HDTV lens design:

Management of chromatic aberrations

BY LARRY THORPE AND GORDON TUBBS

In the last article of this series, optical aberrations that are independent of wavelength were reviewed. In addition to these monochromatic aberrations, there are a variety of additional aberrations associated with colored light. They are, in other words, wavelength-dependent. They result from fundamental optical properties that vary with wavelength. All transparent materials exhibit this phenomenon. There are no exceptions.

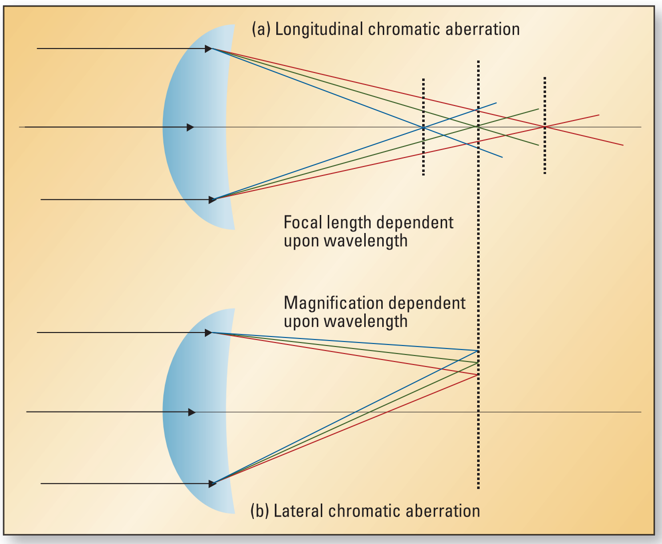

Figure 1. The two chromatic aberrations (in exaggerated form for visibility) for selected RGB wavelengths

Chromatic aberrations are the nemesis of the HDTV lens — especially in its small 2/3in image format embodiment. The real mischief ensues, however, when these chromatic aberrations are transformed into wide-band electronic signals in the HDTV camera and traverse sophisticated digital processing circuits. As mentioned in the last article, the HD camera is a fixed and disciplined system. There is not much it can do if the lens is the cause of mistimed RGB video signals, and the many RGB digital processes then have to contend with this stark reality.

The greatest HDTV lens design challenge: Chromatic aberrations

Different wavelengths of light encounter a different index of refraction within a given optical material. Nature was not kind here. The refractive index of *all* transparent media varies with color wavelength. The phenomenon is referred to as *dispersion*. A single lens element will accordingly form a number of images — one for each

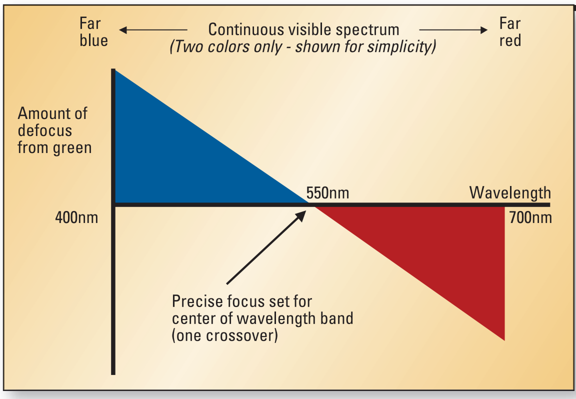

Figure 2. The primary chromatic aberration, where the chromatic lens is focused for the central green portion of the spectrum, and the opposite ends of the visible spectrum defocus differentially

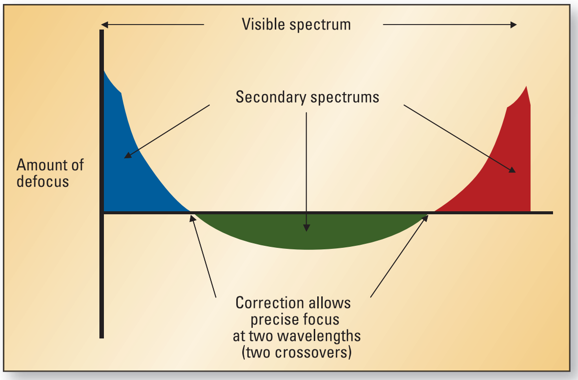

Figure 3. The effect of a compensating doublet having two distinct dispersion properties, allowing focus correction at two wavelengths.

and every color present in the light beam. These are technically described by two separately defined, but physically related, aberrations:

1) *Longitudinal chromatic aberration* — meaning different focus planes for each constituent color within the visible light spectrum.

