Optics 101 - How Our Telescopes Work

Part 2: Time to Play!

By Dan Lessmann

We're back! Last month we took a look at the characteristics and types of telescopes. This month we're going to look at how we can manipulate those characteristics and what we can accomplish by doing so.

Bear with me please for a quick review of the three major characteristics of an optical system:

Aperture

The diameter of the objective lens or mirror. Aperture controls light gathering capacity and resolution.

Focal Length

The distance the light travels from the objective element to prime focus. Focal length controls magnification or power. We learned that any change in the optical elements that changes magnification changes the focal length of the system.

Focal Ratio

The ratio of focal length versus aperture and designated by an f/stop number. Focal ratio is the speed of an optical system. Faster speeds mean lower power and higher resolution. Slower speeds mean higher power and lower resolution.

Okay, let's play! What we're going to do is see just how much performance we can squeeze out of our telescopes and what the road blocks are as we hit the limits. Let's start with eyepieces.

Eyepieces and Magnification

Eyepieces, also known as *oculars,* magnify the image produced by the OTA. The eyepiece power is constant but the resulting magnification depends on the focal length of the scope being used.

Magnification is calculated as:

$$Mag = L_{OTA} \div L_{EP}$$

Where L_{OTA} is the focal length of the tube and L_{EP} is the focal length of the eyepiece. Yes, eyepieces have a focal length too. This is how they are classified. A 26mm eyepiece has a focal length of 26mm.

Okay, back to my 10", 2,500mm Schmidt. What is the magnification of a 26mm eyepiece?

$$Mag = 2500 \div 26$$

Or 96X. Now compare that to my 910mm focal length Newt.

$$Mag = 910 \div 26$$

Or 35X. About a third of my longer focal length Schmidt.

So, to reach something approaching the same power with my Newt will require something around a 9 to 10mm eyepiece.

Who sees the relationship? The focal length for an eyepiece that gives reasonable performance for a particular tube, is about 1% of the focal length of the tube.

Keep in mind that aperture also affects the utility of an eyepiece. This is just a rule of thumb but is a good starting point for eyepiece selection for a typical amateur scope. The 26mm eyepiece is the one that shipped with my SCT and is the one I use most.

How about my highest power eyepiece of 6.7mm?

$$Mag = 2500 \div 6.7$$

Or 373X. That's getting up there. In fact, it's quite uncommon for seeing to be good enough to allow those kinds of powers. Seeing is one of those limits we hit.

What about with my Newt?

$$Mag = 910 \div 6.7$$

Only 135X. That's quite a bit more reasonable. Nights with seeing good enough for this power are very common indeed. However, this is where aperture comes in to play. Since my Newt has only a 4" aperture, it will not gather nearly as much light as my Schmidt. Aperture is also a limit we hit when selecting an eyepiece.

What should now be obvious is that the best selection of eyepieces for any particular scope is *completely* dependent on the focal length and speed of that scope and the average seeing we experience.

The lesson? Before we go shopping for eyepieces, we need do a bit of ciphering and determine what range of powers is going to work best for our tube. Buying that super-duper high power eyepiece makes since only if the scope has a fast focal ratio and we regularly experience good seeing.

Adding Barlows Lenses

Who's looking for a cheap way to double the number of eyepieces they own? Simple! Buy a Barlow. A Barlow is an element that increases power. Barlows are classified by their additional power. A 2X Barlow magnifies two times when normally placed just in front of the eyepiece.

By using a Barlow, we change the resulting power of the eyepiece being used by that same factor. So if a 2X Barlow is used on my SCT with the 6.7mm eyepiece, the resulting power is 373 x 2 or a whopping 746X.

Figure 1 shows the normal position for a Barlow right before the eyepiece.

Figure 1: Configuration for f/20

Now here's a trick. If we use a 1.25" diagonal and we place the Barlow *in front* of the diagonal, the resulting magnification increase is not 2X power. It's closer to 3X.

