THE MELIOR APOCHROMAT

A New Refracting Telescope Optical Design

By Joseph Bietry

Refracting telescopes have developed over centuries, from the humble beginnings of the Galilean telescope to the modern apochromats of today. Advances in astronomical refractors often came about through improvements to optical materials that offered better control of color errors (chromatic aberration). Occasionally, a different optical design offered improvements as well. This article will describe a new optical-design form that offers improvements to chromatic aberration, as well as field of view beyond that of current refracting apochromatic telescopes.

The name, the Melior Apochromat, was chosen for two reasons. First, the English translation for the Latin "melior" is "better" or "improved," and this is indeed a performance improvement over current apochromats. But of more importance to me is that "Meliora" is the motto of my alma mater, the University of Rochester. I was lucky enough to have studied lens design at the UR's Institute of Optics under such greats as Rudolf Kingslake and Robert Hopkins. By using the root of the motto for the naming of this design, I am honoring the University and the professors who gave me the

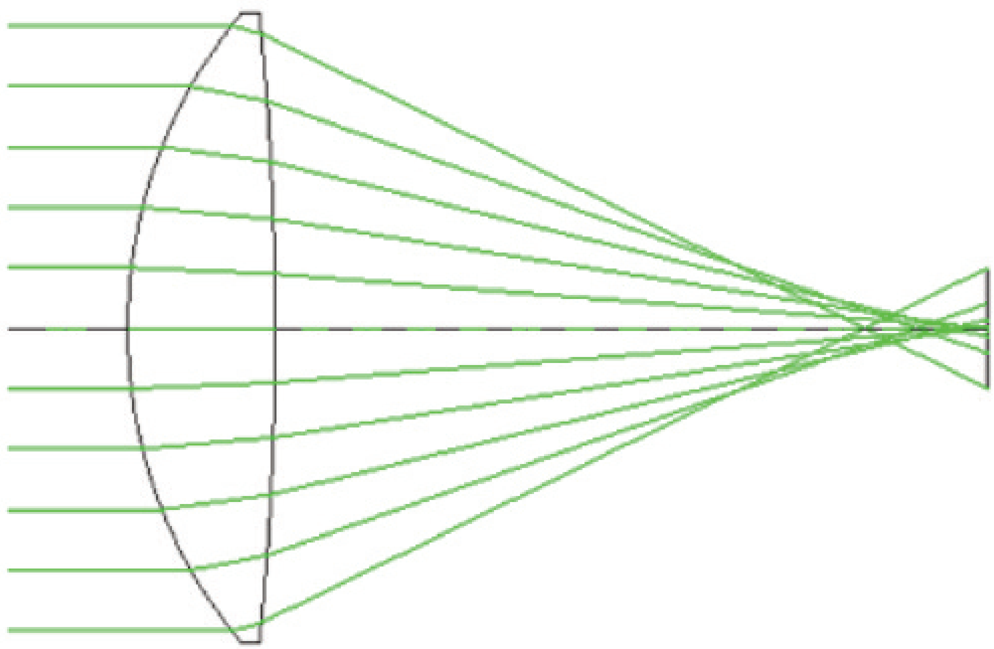


Figure 1: A simple lens with spherical aberration.

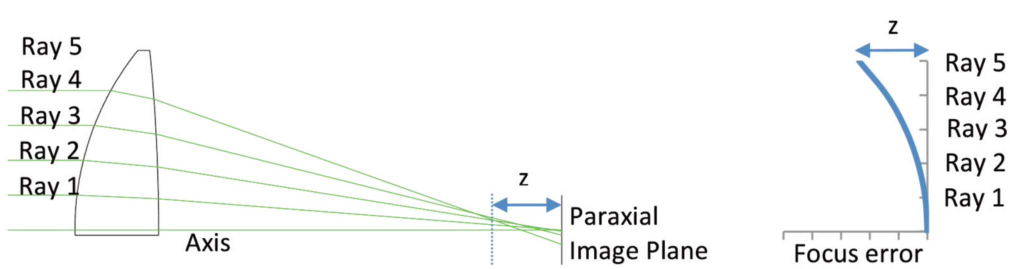


Figure 2: The upper half of a simple lens with spherical aberration. The plot at the right shows the focus error with respect to the position of the ray within the aperture.