2) *Lateral chromatic aberration* — the fact that the focal length of colored light rays varies, causing an associated variation in the lateral magnification. This in turn produces an effective misregistration between the constituent colored images.

Figure 1 illustrates the creation of these two chromatic aberrations in a simplistic form.

Longitudinal chromatic aberration

When white light passes through a lens element, the component wavelengths are refracted according to their frequency. This will result in a different focal plane for all of the different colors throughout the visible spectrum. Figure 1 illustrates this for three selected RGB colors within this continuous spectrum. For a subject point on the central optical axis, the various colors are also on that same axis, but different wavelengths come into focus at different points along that axis. Typically, the refractive index is greater for the shorter blue wavelength. Consequently, a single lens element acts like a prism in a sense and brings the blue end of the spectrum to a focus nearest to the lens.

Longitudinal aberration is, in essence, a tracking error. When the lens is focused for the green wavelength, the blue and red ends of the visible light spectrum become defocused as a result of this aberration. (See Figure 2.) This causes blurring on associated color details in the scene and a loss of sharpness in sharp luminance transitions. If the green ray is focused on the camera image sensor, then a circle of confusion will exist for both the red and the blue image. This is referred to as the *primary spectrum*. An uncorrected lens element is called a *chromatic design*.

Pairing lens elements made of different optical materials having equal and opposite dispersions is the most commonly used technique to reduce this phenomenon. Such a lens doublet allows two selected wavelengths to be brought into focus. (See Figure 3.) This arrangement is termed an *achromatic doublet*.

Having implemented this first order correction for two wavelengths, the residual is called the *secondary color spectrum*. (See Figure 3.) Here, the green center of the visible spectrum is behaving quite differently to the red and blue extremes. The longer the focal length and the higher the aperture, the greater the image impairment due to the secondary color spectrum.

Effective management of the lens chromatic aberrations calls for higher levels of correction. The use of three-group lens elements having different dispersion properties is called an *apochromatic lens group*. The number of corrections can even be raised to four — a system termed the *superachromat*. But, it is less important to achieve an increased number of zero crossovers (two are shown in Figure 3), as it is to manage the deviations of the colors between these crossovers. Controlling the secondary color spectrum to an acceptable level entails the use of special optical materials. A fluorite lens element combined with a wide-dispersion element can effect a useful degree of control over the central green spectrum — and today there are other options with new glass materials.

Following all optimization of the correction strategies, the residual longitudinal chromatic aberration unfortunately varies with focal length. This is a tribulation of *all* zoom lenses. A typical high-performance HDTV studio lens design goes to considerable technological lengths to ensure this variation is well controlled at the shorter focal lengths — but it becomes more difficult to curtail at the longer focal lengths. (See Figure 4.)

Lateral chromatic aberration

Dispersion also causes the image magnification to be a function of wavelength. This produces color fringing around sharply detailed edges and a degradation of the luminance Modulation Transfer Function

(MTF) that impairs overall picture sharpness. It produces in effect a registration error — as depicted in Figure 1(b) (on page 78). Minimizing this aberration constitutes the most difficult design challenge of all in an HDTV zoom lens.

Lateral chromatic aberration also produces a primary and secondary spectrum. Multi-element groups and use of special materials are deployed to control the secondary spectrum. Overall management of the simultaneous optimization of both longitudinal and lateral chromatic aberration in a modern zoom lens is a technological saga in itself.

Typically, from the viewpoint of the camera-output HD video, lateral chromatic effects are subjectively more visible than longitudinal chromatic aberration because of secondary effects stimulated within the camera RGB video processing system.

Lateral chromatic aberration increases from the image center toward the outer extremities. It is typically measured at a selected 3.3mm image height. (See Figure 5.)

Of all the lens aberrations, lateral chromatic is the most unforgiving. The problem is that it can subjectively be a visible impairment even with the tight tolerances achievable today. Some sense of the rigor of the specification for lateral chromatic aberration in a contemporary 2/3in HDTV studio lens is shown in Figure 6.