You don't use a diagonal? You can accomplish the same thing with a simple tele-extender and a few adapters. All we're doing by positioning the Barlow in front of the diagonal is increasing the distance between the eyepiece and the Barlow lens. So, by buying one Barlow lens, we can triple the available powers from our existing eyepieces. Figure 2 shows this configuration.

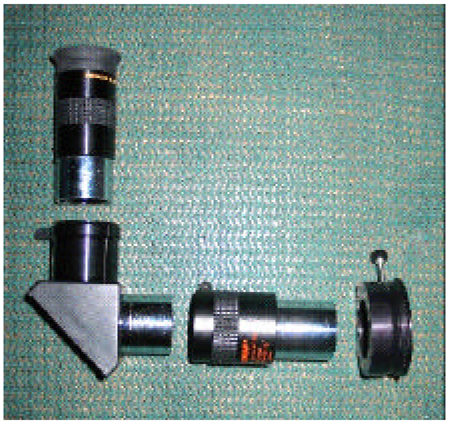

Figure 2: Configuration for f/30

Figure 3 shows the result of these different positions. Here's our old friend Jupiter and a few of it's companions.

Figure 3: Effects of a Barlow Lens

From top to bottom the powers are 1X (no Barlow), 2X and 3X.

These were shot with the same camera and tube on the same night but including the Barlow in various positions is like having three separate cameras. The same is true of eyepieces.

Increasing Focal Length Slows Down Focal Ratio

Adding a 2X Barlow doubles the power which means we double the focal length and the focal ratio. So, what was an f/10 optical system is now a much slower f/20 optical system. Slower ratios mean less light is reaching the eyepiece or camera.

At f/20 half of the light normally in the FOV now falls outside of the FOV. So the image of Jupiter at f/20 will be half as bright as at f/10, and one third as bright at f/30.

The exposures for the Jupiter images in figure 2 were indeed two and three times longer for the f/20 and f/30 shots. We can adjust the exposure time of a camera but not our eyes. So visually, the image is going to be dimmer at longer focal lengths and slower speeds.

We can also see the effect a slower speed has on resolution. Look at Europa just to the left of the planet in the top f/10 image. Europa is a nice, sharp pinpoint of light. At f/20 Europa is starting to fuzz up a bit but this is a more aesthetically pleasing image because the planet's details are more visible. At f/30 everything's bigger still but the resolution is really beginning to suffer. Things just look out of focus and fuzzy.

Actually, all three images are in excellent focus and the seeing that night was exceptional. What we're seeing is my scope's limited ability to resolve detail with its fixed 10" aperture at long focal lengths and slower speeds. Barring seeing, which is variable, this is the limit on the upper end of the power scale.

Adding Focal Reducers

As Barlows increase magnification reducers decrease it.

Figure 4 shows Jupiter again this time shot with an f/6.3 reducer. Note how much smaller Jupiter appears in this image than in the other images. Regardless, adding a reducer once again doubles the available powers

Figure 4: Jupiter with an f/6.3 Reducer

from your eyepieces. Using a Barlow and a diagonal makes each eyepiece like three. Double that again and each eyepiece is now like six!

A focal reducer's benefit is an increase in the FOV and a faster speed. Its detriment is a reduction in magnification. We can easily see this in the Jupiter shots. The image in figure 4 is really too small to see much detail of the planet but notice the expanse of black sky around the planet in this shot as compared to the 3X shot.

Now suppose that black sky is a nebula as in figure 5. For these types of objects we need less power and greater field of view. We also need better resolution since these objects are dimmer. So we need to speed up the optics.

Figure 5: A More Typical Use For Re-

Decreasing Focal Length Speeds Up The Focal Ratio

Focal reducers change focal lengths and ratios just like Barlows. Adding an f/6.3 focal reducer to my f/10 Schmidt means the focal ratio is:

$$10 \times 0.63 = f/6.3$$

The effective focal length becomes:

$$2500 \times 0.63 = 1{,}575mm$$

Now my long focal length, slow scope is a shorter focal length, medium speed scope. How about with an f/3.3 reducer?