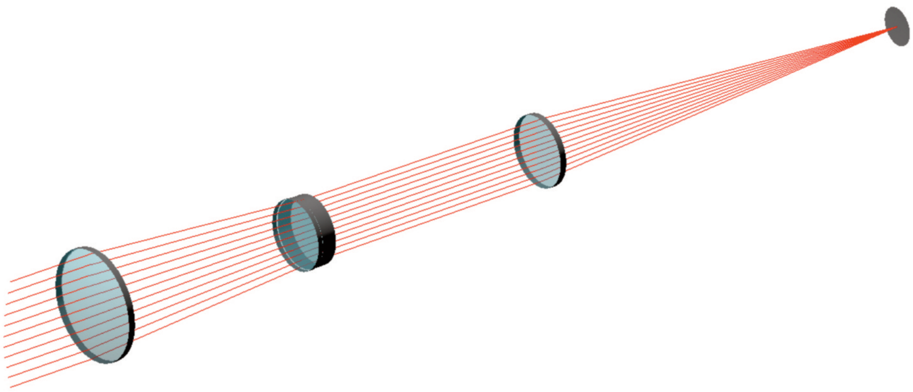


Figure 3: A 3D model of the Melior Apochromat.

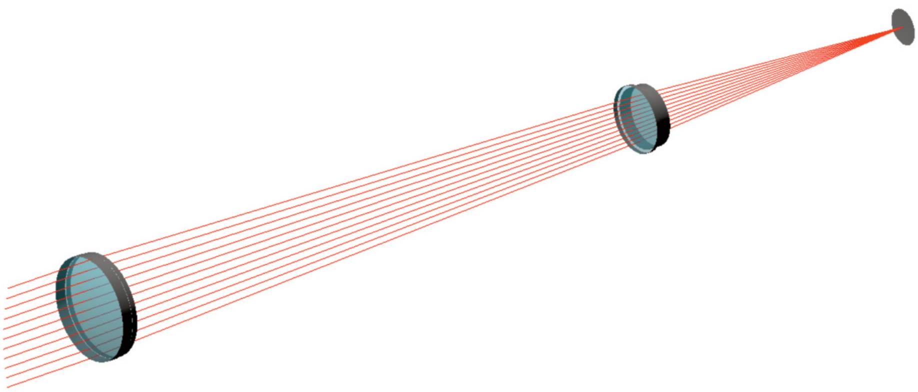


Figure 4: A typical Petzval design – four elements arranged in two widely separated groups.

knowledge and opportunity to pursue my dreams.

The typical apochromat makes use of modern optical materials to control chromatic aberration. They are often referred to as anomalous-dispersion glass or extra low-dispersion (or ED) glass. These materials are a significant improvement over the common glass achromatic refractor designs, but they still suffer from a residual color aberration known as spherochromatism, and it is this error that ultimately limits the performance of the apochromat. Although it may sound complicated, the concept behind it is quite simple. When light refracts through an optical material, it inherently responds differently for different wavelengths (or colors) of light in the same way that rainbows are created. Spherochromatism then, is simply the variation of spherical aberration with changes in wavelength. Anyone who has ground and polished a Newtonian reflecting telescope mirror recognizes the importance of correcting spherical aberration by figuring the surface of the mirror to the shape of a parabola. Since a reflecting surface responds the same to any color, once the figuring is done, the spherical aberration is removed for all wavelengths of light. Such is not the case for refracting surfaces.

To illustrate, I will describe a way to graph spherical aberration and then also graphically show how it changes with wavelength (spherochromatism) for refracting telescopes. **Figure 1** shows a simple lens with spherical aberration. The parallel rays of light entering from the left of the lens represent an infinitely distant point of light (i.e. a star). Ideally, all of these rays should converge to a single point at the image plane, but because of spherical aberration, different radial zones of the lens focus at different locations along the optical axis.

Figure 2 shows just the upper half of the lens. The optical axis and five rays are labeled with each ray representing a certain radial distance away from the axis. Ray 1 is the ray nearest the optical axis and represents the position of the image plane (referred to as the paraxial focus). Ray 5 passes through the outer edge of the lens and strikes the axis inward from the paraxial image plane by a distance "z." The plot to the right in Figure 2 shows this focus error with respect to the position of the ray within the aperture.

