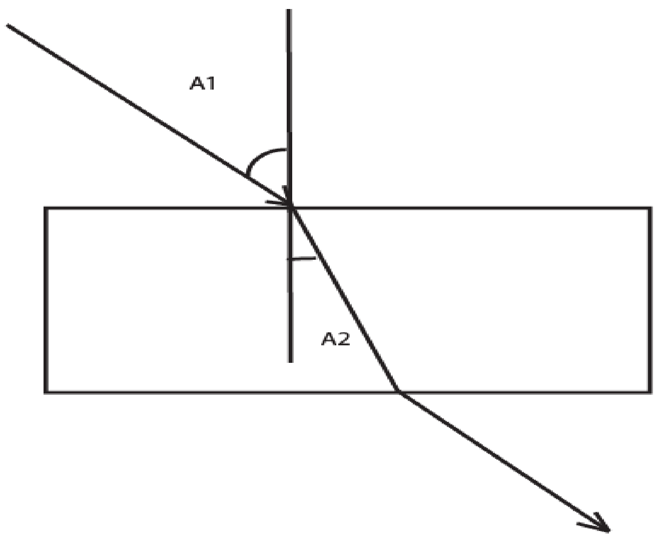
Refractors 101, by Scott Walker, copyright 2008, Rev-A 1/7/08

Introduction

This paper will discuss the basic function of the modern refractor. It should answer many of the questions that commonly arise about refractor such as: What is ED glass, and why do we care? What do those graphs tell us? What is the difference between a triplet and a doublet?

What is Refraction?

When a light ray passes from one material to another, it behaves as is shown in Figure1.This is called refraction. The property can be used to bend light rays. Figure 2 shows how a prism can be used to change the angle of a light ray. Different glasses will have different indexes-of-refraction and different dispersion properties. Dispersion is the change in the index of refraction that is a function of the color or wavelength of the light. Figure 3 shows the effect that dispersion has when “white” light is past through a prism. Because of dispersion, the different colors that make up “white” light are bent to different degrees. The longest wavelengths (reds) are bent the least and the shortest wavelengths (violet) are bent the most. All optical glasses have this dispersion property, but some more than others. The Abbe number is used to rate the dispersion of a glass. A high Abbe number indicates a low dispersion and a low Abbe number a high dispersion. Regardless of Abbe number all glasses have a higher index of refraction for violet light than red light.



$$\sin(A1)*n1 = \sin(A2)*n2$$

n1= index of refraction of first material
n2= index of refraction of the second material

Figure 1. Refraction

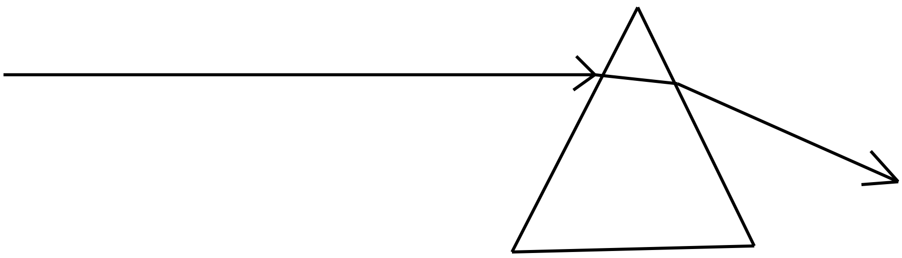


Figure 2. Bending light ray with prism

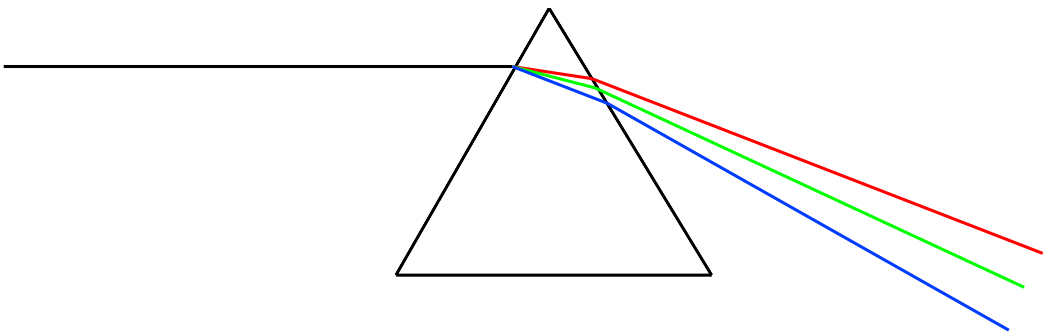


Figure 3. Dispersion Causes different bend to different colors

The Telescope

Ideally the parallel light rays coming from a distance star would all focus to a single point. This idealization does not consider the affects of diffraction. Diffraction is caused by the wave nature of light. It limits how small a spot light can be focused. To start with we will ignore the effects the diffraction. Only the “geometric” effects of refraction will be analyzed. We will later compare the blur caused by geometric effects to that caused by diffraction. The ultimate goal is to design the refractor so that diffraction is the major limitation of its performance.

Figure 4 shows an exaggerated effect that dispersion has on a single element telescope. Because of dispersion, a single element telescope will focus blue light in front of green light and red behind the green. This is referred to as chromatic aberration. Aberration is just an optical term to mean something we do not want. In addition to chromatic aberration a single element telescope will also have what is called spherical aberration. Figure 5 shows an exaggerated example of spherical aberration. In general spherical aberration is when rays that pass through the lens do not all focus at the same point. For a single element lens with spherical surfaces the rays that pass through the outer edges will focus closer to the lens than those that pass through near the center. This aberration is called spherical aberration because a single element lens can not be made with spherical surfaces that focus light to a common point. Spherical surfaces are commonly used in optics because they are easy to make to very high accuracies. A surface that is not spherical is called aspherical. Aspherical lenses are used but they are expensive to make. They are more common in smaller high production optics such of compact digital camera.