10 x 0.33 = f/3.3

The effective focal length becomes:

2500 x 0.33 = 825mm

An f/3.3 scope is quite fast and the 825mm focal length is actually less than my 4" Newt at prime focus but with the much larger aperture of 10 inches. Time to retire the Newt!

With an f/3.3 reducer my SCT is now an excellent platform for quite wide field astrophotography or just viewing a big chunk of the sky. I can't fit Andromeda but a lot of other "big" objects now fit just fine.

Also, consider the faster focal ratio. At f/3.3 I can theoretically view objects that are 66% dimmer than I can at f/10. This opens up observing some of those way out there, dim fuzzies in the deep sky catalogs.

Focal reducers introduce some new limits, this time on the low end of the power scale. If the focal length is reduced too much some new aberrations can popup. These are *vingetting* and *coma*.

Vingetting will show up as a dimmer view around the periphery of the field of view that will fade to black if it's extreme. This is caused by the focal reducer attempting to generate a field of view that is greater than the maximum field of view available from the aperture of the OTA. The black ring around the periphery of the FOV is actually an out of focus view of the front of the optical tube.

Coma will show up as an inability to focus the entire field of view especially at the periphery. Coma makes stars look like little V's with the V pointing towards the center of the field. This is caused by *spherical aberration* or a curvature of the focal plane. To minimize this, most focal reducers are also field flatteners.

Limits From Back and Front Focus

Back and front focus is the total travel available from the focuser. For a rack and pinion focuser, this is the distance from stop to stop on the rack.

The amount of focus travel limits the elements we can add. It's quite easy to add elements where the focus travel is no longer adequate to achieve focus with those elements.

The addition of a few adapters can accommodate this if the problem is not enough outward travel, back focus. But if we can't move the focuser in far enough, front focus, we're probably stuck. Also keep in mind that combinations of elements can overrun our available focus range. So it's usually a case of trial and error with the elements to see if we can achieve focus.

Figure 6 shows the secondary system required for my scope with an f/3.3 focal reducer. Note the T-adaptor and extenders that are required. These allow my focusers to bring the image to focus.

Figure 7 shows the configuration

Figure 6: Configuration for F/3.3

of the secondary for an f/6.3 reducer. Less back focus is required for this reducer so the T-adaptor is shorter.

Note that the farther from native

Figure 7: Configuration for f/6.3

focal ratio I go, the more adjustments I've got to make to the secondary system's optical train to achieve focus. We also lose some of the benefit of the reducer as we move the reducer farther away from the eyepiece or camera. This is analogous to the different positions of a Barlow.

There's One Common Downside to Barlows and Focal Reducers

That's more glass. Anytime light passes through a layer of glass, some of that light is absorbed or reflected instead of transmitted. So it's generally a good idea to keep the layers of glass to a minimum.

You can minimize much of this by buying high quality, fully-coated components.

All of the Combinations

Let's take a look at all of the possible focal ratios and focal lengths with the equipment I've discussed.

No Barlows and no reducers:

f/10 and 2,500mm

2X Barlow in normal position:

f/20 and 5,000 mm

2X Barlow ahead of diagonal:

f/30 and 7,500 mm

f/6.3 focal reducer:

f/6.3 and 1,575 mm

f/6.3 reducer with 2X Barlow:

f/12.6 and 3,150mm

f/6.3 reducer, 2X Barlow ahead:

f/18.9 and 4,725mm

f/3.3 focal reducer:

f/3.3 and 825 mm

f/3.3 reducer with 2X Barlow:

f/6.6 and 1,650mm

f/3.3 reducer, 2X Barlow ahead:

f/9.9 and 2,475mm

All nine of these different optical characteristics are possible with one OTA just by the addition of one Barlow lens and a couple of focal reducers.