The graph shows that the light passing through this lens focuses more inward (towards the left) as the rays move closer to the edge of the lens aperture. This graphically represents spherical aberration. The curve could be bending to the left (as illustrated) indicating under-corrected spherical aberration, or it could be bending to the right indicating over-correction. In a perfect lens, all of the light would focus to a single point and all rays would cross the axis at the same location. This would show in the graph as a straight, vertical line.

Let us now turn our attention to the details of the Melior Apochromat. The design presented here has a 1000-mm focal length and a 155-mm (6.1-inch) entrance pupil diameter yielding an f/6.45 f-number.

Figure 3 shows a 3D model of the design. It has four elements separated into three sections. Starting from the left, the first section is a single common glass element, the second section is a doublet with one anomalous glass element and one common glass element and the third section is another single common glass element. Because of the very unusual distribution of glass types, this unique design offers exceptional color correction and effectively eliminates spherochromatism.

I have recently been awarded a patent that covers this new design concept (patent #9,588,331 issued on March 7, 2017).

It would be instructive to compare the Melior Apochromat to other designs of similar caliber. Details of any optical design are always a closely guarded secret, so to make a comparison, I will need to design the comparison telescope using the same criteria that were used in the Melior design from known literature describing such design forms.

The two most common apochromatic refracting telescope designs on the market today use either the Triplet or Petzval forms. The Triplet, as the name suggests, uses three refracting elements in close proximity to each other. The Petzval, on the other hand, uses four elements in two widely separated groups. While minimizing the number of elements is one goal in a telescope design, a triplet type does not have the ability to operate at a focal ratio much faster than f/8 before performance begins to degrade. Since the Melior is operating at f/6.45 and is itself a four-element solution, a Petzval seems to be the most appropriate design against which to make comparisons.

Figure 4 shows the resulting Petzval solution that I designed with the same criteria used to design the Melior. It is constructed of two doublets that are widely

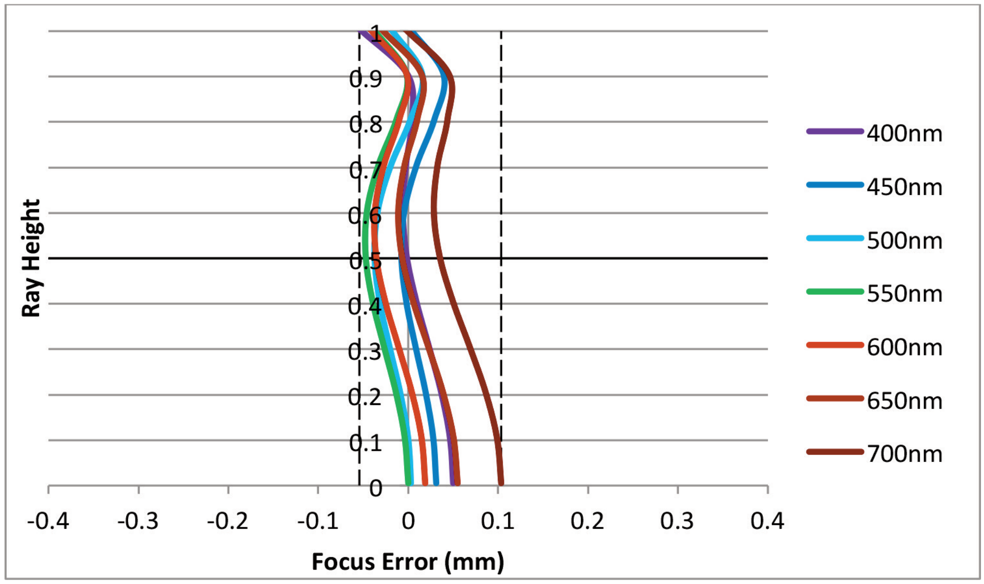


Figure 5: A plot of the Melior Apochromat at various wavelengths from 400 nm (deep blue) to 700 nm (deep red).