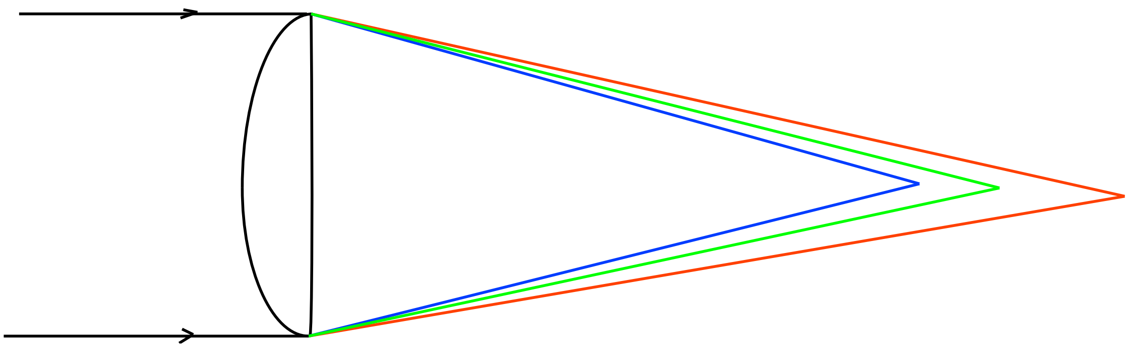


Figure 4. Exaggerated dispersion in single element lens

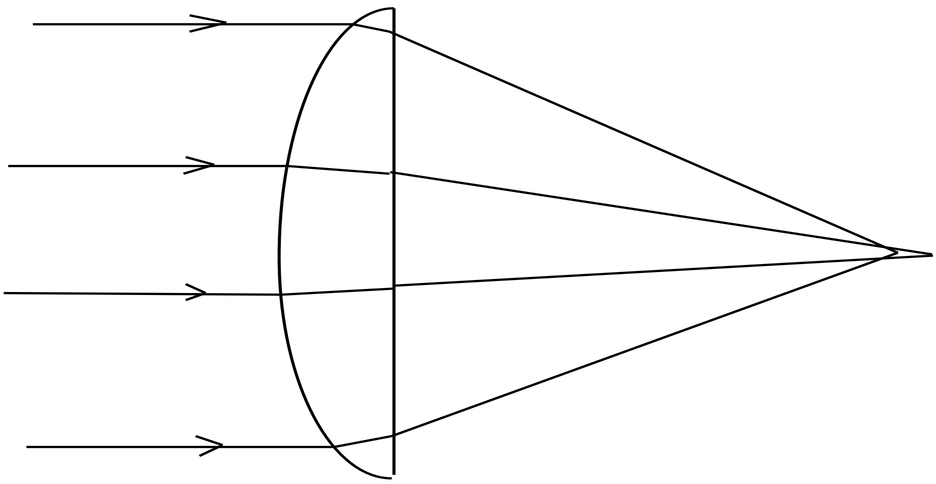


Figure 5. Spherical Aberration

To characterize the performance of a telescope one often will use a longitudinal aberration plot. Let's look at the longitudinal aberration plot for a single element 102mm aperture f/7 telescope, Figure 6. The focal length is just the aperture (102) times the f# (7) which equals 714mm. If the f# was 14 the focal length would be 1428mm. The horizontal axis is the longitudinal focal point. It is typically normalized so that the focus point for green light is zero. The vertical axis is the distance from the center of the lens. Let's first look at the green line. This shows how green light (546nm) behaves. At the center of the lens the light focuses at the normalized zero position. Due to spherical aberration, the focus point shifts towards the lens for rays at the edge of the lens. This is shown by the green line becoming more and more negative for positive "y" values on the graph. We see that the "red" (656nm) line has a similar shape but is shifted to the right (positive x value) due to dispersion. This tells us that red light focuses farther from the lens. The blue (486nm) line has a negative value which tells us that blue light focuses closer to the lens.

This is a simple example of the longitudinal aberration plot. One can graph many more colors but the idea is the same.

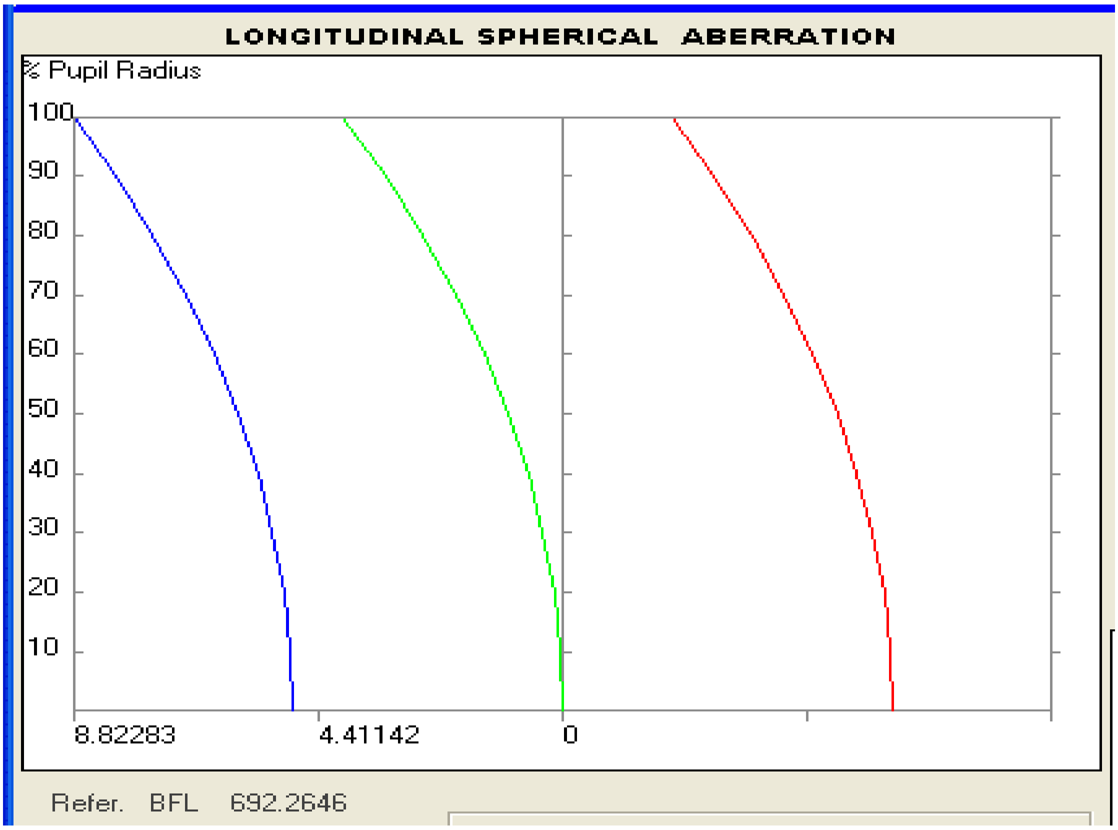


Figure 6. Longitudinal Aberration Curve for single element BK7 102mm f/7 lens

The single element lens plotted in Figure 6 would have no useful purpose as a typical telescope. The chromatic and spherical aberrations are just too large. Even if made from the most costly glass, its performance would be very poor. The glass used is S-BSL7 a common glass, similar to BK7.

The Doublet

Both chromatic and spherical aberration can be greatly reduced by combining two lens elements. The basic principle of a doublet is that the aberrations in two elements can be combined so that they cancel each other. This produces a doublet with much better correction than is possible from a single element. For chromatic correction two different glasses are used, typically one with low dispersion and one with high dispersion. The positive element is made from the low dispersion glass. The negative element is made from the high dispersion glass. By combining a positive element with a power of 2(focal length= 500mm) with a negative element with a power of -1(focal length=-1000mm) the total power is +1(focal length= 1000mm). If the dispersion in the negative glass is twice that of the positive element glass than the nominal dispersion of the combined elements is zero. This is the basic workings of a doublet. This same principle can be used to cancel the spherical aberration of the elements.

For color correction this general principle works very well, but is limited by the similarity in the shapes of the dispersion properties of the glasses used. In general, glasses that have a high dispersion tend to have a more rapid change in refraction in the lower wavelengths. This means that the cancellation between the two elements can not be perfect over a wide wavelength range. Figure 7 shows the change in focal point with wavelength that can be achieved with a doublet made of S-BSL7 and S-TIM8. These glasses are both low in cost. The focal shift from green to blue is over 10 times better that would be achieved from a S-BSL7 singlet, so one can see the a doublet greatly improves the color correction.

