# Gleanings for ATM's / Conducted by Roger W. Sinnott

## A New Approach to Color Correction

THE ART of correcting a refractor lens for chromatic aberration, or "color," is a subject thoroughly muddled by myths. Early makers, plagued by poor glass quality and the severe computational burden of designing lenses by pencil-and-paper arithmetic, often guarded their discoveries jealously and shrouded their methods in mystery to thwart unscrupulous copycats.

The quality of glass has improved tremendously over the years. Optical glass is now highly transparent, transmitting up to 99.7 percent of light per inch of thickness in the visible spectrum, and has far fewer bubbles and imperfections. It is more durable and less subject to atmospheric attack. But many people still believe that some of the old lens makers had magic formulas for highly corrected lenses. It is true that careful choice of curves has a great effect on spherical aberration and coma (*S&T:* November, 1984, page 450). But color correction depends entirely on the availability of suitable glass types. Today's achromatic doublets commonly made for astronomical use have about the same color error as those of over a century ago.

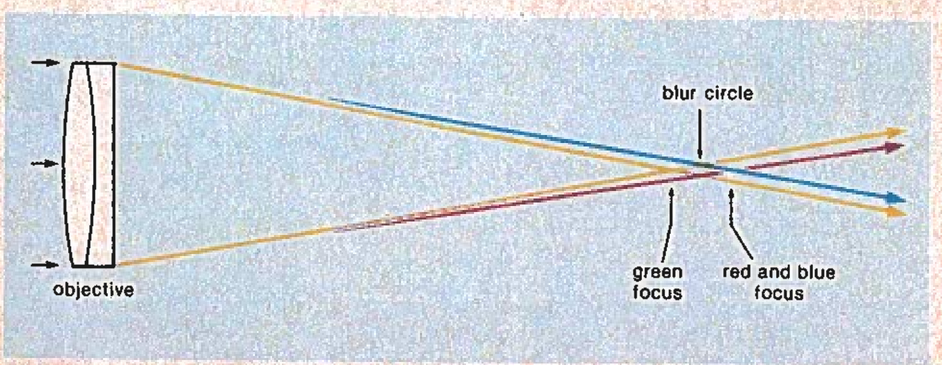
It takes two lens elements to bring two colors to a common focus (see diagram below). Theoretically, three elements of three *different* materials can focus three colors. But to do so for appropriate visible colors in a practical design requires the use of "abnormal dispersion" glasses. Out of some 2,000 commercially available glasses, only a few dozen have abnormal dispersion, notably fluorite, boron flint, some extra-dense flints, rare-earth glasses, and certain special alkaline types. These invariably have drawbacks: either they're costly, difficult to work, chemically unstable, or contain striae (streaklike inhomogeneities).

In a typical achromatic doublet made of such durable, inexpensive glasses as BK-7 crown and F-4 flint, the "secondary spectrum" or color error (difference in focal lengths) is 0.06 percent from red to green, or from green to blue. Three standard wavelengths often chosen to represent these colors are called *C, e,* and *F* (for spectral lines at 6563, 5461, and 4861 angstroms, respectively). The percentage is the same regardless of aperture or focal length. Therefore, in a 6-inch f/15 refractor where *C* and *F* come to the same focus, the *e* wavelength does so 0.05 inch short of this point (that is, 0.06 percent of 90 inches). The eye naturally selects yellow-green light to focus on, being most sensitive at this wavelength, so the red and blue light form an out-of-focus purple halo around star images. Colors bluer than *F* are even more out of focus and form a faint violet haze that can extend tens of arc seconds beyond the image boundary.