It is an especially difficult aberration to manage when lens elements are moving — as in zooming and focusing. Lateral chromatic aberration varies with focal length as the glass elements physically move during a zoom operation. (See Figure 7.) The aberration is generally greatest at wide-angle settings.

Chromatic aberration and the lens-camera system

It has long been recognized that the lens and the camera prism optics constitute a quite complex optical system. Fortunately for HDTV, this complexity was dealt with in an extremely timely manner before the 2/3in 16:9 image format became the mainstream optical format for HDTV cameras and camcorders. In addition to considerations of lens-camera resolution and color reproduction, it was fully recognized by all of the camera and lens manufacturers that chromatic aberrations were a regrettable impairment that could never be totally eliminated. The camera manufacturers and optical manufacturers worked within the Broadcast Technology Association (BTA) in the late 1980s to address all aspects of the 2/3in HDTV camera and lens interface — optical, mechanical and electrical. The studies included grappling with the issue of longitudinal and lateral chromatic aberration and its variances with focal length.

A key element within this standard was the agreement on a precision Flange Back dimension of 48mm (designed to accommodate future advances in prism optics). Another was the offset of the path lengths of the red (10 micrometers) and blue (5 micrometers) image sensors relative to that of the green imager. (See Figure 8.) These particular numbers emerged as a compromise between the different design aspirations of the various optical manufacturers, following a protracted examination of the many variables. While not a perfect solution, it has helped to alleviate the chromatic aberration challenge, to a degree, for all. This compromise was a key element in achieving the interchangeability of all HD lenses on all HDTV cameras (regardless of manufacturer) on the 2/3in image platform.

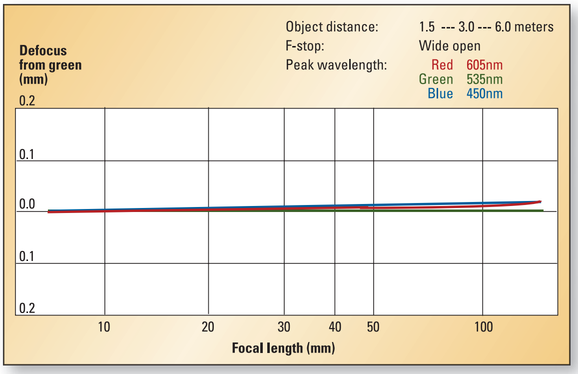

Figure 4. Longitudinal chromatic aberration changes of red and blue wavelengths (with respect to green) with focal length in an HDTV zoom lens — error typically being greatest at telephoto setting

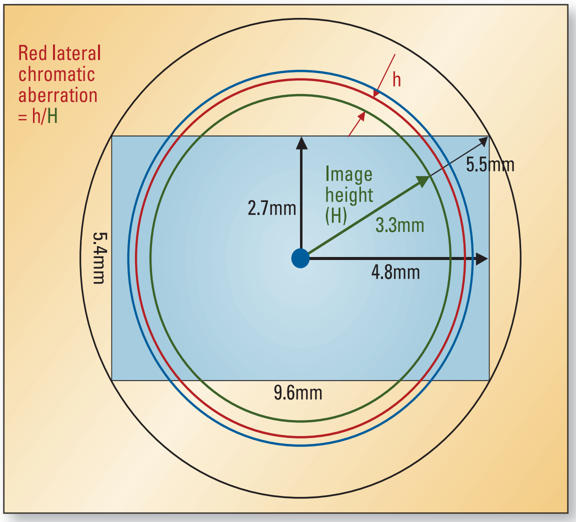

Figure 5. Lateral chromatic aberration (exaggerated here for visibility) is measured at a specific image height of 3.3mm within the 2/3-inch 16:9 image format

Lateral chromatic aberration and HDTV camera processing

The truly insidious aspect of lateral chromatic aberration arises because of what it can stimulate in the RGB video processing system of the HD camera. Lateral chromatic aberration from the lens means that the precision mounted imagers will create three video signals that have associated dif-