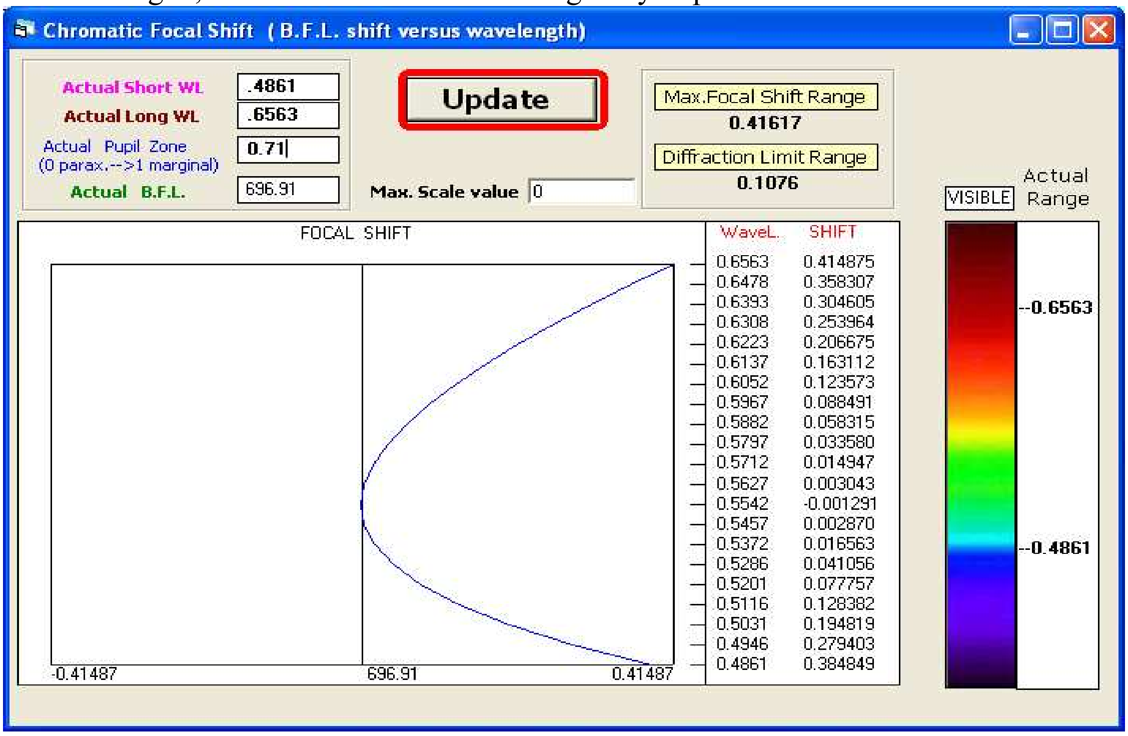


Figure 7. Focal shift versus wavelength for BSL7/TIM8 doublet

Figure 8 shows the longitudinal aberration plot for the S-BSL7/ S-TIM8 doublet. The scale of the horizontal axis has been changed. As one can see by comparing Figures 6 and 8, a doublet has much lower chromatic and spherical aberration than the single element lens. In fact the correction for green light is nearly perfect. The green line is nearly vertical which means the spherical aberration is very low. The blue and red curves are also pretty vertical. The main problem is that the blue and the red lines are displaced from the green line. This means that when focused on green the blue/red image will be a little out of focus.

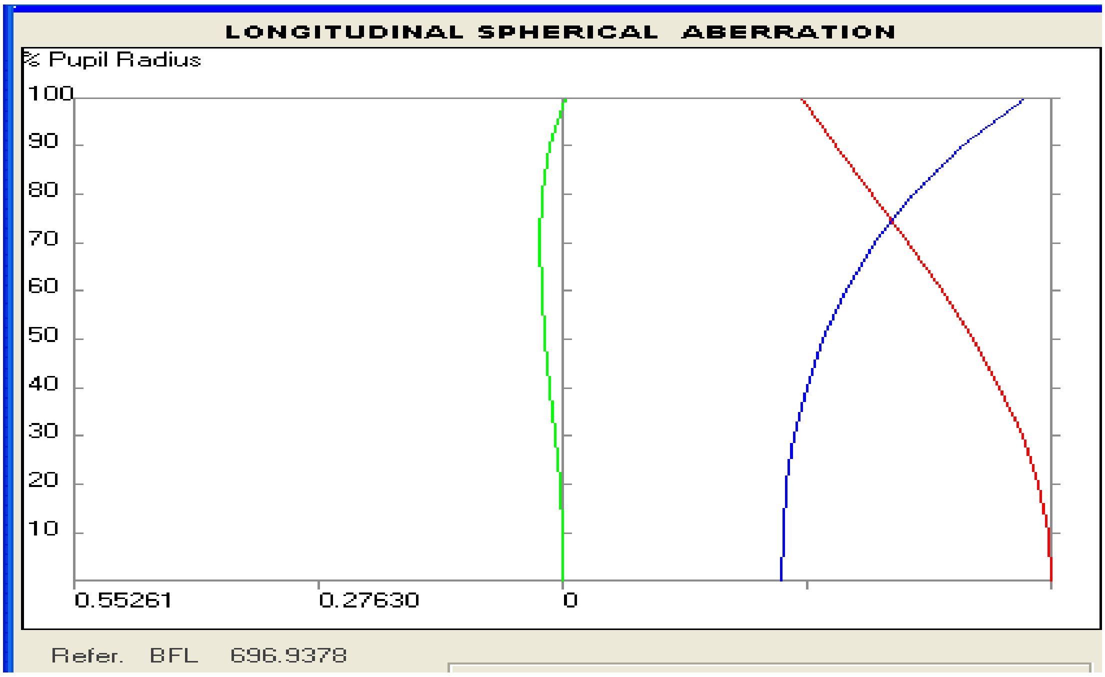


Figure 8. Longitudinal Aberration for BSL7/TIM8 Doublet.

Another way of looking at the performance of the above doublet is to look at the "spot diagram". Figure 9 shows this spot diagram. This diagram shows the blur caused by the refractive affects, and does not include diffraction affects. One will notice the dots of color. These are "rays". The computer program traces rays through the optics. Each spot is one of these rays. In general the program will distribute a set number of rays evenly over the lens surface. If all the dots fall at the same spot the light is well focused. If the dots are spread over a wide area the focus is poor. The different dot colors show how well the different colors focus. In addition a black circle is often shown. This is the diameter of the "airy disk".