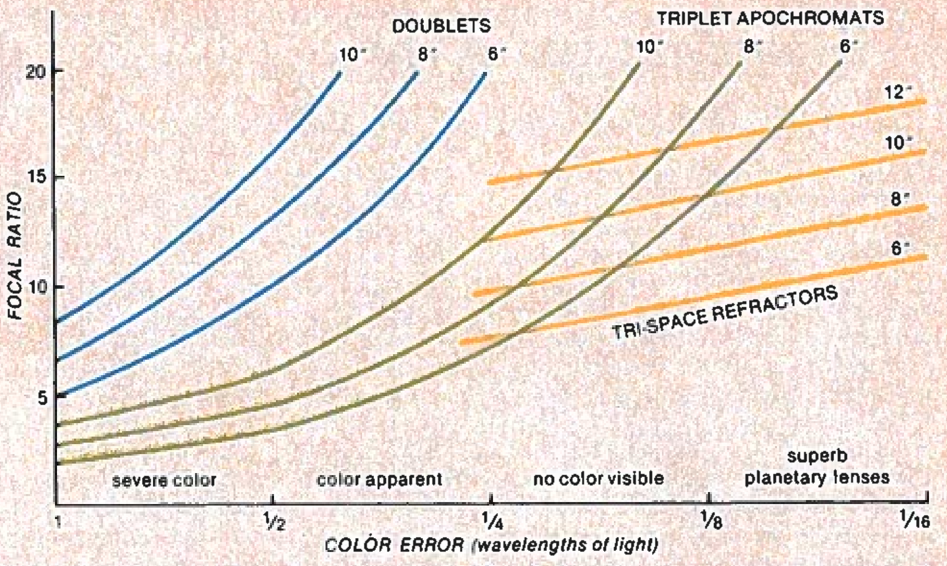
By going to more exotic glass, such as PKS-1 crown and KzFS-1 flint, we could cut the color error almost in half. But these are incredibly expensive and have undesirable chemical properties. Even better optically would be a combination of BK-6 crown and fluorite, to give a lens essentially free of color. But the last time I had a 6-inch fluorite blank quoted, the price was $1,500! Fluorite also has more than twice the thermal expansion coefficient of crown or flint, so designing the cell is a problem.

There is another way to reduce color error with two elements. We could choose a pair of glasses with almost identical dispersions and differing but little in refractive index. A good example is the 4¼-inch f/32 doublet described by Horace E. Dall in *Amateur Telescope Making — Book Two,* page 422. These steeply curved lenses are only practical when made of long focus, and they are quite tricky to center and align. At shorter focal ratios, the elements would resemble bowling balls.

Considering the wave nature of light (as opposed to ray optics), we want the *C, e,*




**In a properly designed achromatic doublet, yellow-green light (to which the human eye is most sensitive) has the shortest focus. Red and blue light rays come to focus together at a point slightly farther back.**

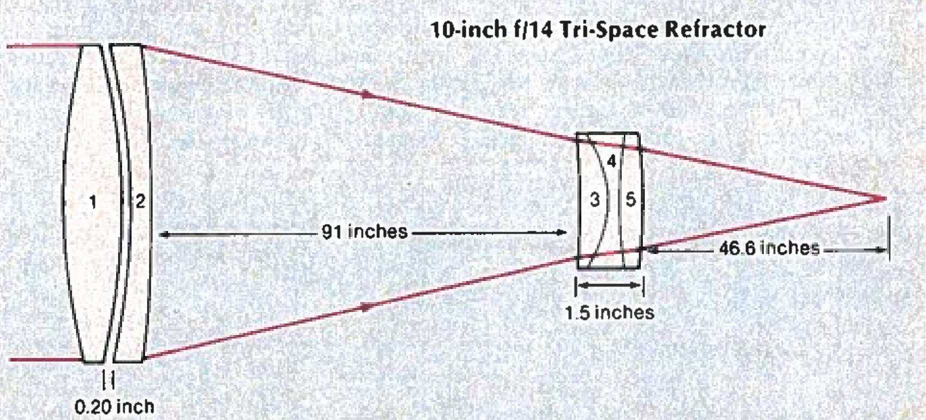



Roland Christen's chart shows that the f/15 rule of thumb for astronomical refractors needs qualification. A 3-inch f/10 doublet of the usual glasses has the same color error as a 6-inch f/20. To achieve really high performance without excessive focal length, a more highly corrected design with special glass is necessary. The color errors have been calculated from the longitudinal aberration and refer only to wavelengths between *C* and *F*.