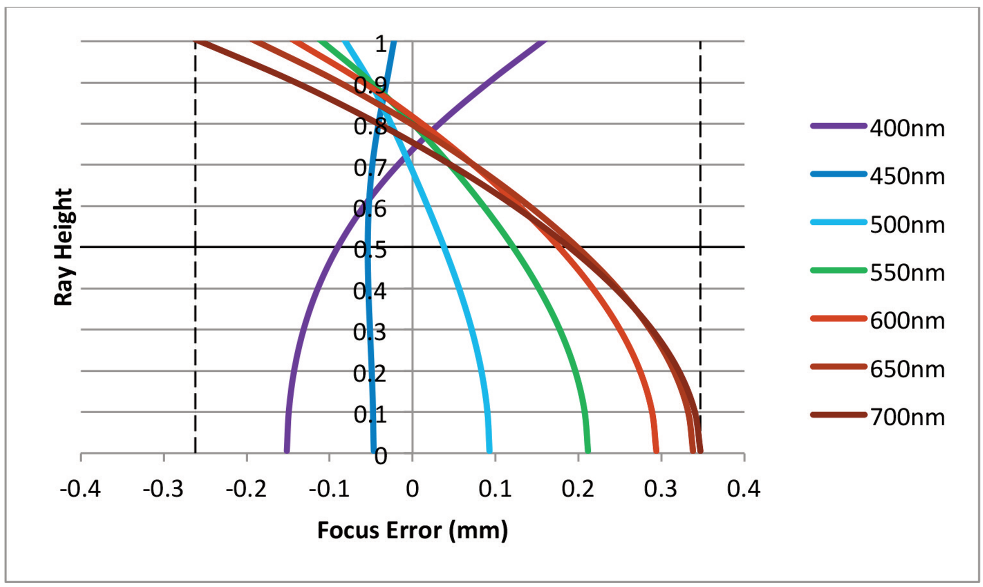


Figure 6: A plot at the same scale for the Petzval design at various wavelengths from 400 nm to 700 nm.

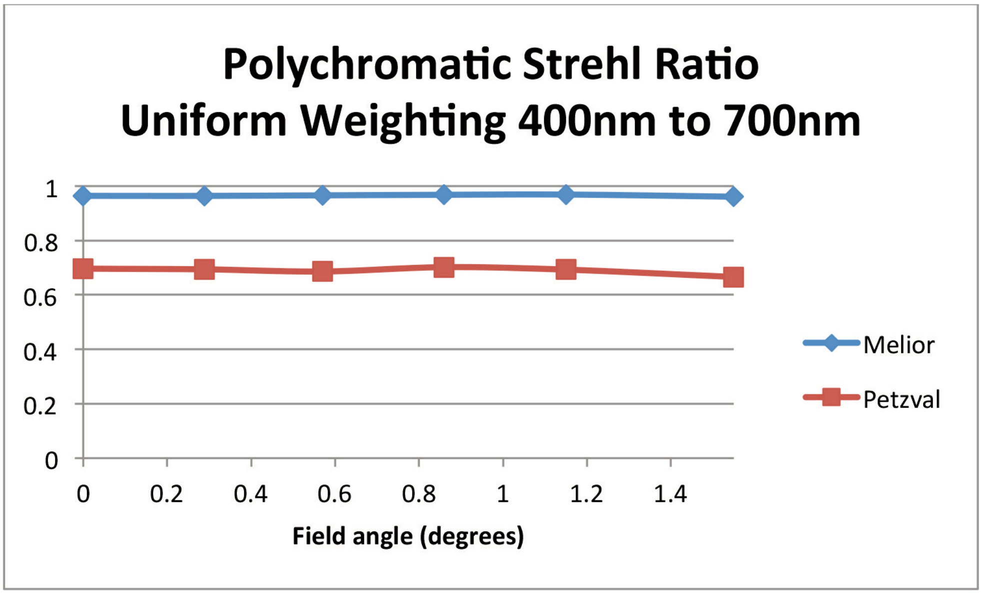


Figure 7

spaced. Each doublet is well corrected for color by using an anomalous glass (Ohara S-FPL53 in this case) element. The Petzval-type design does an excellent job of correcting primary and secondary color, which allows it to be designated as an apochromat, but it does not offer any significant relief from spherochromatism.