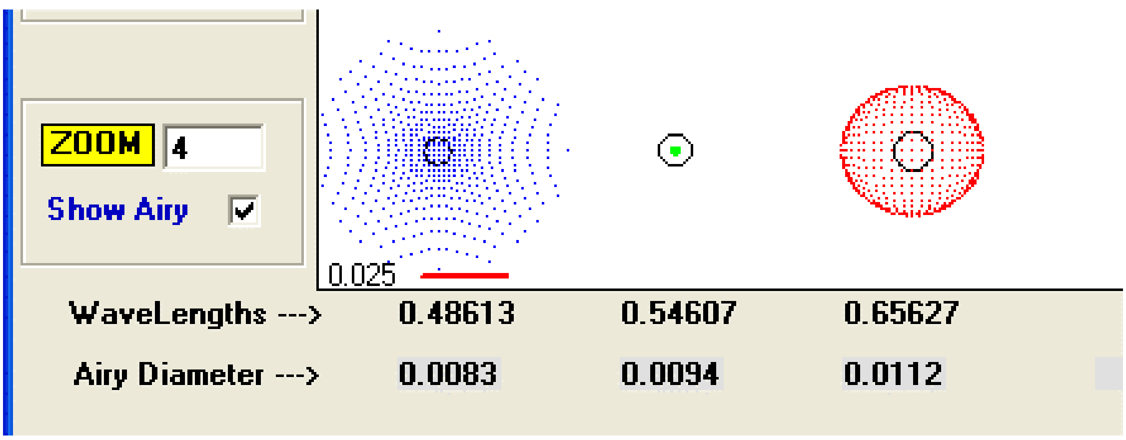


Figure 9. Spot diagrams for BSL7/TIM8 doublet

If the telescope was perfect the light would still not focus to a point due to “diffraction”. The blur due to diffraction is a center spot surrounded by a series of rings. 84 % of the energy is inside this center disk which is the “airy disk”. As a general guide if all of the spots are well within the airy disk, the scope will give near perfect performance. As one can see from Figure 10, green light is very well focused, but the blur in the red and blue light is much greater than the airy disk.

How Much Chromatic Aberration is too Much?

The acceptable amount of chromatic aberration will depend on application and taste. In general one can stand more chromatic aberration for visual use than one can for imaging. In general, even cameras used for daytime shooting tend to produce images that show more chromatic aberration than is seen through the eyepiece. In addition specialty cameras that are used for astro work may need good performance over an even wider range of wavelengths.

The human eye, for convenience, can be thought of as being sensitive over the wavelength range of 400 to 700nm. Under conditions where the eye is sensitive to color, the eye has a peak sensitivity at 555nm. The sensitivity drops to about 50% at 510 and 610nm. At blue (486nm) the sensitivity drops to about 18% and to about 8% at red, 656nm. The 1% points are at about 430nm and 685nm. Because of this variable sensitivity, performance around the peak is much more important than at the extremes. Typical the sensitivity is optimized around green (546nm). This is just a guideline. Different designers may use somewhat different wavelengths. If a scope is also going to be used for imaging the optimization point may shift somewhat but not likely by a great deal. Different people will have different tolerance to chromatic aberration.

One good “bench mark” for good visual performance in a refractor that uses normal glasses, is the blur size for blue and red shall not exceed 3-times the airy disk diameter for green. (from Rutten and van Venrooij, “Telescope Optics”). From my limited experience this is a good guideline. One will still see some chromatic aberration at this level of color correction, but if the scope is well made the image will still appear pretty sharp. This is the color correction that one would see in an f/9 to f/11 80mm achromatic (doublet) that uses low cost glasses. The color correction is a function of both glasses used, the aperture and the focal length. For the above 102mm doublet one would need to change the focal length to about 1300 mm to achieve this level of correction. Some low cost doublets may use glasses with a slightly better color match, but in general the difference is not major, 10 to 30 percent.

It should be noted the human brain processes color information and brightness/detail information somewhat separately. The brightness and detail sensitivity can be thought of as a monochrome system kind of like a black and white photograph. The color perception part of our vision contains less detail. This is one reason that one can see detail and still notice color fringing.

How Does One Get Better Color Correction from a Doublet?

As was stated earlier, the chromatic aberration of a doublet will depend on how closely the shapes of the dispersion curves of the two glasses match each other. In general for a doublet one wants two glasses that have greatly different dispersions (Abbe numbers). Unfortunately glasses that have greatly different Abbe numbers tend to have different shaped dispersion curves. This means that for most pairings, the color correction will be similar to that of the above doublet. This doublet has a focus shift between green and red/blue of about 1/1800 times the focal length. This is often the figure-of-merit used to talk about color correction. It is also called the secondary spectrum or color.

The shape of the dispersion curve can be characterized by a term called the partial dispersion of the glass. In general the partial dispersion of glasses change with Abbe number. When partial dispersion is plotted versus Abbe number most glasses fall close to a theoretical line called the normal glass line. If one used a pairing of glasses that fell on the "normal glass line" the secondary color would be 1/2000. Figure 10 shows this plot with the normal glass line and the two glasses used in our doublet. In addition other glasses that will be talked about later are shown. This plot is important for determining the chromatic aberration of a doublet. The slope of the straight line that joins the two glasses of a doublet is a good indication of the chromatic aberration in the doublet. The steeper the slope the greater the chromatic aberration. As one can see the BSL7/TIM8 doublet slope is a little steeper then that of the normal glass line. One reason for that is the above doublet uses "eco-friendly" glasses. Sometimes it is easier to find a better match with non eco-friendly glasses.

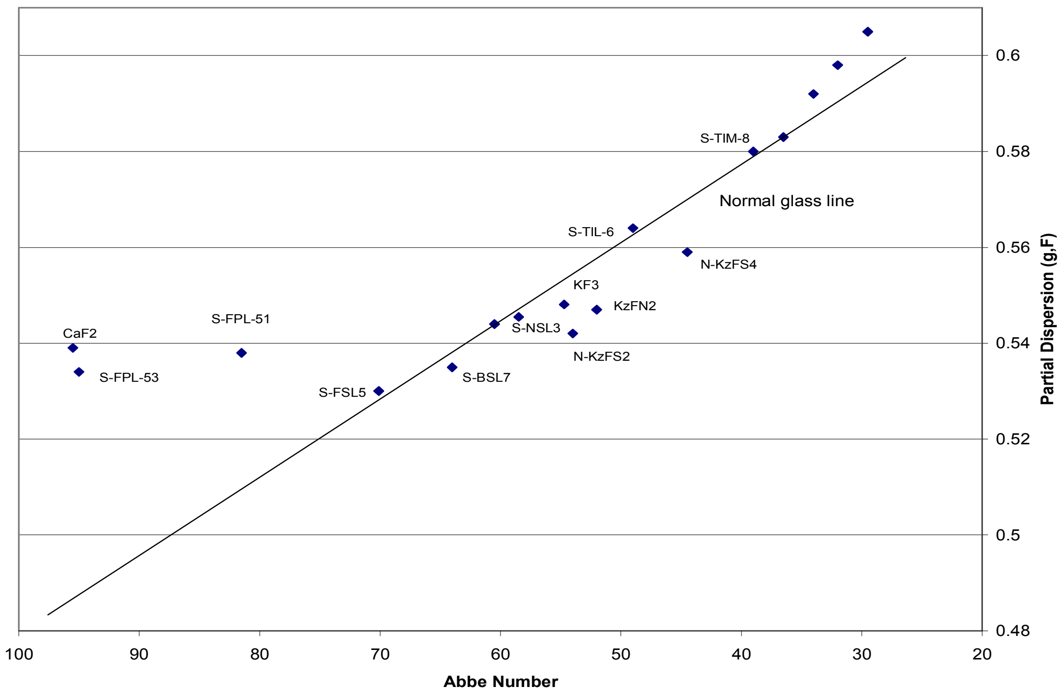


Figure 10. Partial Dispersion versus Abbe Number

To get better color correction in a doublet one needs to make a pairing of glasses where one or both glasses deviate from the normal glass line. This is where the "ED" glasses become very important. ED stands for Extra low Dispersion. The two main ED glasses used today are S-FPL-53 and S-FPL-51. These are the names given by the Ohara glass company. Other glass companies have similar glasses by different names. These glasses are special in two ways. First they both have very high Abbe numbers. This means the dispersions of these glasses are low. Remember that when pairing up glasses for a doublet we would like to have glasses with a large difference between the Abbe numbers. In addition both ED glasses deviate greatly from the normal glass line and in the correct direction. This helps improve color correction. Also shown in Figure 10 is the crystal CaF2. This crystal also has a very high Abbe number and deviates greatly from the normal glass line.