and *F* colors to have minimal wavefront errors at some intermediate focus. The chart above plots the typical chromatic wavefront error for various apertures and focal ratios. It is divided into four regions, ranging from severe color error at the left to essentially none at the right. Errors of less than ¼ wave result in a white Airy diffraction disk. The curves show how quickly the secondary spectrum becomes noticeable in larger refractors, and why smaller instruments enjoy a decided advantage. In fact, 2-inch and 3-inch lenses can be made quite fast before color becomes obtrusive.

Note that a 5-inch lens of 75-inch focal length (f/15) should be quite free of visual color, and according to W. F. A. Ellison in *ATM — I* this is indeed the case. Such 19th-century lens makers as Alvan Clark and K. A. Steinheil made quite a few instruments in this size range, and the chart would suggest that the color correction they achieved had little to do with their skill as opticians. This is reinforced when you look through a larger Clark glass, such as the University of Wisconsin's 15-inch, and see gobs of color.

Still, ¼-wave color correction is not by any means ideal, and a residual violet haze detracts from really low-contrast subjects. James G. Baker, in a landmark paper entitled "Planetary Telescopes" (*Applied Optics*, February, 1963, page 111), emphasizes that for high-resolution planetary work a refractor should have considerably improved correction in violet, and that the




*Specifications in inches:*

1. Schott K-7 crown, diam. 10.4, thickness 1.00, $R_1$ +82.0, $R_2$ −51.0
2. Schott SF-2 flint, diam. 10.4, thickness 0.45, $R_3$ −51.85, $R_4$ −194.0
3. Corning B58-53 crown, diam. 3.5, $R_5$ −22.4, $R_6$ −4.0
4. Schott KzFS-N2 flint, diam. 3.5, $R_7$ −4.0, $R_8$ +16.0
5. Schott BaK-5 crown, diam. 3.5, $R_9$ +16.0, $R_{10}$ −21.5

wavelengths between *C* and *F* should not have errors much more than $\frac{1}{10}$ wave.

To meet such stringent performance with an ordinary crown-flint combination requires a very long telescope, reminiscent of the early mast-mounted instruments of Hevelius and Cassini. For example, a 6-inch f/100 doublet would work! At the more manageable f/15, we *must* resort to glass with abnormal dispersive properties. The facing chart shows how a triplet lens made with inexpensive BK-7, KzFS-N4, and BaF-N10 glasses can reduce the secondary color dramatically. Although costlier glasses can further reduce this error, lenses of large aperture would still require large focal ratios.

I would like to present a new approach to color correction that eliminates some of these problems and results in a less costly design. This concept, which I have dubbed "tri-space," makes use of a small color-correcting element installed some distance behind the main objective, the latter being just a normal achromatic doublet. The corrector is actually a sandwich of three glasses, with the abnormal-dispersion lens surrounded by two protective glasses. The fact that this element is smaller than the objective reduces the price considerably.

Several other advantages accrue with the corrector. The lens curves can be calculated to eliminate second-order aberrations such as spherochromatism, always present in closely spaced achromats. Also, field curvature and astigmatism can be reduced or completely eliminated. Most importantly, I found that a large lens can have a reasonably short focal length and still achieve a high degree of color correction. The yellow lines in the chart illustrate the superiority of this approach over ordinary doublets and even triplets.