Figure 5 shows a plot as described above for the Melior Apochromat at various wavelengths from 400 nm (deep blue) to 700 nm (deep red), and **Figure 6** shows the same plot at the same scale for the Petzval design. You will notice that all of the colors in the Melior Apochromat have the same general shape and cluster together quite closely. The Petzval, on the other hand, clearly exhibits the issue of spherochromatism. At 400 nm, the graph curves strongly to the right indicating over-corrected spherical aberration. At 700 nm, the graph curves strongly to the left indicating under-correction. The range of focus error across all colors exceeds 0.6 mm for the Petzval design, while the Melior contains all colors within a focus range of 0.15 mm; a four-times improvement to that of the more conventionally color-corrected Petzval design.

You may notice in the focus error plot of the Petzval design (Figure 6) that the colors tend to converge at between 0.7 to 0.8 (or 70 percent to 80 percent) in aperture height. For minimizing the impact of spherochromatism, this is the desired location for the colors to converge. It is instructive to note that color correction in an optical design is usually reported at only this minimum aberration zone.

Using that notion, it could be said that the Petzval design has approximately the same color correction as the Melior when looking at this zone only. However, when looking over the entire aperture of the telescope, the Melior has significantly superior color correction and will focus more energy to the desired location.

The graph in Figure 5 clearly shows a dramatic improvement in color correction for the Melior design, but it does not necessarily quantify how much better the telescope would perform in actual use. One way to convey that is to use a Strehl ratio.

A Strehl ratio is a normalized metric to indicate how closely the optical system approaches theoretical perfection, and a Strehl ratio of 1.0 thus indicates a perfect system. Typically, a Strehl ratio is only reported at a single wavelength (monochromatic), and in the presence of spherochromatism, the wavelength is carefully chosen to be one that has very little spherical aberration. The wavelength that would offer the highest Strehl ratio for the

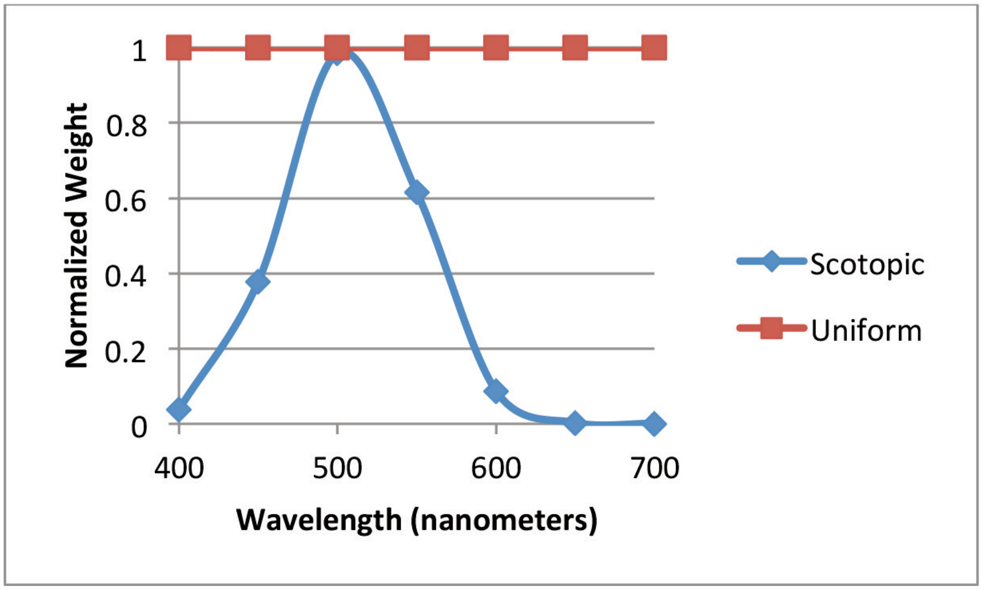
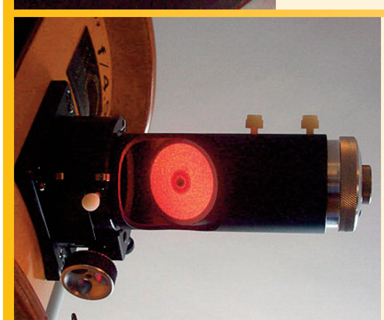


Figure 8: Color sensitivity variation over wavelength for a dark-adapted eye.

Petzval design (see Figure 6) is 450 nm, since it is the color closest to a vertical line in the graph.