If FPL-51 is paired with S-TIM8 we can see the slope of the line between the two glasses is less than that of the S-BSL-7/S-TIM-8 pairing. Even further color improvement can be achieved by pairing the S-FLP-51 with S-TIL-6. Figure 11 shows the longitudinal aberration curves for this pairing. As one can see the correction for green is still very good but now the focus shift between green and red/blue has been greatly improved. This pairing produces a focus shift of about 1/4500, which is about 2.6 times better than the other pairing.

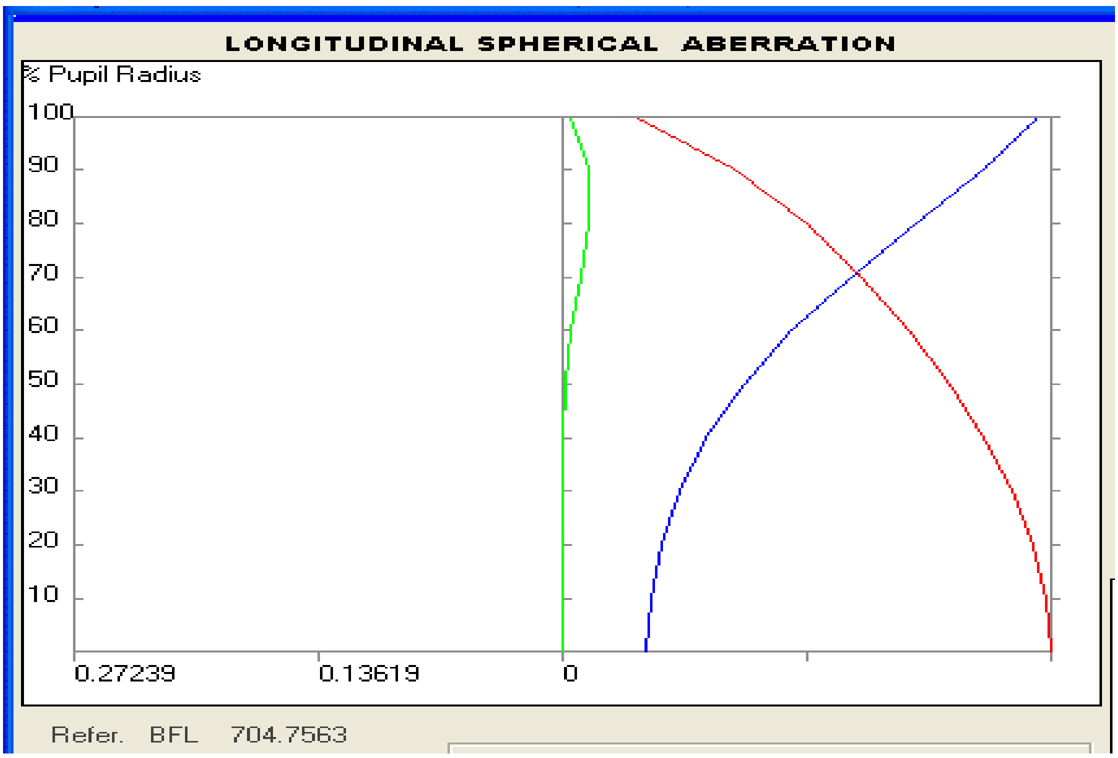


Figure 11. Longitudinal Aberration for FPL51/TIL-6 Doublet

Figure 12 shows the spot diagram for the ED doublet. At first look of the spot diagram one might concluded that the blue response will be much more blurred than the red, but this is not a correct conclusion. One needs to not only look at the total diameter of the blur spot but also the distribution in the spot. The blue spot is bigger but more of its spots are located in its center. In contrast the red spot is smaller but the center is not very dense. On average these two spot produce about the same overall Modulation Transfer Function (MTF). The MTF is similar to the frequency response used to rate audio equipment response. It is just another tool one can used to help understand optical performance.

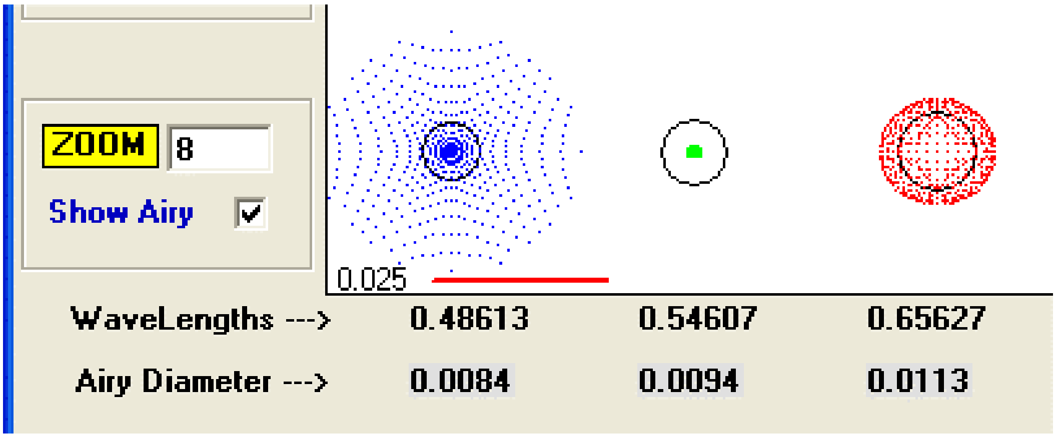


Figure 12. Spot diagram for FPL51/TIL-6 Doublet

The difference in the red and blue blur character is due to what is called spherochromatism. Spherochromatism is the change in the spherical aberration with wavelength. Figure 11 shows us that the spherical aberration for green is almost zero (line is nearly vertical). The blue line curves to the right which is called over corrected spherical aberration. The red line is curves to the left which is called under corrected spherical aberration. Typically as the chromatic aberration of the doublet improves, spherochromatism becomes a larger percentage contributor to the overall aberration of the doublet. For the smooth changing curve shown in Figure 11 the best focus point is typically the 71% Pupil Radius point. For both red light and blue light this is about .16 mm from the best focus point for green light.

After accounting for the shape of the blur spots, the FPL-51/TIL-6 102mm f/7 will meet the guide lines for good visual performance from Rutten and van Venrooij, “Telescope Optics”, but imaging performance will be a little more questionable. For imaging, performance at lower wavelengths becomes more important. The ED doublet when focused on green has a blur spot diameter of 138micro-meters for 436nm light. This is about 15 times larger than the green airy disk size.