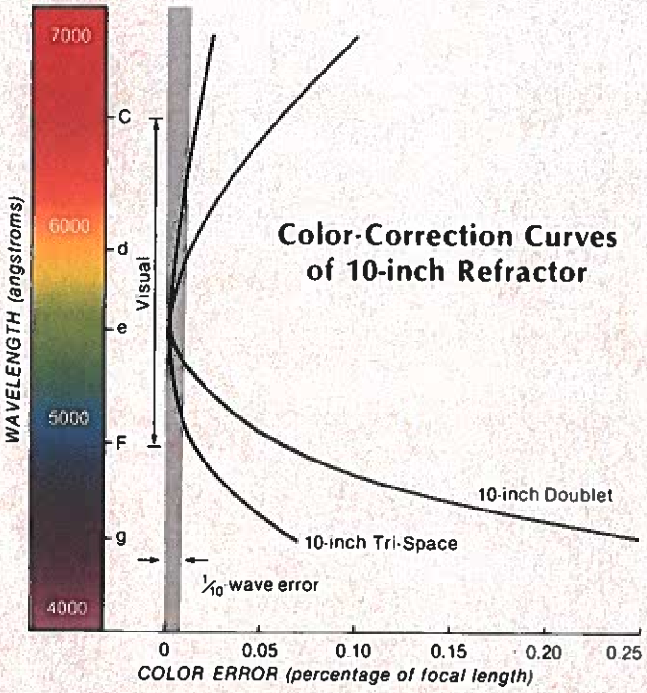
Many abnormal-dispersion glasses can be used to make the corrector. The most practical combination I found uses BaK-5, KzFS-N2 (Schott boron flint), and B58-53 (Corning-France). All three may be obtained from Glass Fab, P. O. Box 4724, Rochester, N. Y. 14612, at reasonable prices.

My first tri-space refractor used a commercial 6-inch f/10 Jaegers achromat and a 3.3-inch corrector placed some 30 inches behind it. This combination worked extremely well and was exhibited at the 1983 Stellafane meeting in Vermont. The 6-inch Jaegers lens by itself was very well corrected for spherical aberration. (It showed less than a $\frac{1}{16}$-wave error on my double-pass interferometer.) However, the achromat alone had the usual purple halo around bright objects, and the Moon showed a blue mist extending across the dark regions along the terminator.

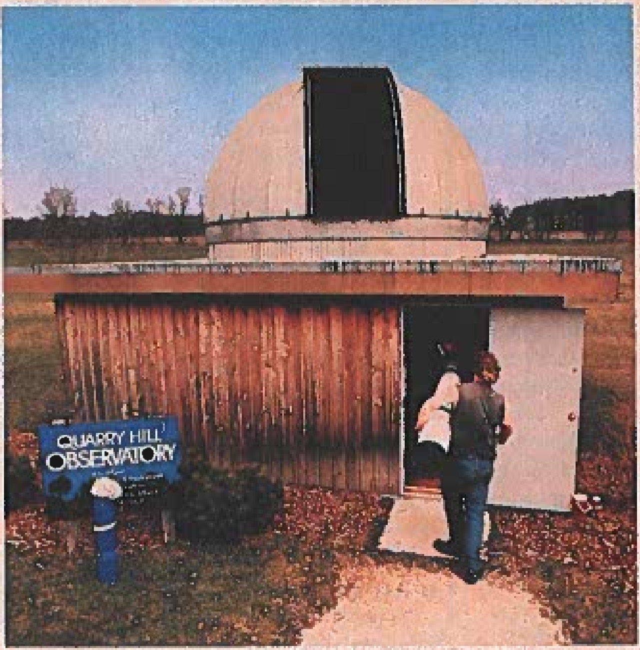
With the corrector in place, the Moon was pure white in the light areas and crisp black in the shadows of craters and mountains. Very subtle features were clearer and more pronounced. With the corrector, the faint violet haze normally seen at the Moon's limb was almost completely gone.