The Melior, on the other hand, would have about the same Strehl ratio no matter what color is chosen. In use, all wavelengths (polychromatic) contribute to the final image and should therefore be considered. I will use a particularly rigorous requirement and suggest that all wavelengths will contribute equally to the system performance. This seems a reasonable approach when using a camera, because camera sensors have high sensitivity



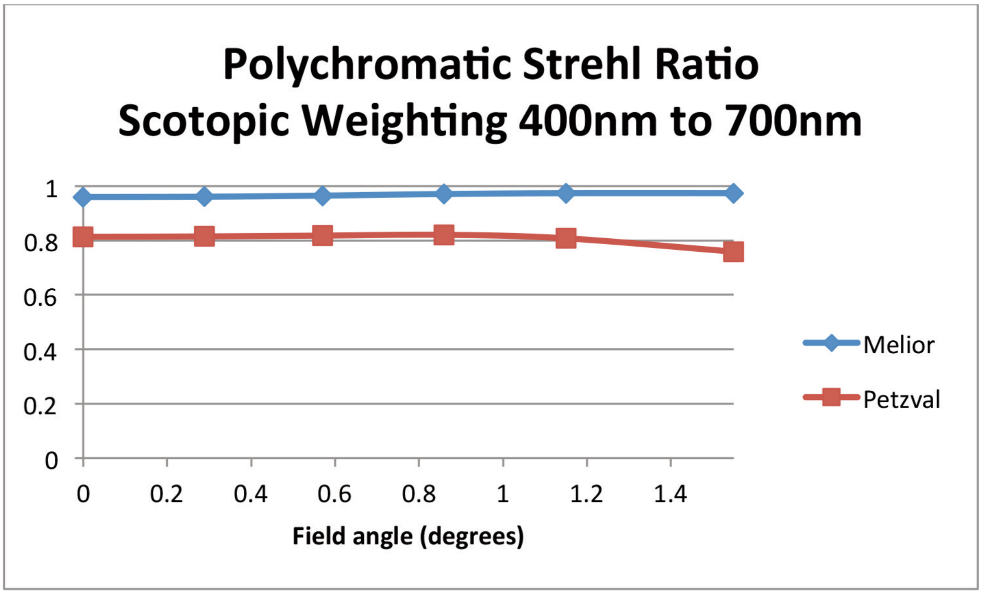


Figure 9

over a very large spectrum.

The plot in **Figure** 7 shows the polychromatic Strehl ratio with uniform weighting over a wavelength range from 400 nm to 700 nm for a series of field angles. It is conventionally accepted that a Strehl ratio of 0.8 or better is considered diffraction limited (see http://www.telescope-optics.net/Strehl.htm). It can be seen that, as a result of spherochromatism, the Petzval design does not meet the diffraction limit with this uniform polychromatic criterion. The Melior calculates well above the minimum diffraction limit and is above 0.96 across the entire field of view.

Both designs perform quite uniformly across the plotted field of view of 1.55-degrees semi-field. For the given focal length of 1000 mm, this corresponds to an image-circle diameter of 54 mm. However, it should be noted that for both designs, I allowed the image surface to be curved. This minimizes the amount of astigmatism in the field, and it is my belief that defocus due to a curved field is a more acceptable error than astigmatism.

The Petzval design has an image radius of 817 mm and the Melior design has an image radius of 1041 mm. So, the Melior design naturally tends toward a flatter image surface than that of the Petzval design. These are both fairly long radii and for many uses may not cause any problems at all. For extremely demanding applications, there are well known techniques for adding a field flattener.

While uniformly weighting the wavelengths may be a reasonable approach for a camera system, it is overly pessimistic for visual uses. The human eye sensitivity varies significantly over the 400 nm to 700 nm range. When the eye is well dark adapted, it has a response to color known as scotopic vision (https://en.wikipedia.org/wiki/Scotopic_vision). **Figure 8** shows how this sensitivity varies over wavelength for a dark-adapted eye. The deep-red region has very little sensitivity, and the peak sensitivity is in in the blue-green region of 500 nm.

The result of calculating the polychromatic Strehl ratio using the scotopic color weighting is shown in **Figure 9**. The Melior Apochromat is little changed with this reduced spectrum weighting, indicating that chromatic aberration is quite small over the entire wavelength range. The Petzval design using the scotopic weighting is improved to place it within the diffraction limited category (Strehl greater than 0.8) over most of the field, suggesting that chromatic aberration (specifically spherochromatism) is a significant contributor to polychromatic Strehl ratio.