One way to improve the performance of a doublet is to use a different glass pairing. The FPL-51/TIL-6 pair produces a large improvement over a “normal glass” pairing and TIL-6 is a low cost glass that can be produces with a high quality level. To get a better performing doublet one can change the glasses. A small improvement can be achieved by changing from FPL-51 to FPL-53. A larger improvement can be achieved by changing the matching glass to FK3. Figure 13 shows the longitudinal aberration curves for a FPL-51/FK3 doublet. The FK3 glass produces a notable improvement, but unfortunately it is not produced much any more for environmentally reasons. It should be noted that though the focus shift between green and red/blue has decreased (look at the 71% points), the spherochromatism is larger. The net result is still an improvement, but one needs to keep track of both focus shift and spherochromatism.

To get a large improvement, the FPL-53/N-KZFS2 pairing can be used. This pairing produces a very well corrected doublet but both glasses are expensive and delicate. Figure 14 shows the longitudinal aberration curves for this pairing, 102mm f/7. The curve for 436nm has been added to this plot. In addition the design has been shifted slightly to give better performance at 436nm. Because of the excellent matching of these glasses one can shift the design towards 436nm without having much effect on the visual performance. With this improved pairing and different optimization, the 436nm blur diameter shrinks to 51 micro-meters, with a concentration of rays in the center.

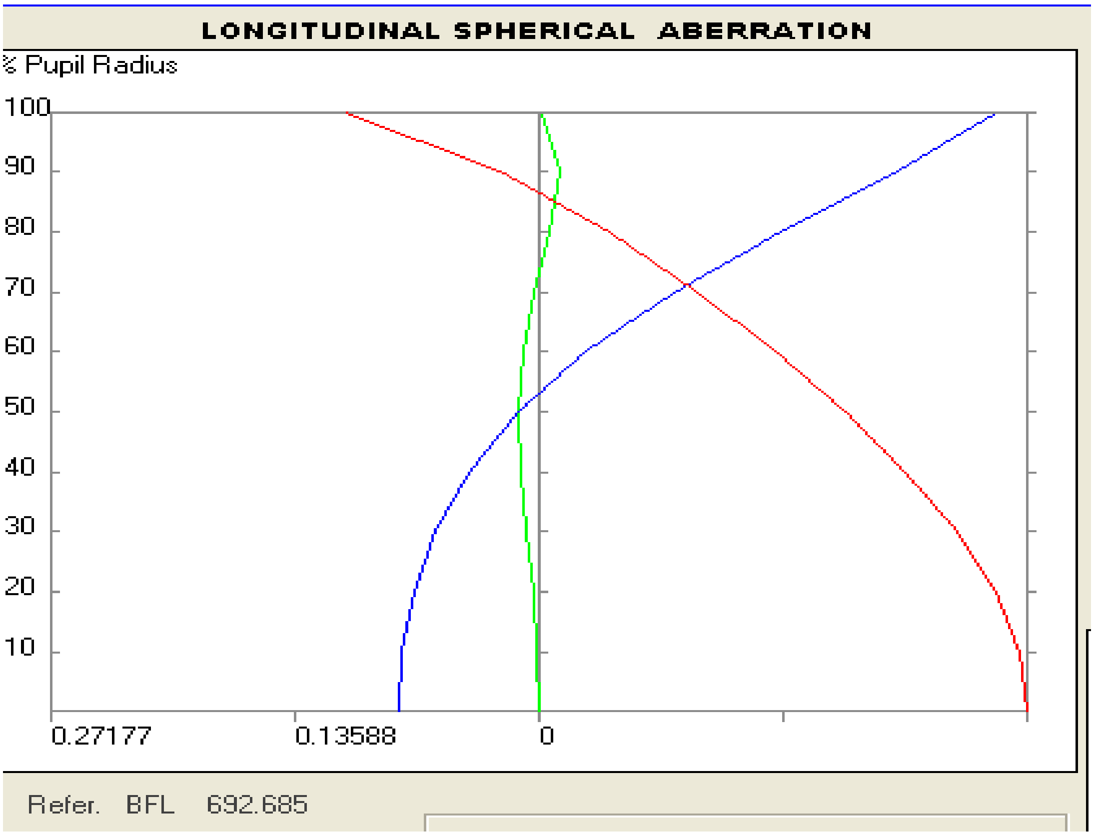


Figure 13. FPL-51/KF3 Doublet.

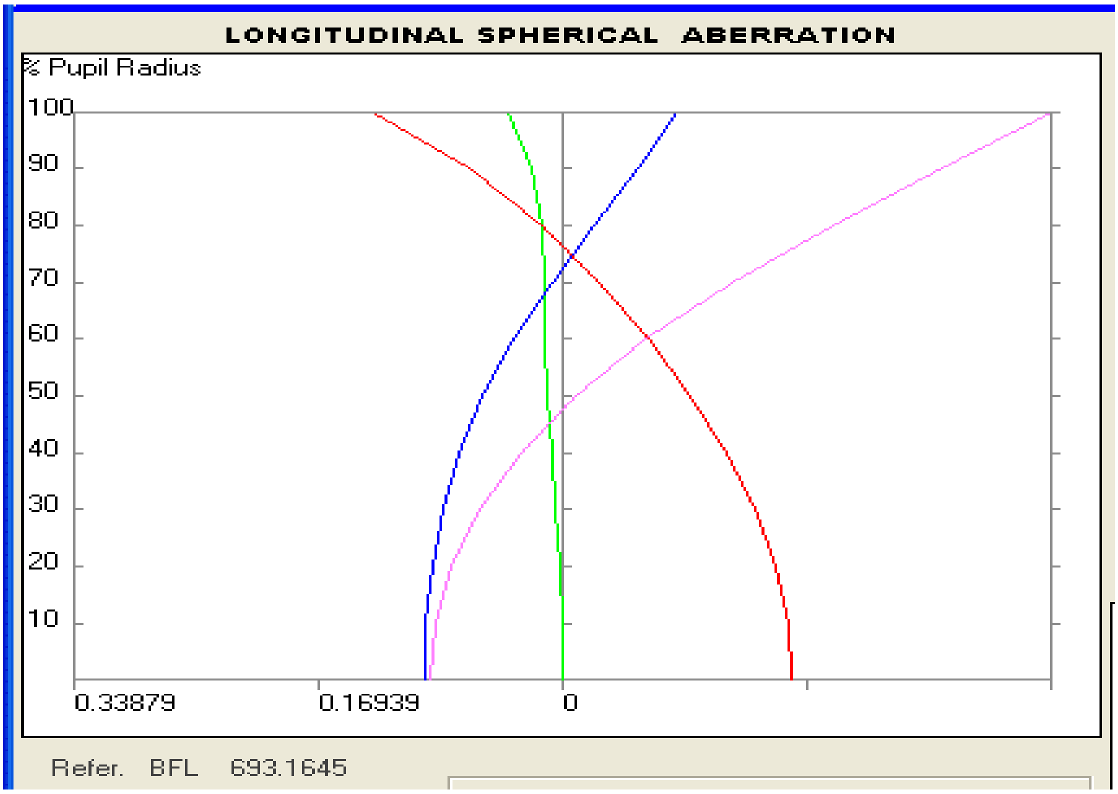


Figure 14. Longitudinal Aberration for FPL-53/KZFS2 Doublet

One should realize that matching the partial dispersions of the two glasses does not guarantee a good performing doublet. Looking at Figure 11 we see that FPL-53 and BSL7 have almost the same partial dispersions. Figure 15 shows the longitudinal aberration curves for this pairing, in a 102mm f/7 doublet. With this pairing with a 102mm aperture and f/7, what is called “5^{th} order spherical aberration”, is large and will greatly degrade the performance of the scope. One problem with this pairing is that the ratios between the Abbe numbers for the two glasses is not high, 95/64= 1.48. A low ratio requires strong curvature in the glass elements. Strong curvature tends to generate aberrations. Also the index-of-refractions of the two glasses affect how well they will work together.

