your view of the sun.

Remember! Only you can prevent forehead fires! (Sorry Smokey)

When changing the aperture, I can only go smaller unless I get a bigger scope and when I go smaller, I'll slow down the optical system if the focal length remains the same.

Changing the Focal Length

Focal length controls power and the ratio of this and aperture is the focal ratio. Does this mean two telescopes that have the same focal ratio will have the same performance?

Nope. A scope with a 1" aperture and a 250mm focal length has the same f/10 focal ratio as my Schmidt. But we won't be able to see the same things with both scopes.

It's important to remember that focal ratio is merely a ratio of two characteristics. Its these characteristics that determine performance, not the ratio between them. What we're interested in is how we can change the characteristics to produce different results.

Okay. What about changing focal length? Though you may not know it, you adjust focal length all the time. Any change of the magnifying optical elements in the system will change the focal length. When you use a higher power eyepiece, you increase the focal length and slow down the focal ratio. That is, you increase magnification and decrease resolution. When you use a lower power eyepiece, you speed up the focal ratio or, you decrease magnification and increase resolution.

Focal Ratio Controls Field of View

Here's a simple experiment. Nab on to a paper towel roll and cut a 1" section off of one end. You now have two optical tubes. One is 1" long, the other about 10" long and both about 1 ? " in diameter.

Look through the 10" tube and center some object across the room. Now look around the edge of the field and note a few other objects that are near this edge.

Now do the same thing with the 1" tube and note where the same objects are in this FOV.

The 1" tube has a much wider field of view than the 10" tube. This is due to the difference in focal ratios of the two tubes.

The 10" long tube has a focal length of 10" and a 1.625" aperture so the focal ratio is:

$$10 \div 1.625 = f/6.2$$

For the 1" long tube:

$$1 \div 1.625 = f/0.6$$

What aperture would a 10" long tube need to have for the same FOV as the 1" long tube? The focal ratio of this tube has to be f/0.6 so work it backward:

$$10 \div ? = f/0.6$$

-or-

$$? = 10 \div 0.6 = 16.6''$$

A 10" long, 16.6" diameter tube will have the same FOV as the 1" long tube. Optical systems of the same focal ratio will have exactly the same field of view at prime focus.

So, while we can't see the same things with that little 1" aperture, 250mm long scope in the previous example, it would have the same FOV as my 10" Schmidt when at prime focus.

I should also note that other things can reduce the FOV. The field of view allowed by the focal ratio at prime focus is the *greatest field of view I can achieve with this tube.*

So Ends Part One

I think that's enough for this month but let's review a few key points.

We've leaned a bunch of terms used to describe an optical system and its components.

We've reviewed the major amateur telescope types and their characteristics.

We've learned how a telescope is focused and that focus is achieved when the focal planes, or the CFZs, of the primary and secondary systems are aligned.

We've leaned that all telescopes have some common characteristics:

Aperture

The diameter of the objective lens or primary mirror. Aperture determines light gathering capacity. We've learned there's not much we can do to increase aperture but we can decrease it with a simple mask.

We've learned that, because we can't increase aperture, this characteristic is probably the most important one when choosing a scope as long as we can afford it and can still tote the thing around.

Focal Length

The distance light travels from the objective element to prime focus. Focal length determines magnification power. We've learned that we change focal length with any change in the optical elements that affect magnification.

Focal Ratio

The ratio of focal length versus aperture. Focal ratio is the speed of the optical system. Larger focal ratios are slower speed and smaller focal ratios are faster speed and they are designated by an f/stop number like f/10.

We've learned that faster focal ratios are at lower power and higher resolution and brightness and that slower focal ratios are at higher power and lower resolutions and brightness with the same OTA.

We've learned that focal ratio determines the maximum field of view for the system.

Next month we're going to look at the different methods and equipment we can use to alter these characteristics and what capabilities can be gained by doing so.

Until then… *Clear Skies!*