It can also be seen that there is some degradation at the edge of the field due to other aberrations. The Petzval appears to be reaching a limit in its field of view, whereas the Melior remains constant and could easily be extended to larger fields of view without significant impact to image quality. Both designs were only optimized over the 1.55-degree semi-field of view, but when analyzed at 2.0-degrees semi-field, the Melior performance is unchanged at 0.96 Strehl, while the Petzval drops to 0.64 Strehl. I chose the 1.55-degree field to cover the largest camera sensors of which I am aware. However, the Melior design could easily cover larger sensor formats, if desired.

Figure 10: A Melior Apochramat prototype on a Celestron CGEM-DX mount.

Yet, a theoretical design has no real value if it can't be built. The worth of a design is only realized if it delivers high quality when constructed. To satisfy myself that this is indeed a design that can be built, I set off to build a few prototypes. Four prototypes have been built to date, and all have performed admirably.

Figure 10 is a photo of one of the prototypes on a CGEM DX mount. To measure performance of the prototypes, I am using a double-pass (also known as auto-collimation) static fringe interferometer. **Figure 11** is a photo of a double-pass interference pattern using a Helium Neon red laser (632.8 nm) at a field angle of 0.5 degrees.

I used the program called FringeXP to analyze the captured fringe patterns,

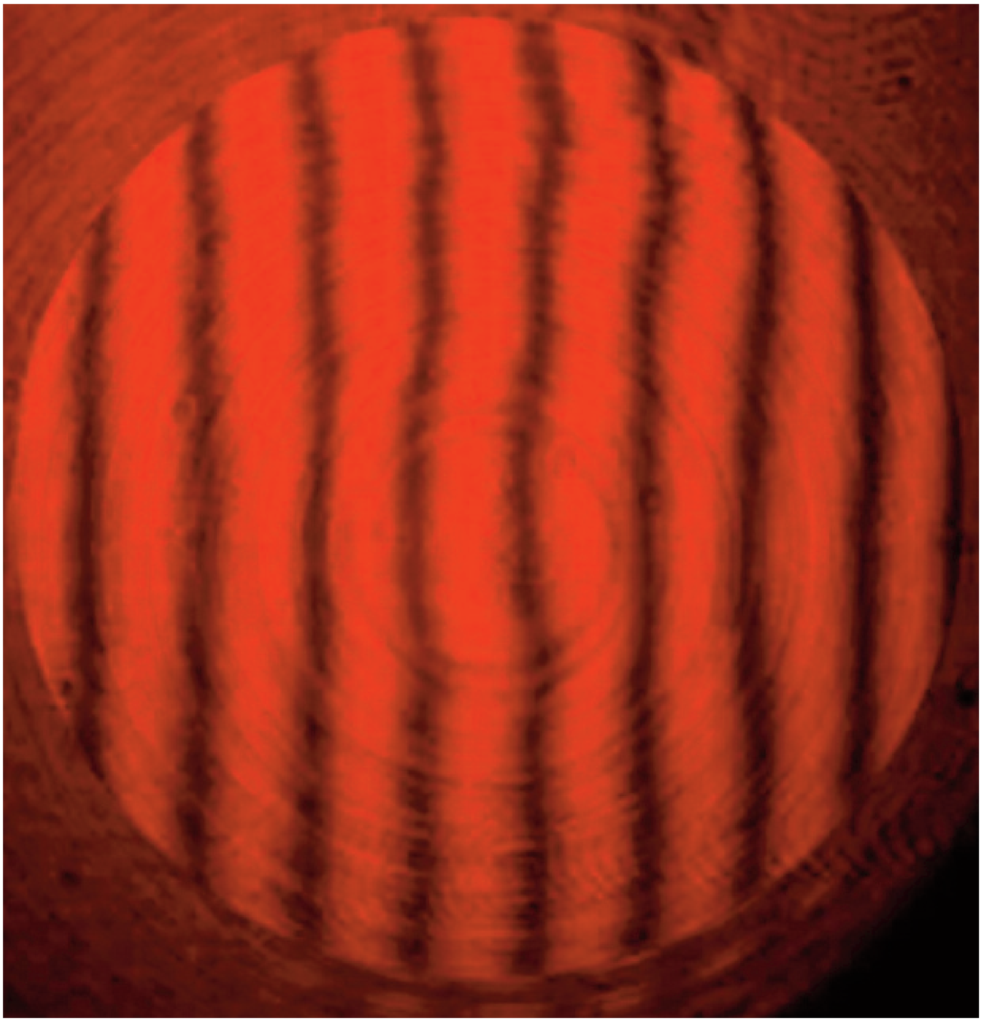


Figure 11: Photo of a double-pass interference pattern of a Melior Apochromat prototype using a Helium Neon red laser (632.8 nm) at a field angle of 0.5 degrees.

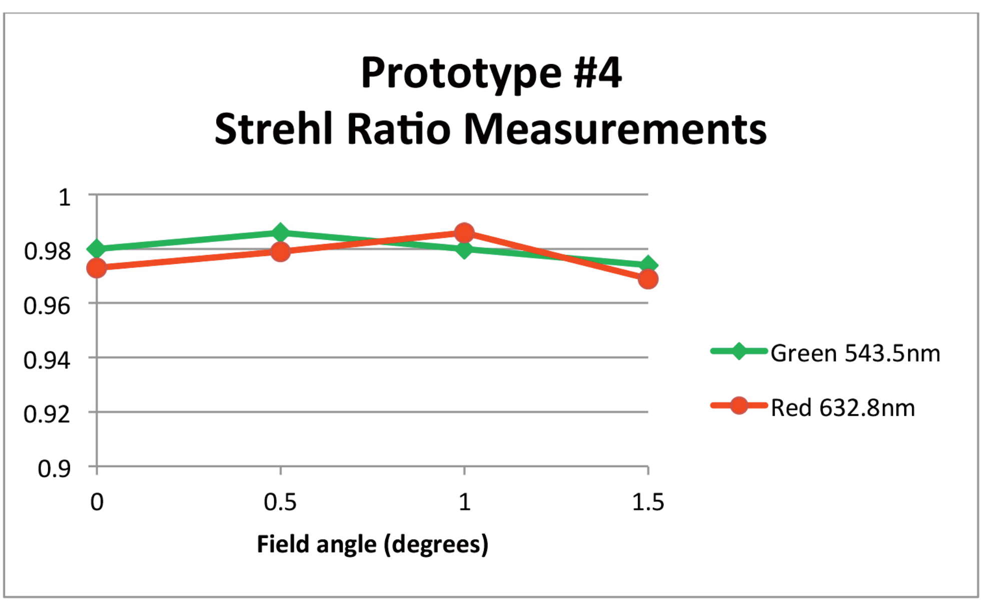


Figure 12