5^{th} order spherical aberration can be reduced by increasing the f-ratio. Increasing the f-ratio decreases the curvature in the elements. This help reduces the 5^{th} order spherical aberration. Figure 16 shows the longitudinal aberration curves for the FPL-53/NSL3 doublet with a 102mm aperture and an f-ratio of 8.5. With this higher f-ratio the 5^{th} order spherical is quite low. At f/7 the 5^{th} order aberration is much more noticeable. This pairing at this f-ratio produces very good correction. NSL3 is much less costly than KZFS2. This pairing has a secondary spectrum of about 1/11,000 of the focal length.

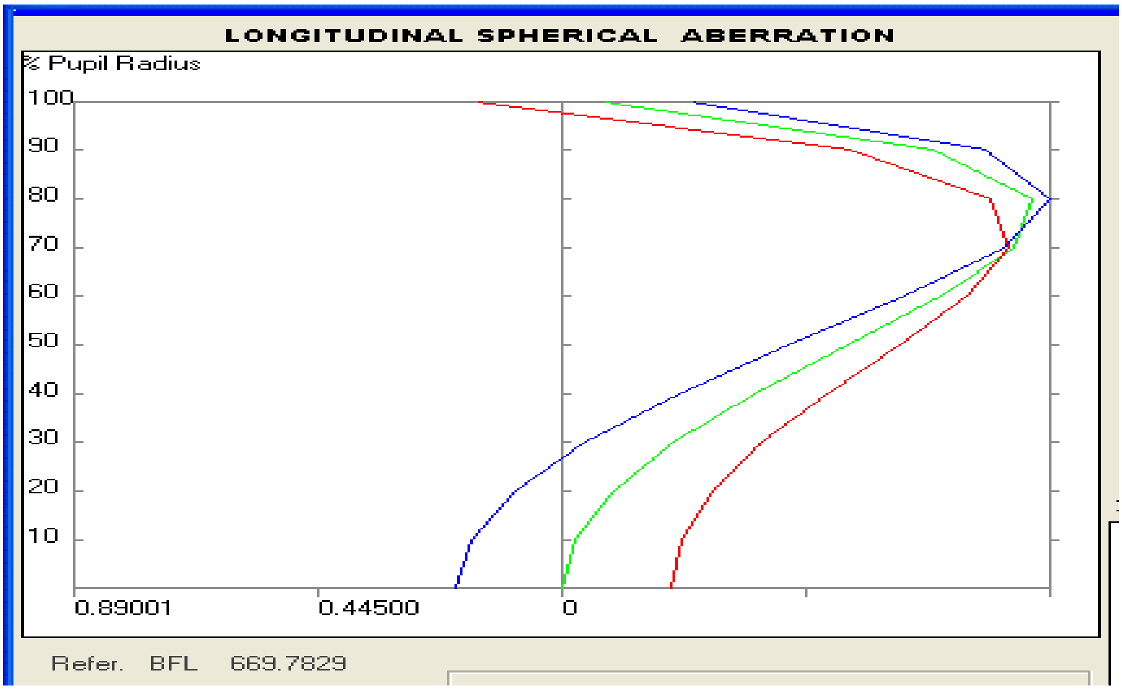


Figure 15. FPL53/BSL7 Doublet

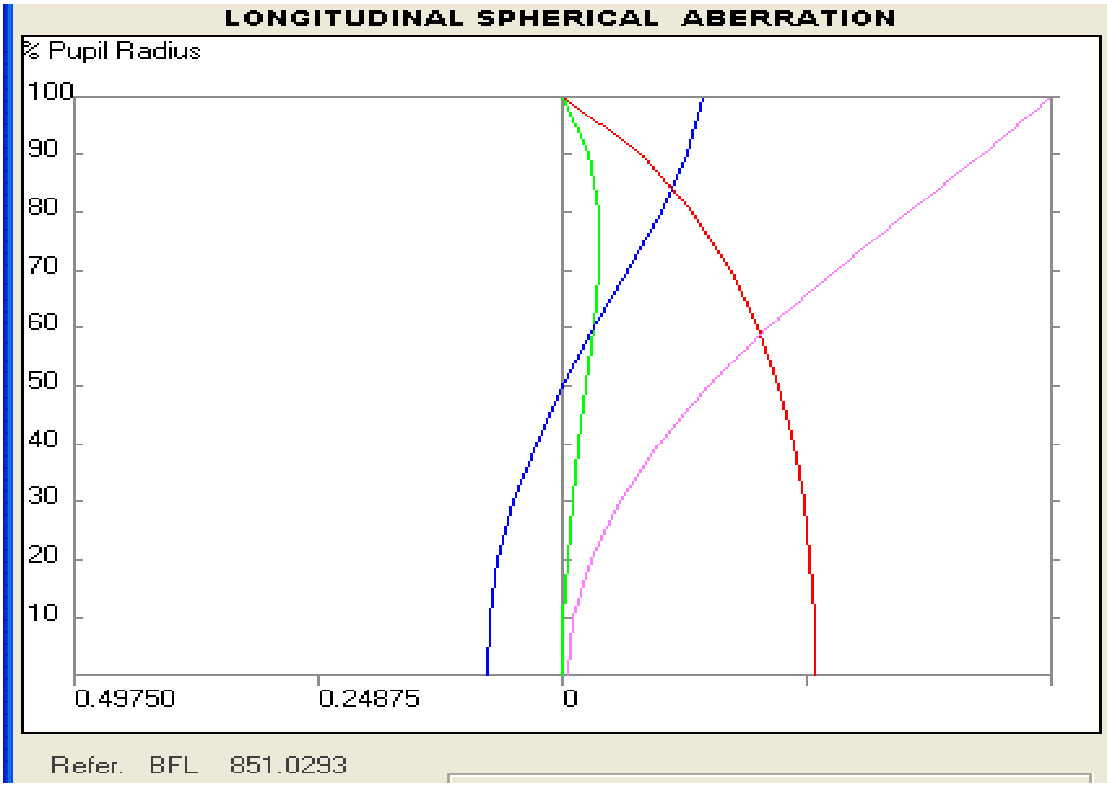


Figure 16. FPL53/NSL3 Doublet, 102mm f/8.5

The Triplet, So Misunderstood.

Typically three elements, triplet, are used to improve the performance of a scope. Many different forms of triplets exist. Though a triplet often has excellent color correction, the use of 3-elements does not ensure good color performance. In general a triplet design does give the designer more “degrees-of-freedom” to correct aberrations. As was shown above, changing from 1 element to 2 elements greatly improves the performance of the lens design. Added a third element does the same though not quite to the same extreme.