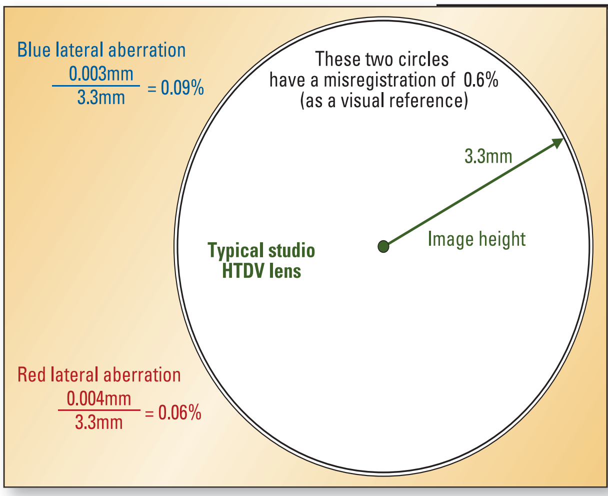

Figure 6. The two circles are intended as a 0.6 percent reference to convey a sense of the magnitude of lateral chromatic aberration in a contemporary HDTV studio lens. The actual red and blue aberrations are shown calculated.

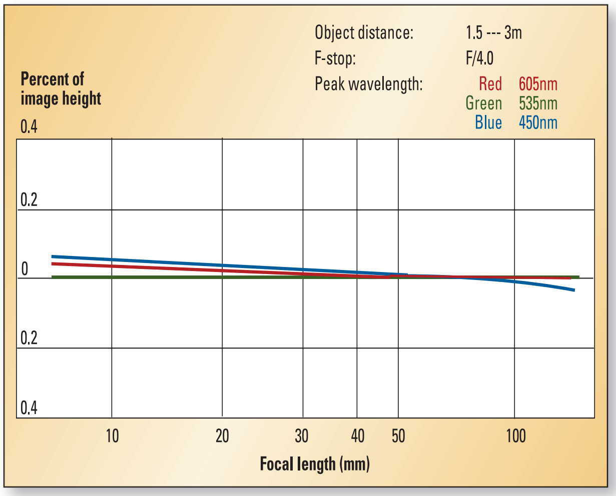

Figure 7. Shown here are lateral chromatic aberration changes with focal length in an HDTV studio zoom lens. This error is typically greatest at the wide-angle setting.

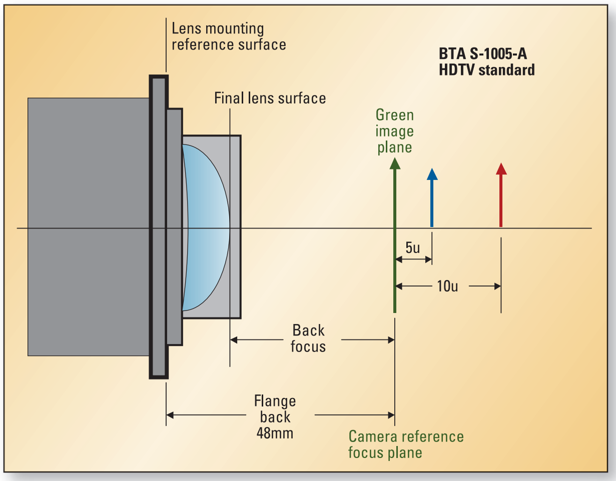

Figure 8. The physical offset of the red and blue image sensors that have been standardized for all 2/3in HDTV cameras — the 1994 BTA S-1005-A standard

ferential timing errors. It is a differential RGB timing error that the digital HDTV camera can inadvertently compound under certain conditions.

A sense of the artifact is illustrated in Figure 9. Assume the lens-camera is imaging a white background on which a small black patch is positioned near the image extremity where lateral chromatic aberration will generally manifest itself. Because of the increasing magnification of red and blue wavelengths relative to green, all of the optical transitions between white and black will be affected. The resultant mistimed optical output of the lens will now be transformed to a digital representation by the RGB image sensors of the camera. A single scan line through that patch as shown in Figure 9(a) will produce a video representation in the form of a horizontal white-to-black transition followed by a black-to-white transition as shown in Figure 9(b).

On the assumption that the aberration is progressively increasing toward the image edge, the delays on the second black-to-white transition will be slightly greater. When the three RGB video components are later matrixed to form a Luma Y signal, the white-black-white transitions will be colored in the manner shown — having a blue-magenta leading transition and a green-yellow trailing transition. In practice, because the transitions will actually have finite rise times (increased by the limited bandwidth of the digital video system), the edges will include more colors. Now, the meaning of the secondary color spectrum visibly manifests itself — as a color fringing contamination of that desired luminance reproduction of the original white-black-white scene.