and a Strehl ratio was calculated from that image. I captured interferograms at red Helium Neon (632.8 nm) and green Helium Neon (543.5 nm). The plot of Strehl ratio versus angular semi-field of view for one of the built prototypes is shown in **Figure 12**. All of the prototypes have exhibited nearly identical measured performance suggesting a build consistency even with variations from part to part.

The prototypes now are in the skilled hands of a few expert amateur astronomers. They will make evaluations of the telescope – both visually and photographically – to see how this design improvement translates into better observing.

Assuming the field testing is positive, where do we go from here? If there is interest from the astronomy community, I would like to consider making a production run of telescopes. I chose a 6.1-inch aperture for the prototype, because it appeared to be a popular diameter for refractors, and this could be the first product. However, I think the real value in this design is in larger apertures. Since the spherochromatism of the Melior is unusually well controlled, scaling the design up to a larger aperture does very little to diminish performance. I have an 8.1-inch (205-mm) diameter 1325-mm focal length (f/6.46) design on the drawing board right now that has very nearly the same level of performance as its smaller counterpart.

I present a new refracting telescope optical design in this article. It exhibits exceptional performance both theoretically as well as in telescopes that have been constructed. I compare it to other types of apochromatic telescopes to show how this improved design translates into actual performance metrics. It is not my intention to disparage the quality of the other designs. The Petzval and triplet apochromats are quite excellent telescopes. But for very demanding applications, particularly with larger apertures, the Melior Apochromat offers a unique advantage.