To show the power of the additional element, an f/7, 102mm triplet design that uses FPL-53 and BSL7 will be presented. As was shown above, a doublet using these glasses produces poor results at f/7. Figure 16 shows the longitudinal aberration of a triplet that uses a single FPL-53 element between two BSL7 elements. By adding the additional element a very well corrected telescope is produced. Because the two glasses that are used have nearly the same partial dispersion, the focus shift with wavelength is very small. Figure 16 shows the focus shift for rays that enter at 71 % of the radius of the lens, as a function of wavelength. As one can see the curve has an “s” shape that crosses through the horizontal axis three times. All the previous designs have only 2 crossings. Some people consider this a requirement for a true “APO” design. In general three crossings give better color correction over a wider range of colors. The triplet design has a 436nm blur diameter of 27 micro-meters, with a concentration in the center. In this design the average focus shift with wave length is very small. It is the spherochromatism that limits the performance over the range of colors.

This triplet is very well corrected. Some like to use “wave-front” error to rate the quality of the telescope. The wave front error at green is .014 peak-to-valley. Over the range of red to blue it is less than .2 waves, and at .435nm it is .3 waves. These numbers are just design numbers and assume every thing is perfect.

Above is just one form of triplet. Some others combine three different glass types to control chromatic aberration.

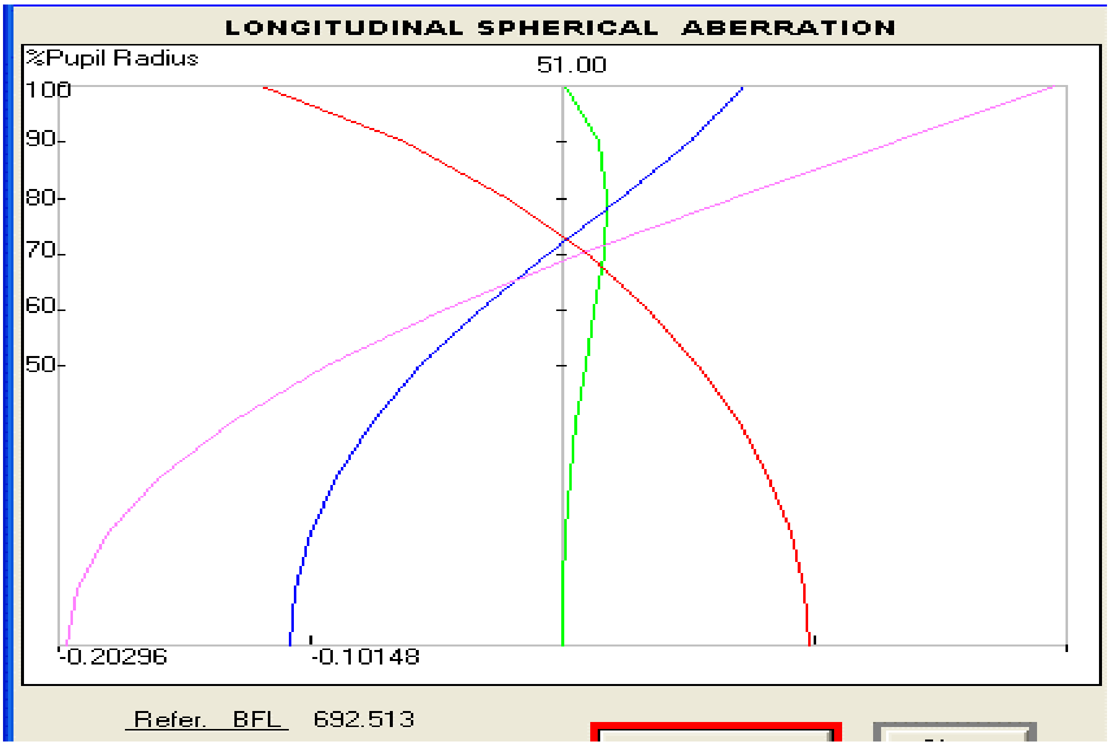


Figure 16. Longitudinal Aberration for BSL7/FPL-53/BSL7 triplet

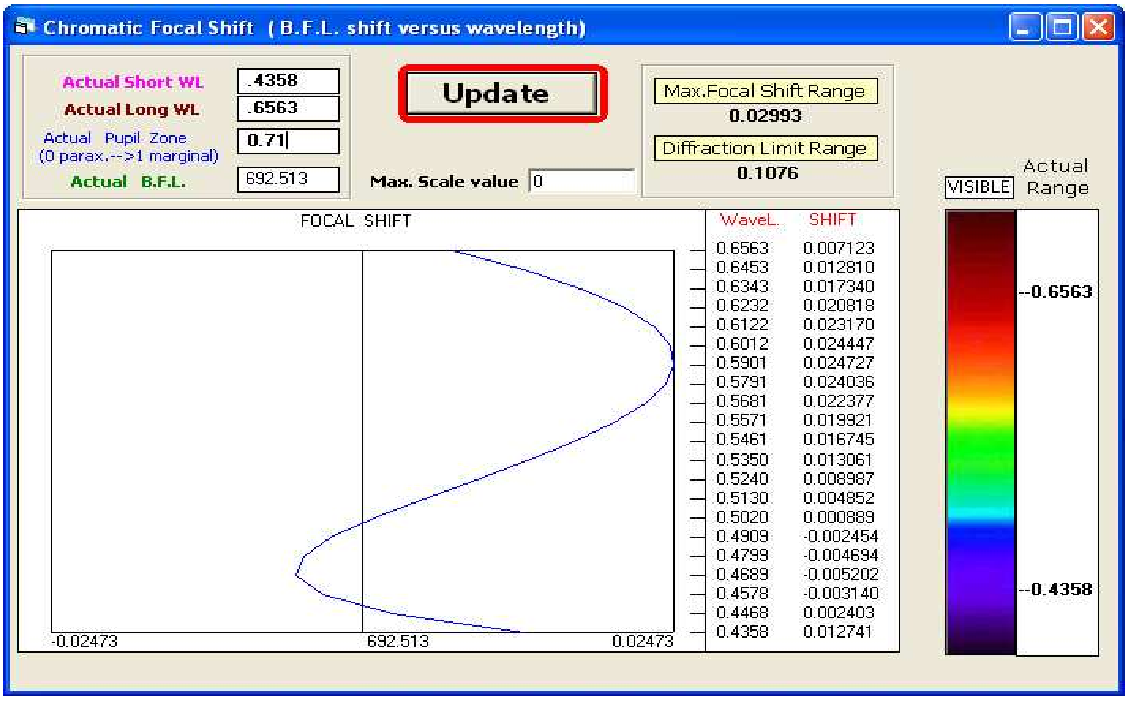


Figure 17. Focus Shift for BSL7/FPL-53/BSL7 triplet

It is Not Just About the Design and the Glass

The above presented performance assumes perfectly made scopes with glass properties at their nominal values. In the “real world” the performance of the scope could be far from that presented. The accuracy of the grind and polish of the lenses will affect the performance of the scope. Also lens element alignment can greatly affect performance. The quality of the glass can be a big factor. The same manufacture can produce the same glass type in different quality level and different manufactures produce different quality of glasses. Some glasses are much harder to make well, so even though one design may look better on paper, its may not produce as good a result due to glass quality issues such as homogeneity. The same glass type will vary from batch to batch. To get the ideal performance from a scope this variation needs to be accounted for. These are just some of the factors that can affect the scope performance, so remember it is not all about the glass.