The situation can be worsened by the fact that there are a variety of video processes that take place in the digital RGB processing system that are sensitive to any such differential timings between these three video signals. These are circuits that may be adding or subtracting these three signals from each other. They include linear matricing (for colorimetric control), image detail (for sharpness enhancement) and differential digital filtering (when Y, R-Y and B-Y components are formulated). Unfortunately, the associated mistiming is present in both the horizontal and the vertical domain (where different RGB processes occur). *It must be emphasized that the HDTV camera is not originating these errors.* The lens is doing that. The camera is, however, inadvertently *transforming* the differential errors presented by the lens. The magnitude and subjective visibility of the various color fringing effects that can result is a complex combination of the original lens error that stimulates these camera circuits — and the particular settings and adjustments in the camera proper. The visibility is highly dependent upon picture content.

Happily, based upon extensive experience, most scenes are benign in terms of their content. It is rare that chromatic aberrations become subjectively apparent on HDTV video originated in studio settings (although this can sometimes occur). While the chromatic aberration may indeed be present, it is generally invisible to the human eye even on a large HDTV screen. Outdoor shooting at wide angles, on the other hand, will occasionally encounter high contrast scene content, where the aberration becomes distinctly visible on the HDTV monitor. It is one of the realities of the small 2/3in HDTV image format that these impairments will statistically surface from time to time, and there is little that can be done to eliminate them. Lens manufacturers relentlessly continue to wrestle with this challenge in an unceasing quest to tame this optical shrew.

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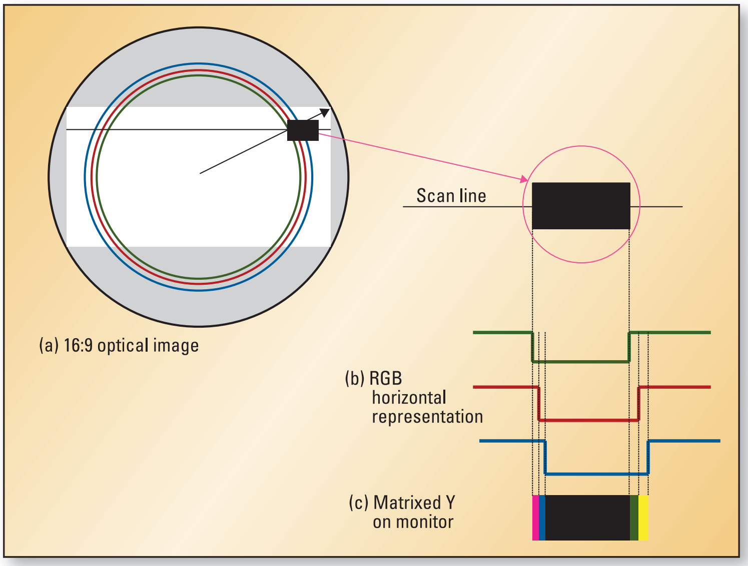

Figure 9. The creation of color fringing around a white-to-black followed by a black-to-white transition (in exaggerated form for visibility)

Summary

Lateral chromatic aberration remains the singular most daunting challenge to the 2/3in image format HDTV system. Contemporary specifications are nothing short of remarkable for such a small image format — a testament to the astonishing technological advances in optical design over the past decade. Yet, it can still, under certain shooting conditions, introduce a disturbing color fringing at the extremities of an HDTV image.

Many lens-camera evaluations have wrestled with this issue — and encountered frustrating experiences in attempting to make rational judgments on competitive cameras and lenses. Every combination of the lens and camera merely alters the nature of the color fringing affects that can appear under taxing test conditions. Although there are certainly differences in lens designs that will exhibit different design optimization strategies in dealing with chromatic aberrations — none are free of it. And, while differences in digital design strategies for RGB video processing in HD cameras will alter the transformation effects — they too can never avoid the inevitable picture impairments that are a consequence of the lens aberrations.

It is wise under such challenging circumstances to carefully test the contending lenses and cameras in the specific environment in which they will largely be used — carefully checking for these impairments over the most anticipated scene lighting, focal range, aperture settings and camera video processing settings. Better still if the test can include some test shots on the set where the system is ultimately intended for use.