We can take those nine configurations and multiply them by the number of eyepieces we have and that's the total number of combinations we have available to us. For me that's eighty-one different combinations and that's way more than enough!

A Bit More On Eyepieces

We haven't discussed the various types of eyepieces available. A few comments on this would probably be appropriate.

The most commonly used are Plössl eyepieces and these are a good start for our collections. There are many other kinds that provide wide or ultra wide fields of view or are specialized for guiding during photography. However, they all have one characteristics in common that we should know about.

Eye Relief

This is the distance our eye can be from the eyepiece while still being able to see the entire field of view. This is especially critical for those of us that must wear eyeglasses while observing. This varies quite a bit based on the power of the eyepiece, its type, its size and its brand. However, shorter focal length (higher power) eyepieces have a shorter eye relief. We should take this into account when selecting an eyepiece.

The size also affects eye relief. By size, I mean the size of the nosepiece. Generally, the larger the size, the greater the eye relief. The most common size is 1 ¼". 2" and 15/16" sizes are also available. Generally, 15/16" eyepieces come with less expensive, low end scopes. 2" eyepieces come with higher end scopes. Regardless, our focuser's diameter determines whether or not we can use larger eyepieces. Most quality scopes can accommodate both 1 ¼" and 2" eyepieces.

Eyepieces with greater eye relief are generally easier and more comfortable to use so here's another trick. Suppose I'm observing something and find that the optimal eyepiece for the object and the seeing is a 14mm. My 14mm eyepiece has an okay eye relief but it's not nearly as comfortable as some of my lower power ones.

So, instead of using the 14mm, I'll install a 2X Barlow and my 26mm. It's much more comfortable and I'm at virtually the same power as provided by my 14mm. Or I may just go all out and install the Barlow in my f/30 (3X) position before the diagonal and use my 40mm. That big eyepiece is almost like watching TV and is VERY comfortable to use.

I do add some glass but, I'm using a fully coated Barlow so the loss in light transmission is not terribly noticeable.

Eyepiece Field of View

We might also talk about the field of view available from a particular eyepiece and OTA.

In addition to focal length, eyepieces are rated by their *inherent field of view*.

Most Plössl eyepieces have an inherent field of view of around 40°. The true field of view is found by dividing the inherent field of view by its magnifying power on the OTA. Back to my Schmidt and my 26mm eyepiece with an inherent FOV of 40°.

The power is:

$$2500 \div 26 = 96X$$

So the true field of view is:

$$40 \div 96 = 0.4°$$

Or a little less than ½° of sky is visible in the eyepiece at this focal length. Of course, if I throw a barlow or focal reducer into the mix, I alter this FOV just as I alter the focal ratio and focal length so I need to take that into account as well.

Bringing It All Into Focus

Here's what we've found out in this part…

We found we don't need a huge collection of eyepieces.

Three or four will probably do just fine. Adding Barlows and/or focal reducers, doubles, triples or more the available powers of our eyepieces.

We found that Barlows and focal reducers expand the scale of powers available from our OTA and eyepieces.

However there are limits to this expansion. On the upper end, seeing or poor resolution from a slow focal ratio will limit us. On the low end, vingetting or coma will limit us.

On either end the available focus range can limit us but some T-adaptors and tele-extenders can handle some of this if the problem is back focus.

We found before considering the purchase of an eyepiece or Barlow, we should do a bit of math to see just what the resulting powers and focal ratios will be.

We now know a good starting point for eyepieces is to consider one with a focal length somewhere around 1% of the focal length of the OTA for most amateur scopes.

We also know there's not much point in buying a 5X Power Mate if our scope's focal ratio or seeing won't support that power.

What Else?

I think that's about it. I hope this series of articles was helpful to you and I will see you soon under some nice, dark and clear skies!