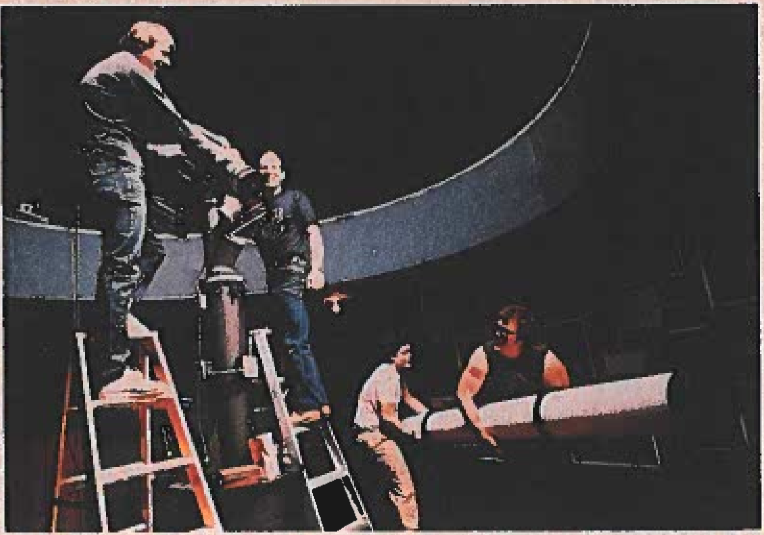
The success of this experiment inspired me to try a larger objective. For a long time our local club, the Rockford Amateur Astronomers, had wanted to replace the awkward 12-inch f/7 Newtonian reflector of the Quarry Hill Public Observatory with a more accessible instrument. We decided that a 10-inch f/14 refractor would fit nicely into the existing dome. In addition, the general public would find it much easier to look through, with the eyepiece near ground level. The 12-inch Newtonian, with nonrotating tube, had required a precarious climb and various body contortions to reach the eyepiece.

The design of our tri-space refractor is shown opposite. The front doublet is an




Color-error curves of the Rockford Amateur Astronomers' 10-inch refractor. Note that critical $\frac{1}{10}$-wave performance is achieved for a much wider range of colors with the subdiameter corrector installed. Such a corrector does not change the telescope's focal length, and could be built as an accessory for existing refractors. The author has even designed a 10-inch version that would greatly reduce the color error of the Yerkes 40-inch refractor!



These pictures of the 10-inch refractor's installation at Quarry Hill Observatory were taken by Wendy Vissar of the Rockford *Register Star*. In the view above are (from left) Roland Christen, Barry Beaman, Jim Elliott, and Mike Caldwell.

air-spaced Fraunhofer type corrected for spherical aberration and coma at the yellow-green visual peak. The glass was chosen not for any decided color advantages but because it is readily available cheaply. Both elements are very clear and highly transparent (with less than two percent internal losses, neglecting surface reflection). We had a very interesting time constructing the 10-inch doublet. Club members helped with the grinding and carefully monitored the curves with a precision spherometer.

The color corrector is a triplet with some fairly steep curves, but because of the small size it was not too difficult to construct. The elements are in contact and can either be cemented or oiled. Some very good cements are available today with characteristics much superior to Canada balsam. It is not wise to air-space this lens, owing to its extreme sensitivity to decentering.

The 10-inch f/14 refractor was dedicated on April 17, 1985, by officials of the Rockford city council and the park district. The observatory is open to the public every second and fourth Saturday of the month. The instrument works beautifully in all respects. A 60-mm ocular in a 2-inch cell gives almost a 1° field, providing good low-power views of deep-sky objects, while shorter oculars provide close-ups of the Moon and planets.

The corrector design presented here is by no means the only one. Many improvements can be made by increasing the power of the central element or by using other combinations of glass. Amateurs with computers might try to see how far they can correct achromatic lenses with different spacing and radii. I've already computed over 60 combinations, some of which exceed the color correction of fluorite lenses.

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*Facing picture:* The nine-day-old Moon formed a 1¼-inch-wide image at the 10-inch refractor's prime focus when Roland Christen took this photograph last May 28th. The Sun is just rising on huge Clavius, situated along the shadow terminator near the top (south). Fully 140 miles across, Clavius is the largest lunar crater visible from Earth. The 60-mile Straight Wall is a thin black line 3.7 inches from the top. The walled plain Ptolemaeus, nearly centered on the disk, contains the prominent 6-mile craterlet Ptolemaeus A. This photograph was taken on Kodak Technical Pan 2415 film.