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HDTV Lens Design: Management of Optical Aberrations

By Larry Thorpe and Gordon Tubbs

As discussed in previous editions of the "HDTV Lens Design" series in this publication, the design of a modern HDTV lens involves wrestling with an enormous number of variables. The goal of such design is an overall optimization of desired performance criteria (which often entails conflicts in design criteria) within the limits of various fundamental optical and physical boundaries. Powerful computers, advanced software, new optical materials, and refinements in manufacturing processes have made the remarkable overall performance of today's HDTV lenses possible.

Despite their excellent performance, however, these latest HD lenses are all still challenged by multiple optical impairments that can be collectively minimized, but never totally overcome. Optical impairments generally separate into two categories:

(a) *distortions* to the optical image (in shape and size);

(b) *aberrations*, which are image defects associated with the fundamental behavior of light rays passing through a lens element.

Ultimately, HDTV lens design strategy seeks to optimize all of these factors so that aberrations are reduced to an acceptable level and picture impairments are subjectively invisible.

Optical Image Distortions

Distortions are an inherent part of all lenses; they relate to the unwanted alterations to the overall size and shape of the image created by the lens.

Geometric Distortion

This is a distortion that alters the accuracy of the geometric representation of an object scene in the optical image plane. A distortion of the image shape—described as a *pincushion effect* (positive geometric distortion) or a *barrel effect* (negative geometric distortion)—and the amount of that distortion is generally expressed as a percentage of the picture height as outlined below in Figure 1.

Typically, a zoom lens will exhibit *barrel distortion* (considered a negative distortion) at the short focal length (that is, at the wide angle) and *pincushion distortion* (positive) toward the telephoto extreme. In addition, the wider 16:9 aspect ratio of HDTV imposes a more severe challenge to managing geometric distortion over the entire zoom range. Within the 2/3-inch image format size, a 1.5 percent level of pincushion or barrel distortion in a 4:3 image translates into almost 2.2 percent in the 16:9 format. This exacerbation of geometric image distortion in 16:9 widescreen is illustrated in Figure 1.

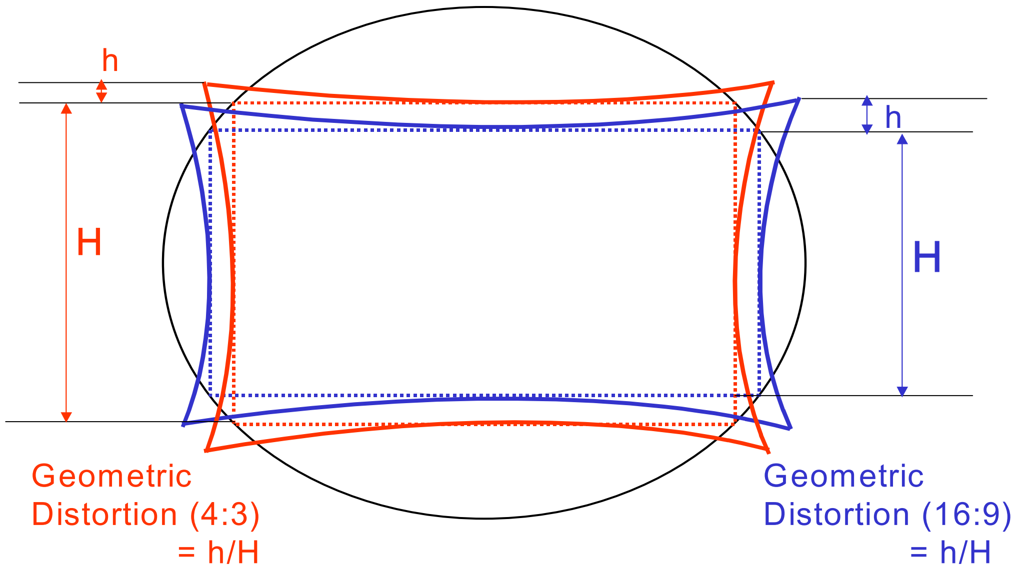

Figure 1: Shows the same degree of pincushion (a positive geometric distortion) for a 4:3 aspect ratio image and a 16:9 aspect ratio image—note that the percentage of distortion is visibly greater in the widescreen image.

Focus Breathing

This is not strictly classified as a distortion. In the eyes of practitioners, however, it behaves as an image distortion. *Focus breathing* refers to the phenomenon of the change in image size when operating the focus control. It is an unwanted alteration in picture angle of view that is a consequence of moving optical elements during focusing (an undesired result of zooming). While traditionally accepted in ENG shooting, it can be totally unacceptable in high-end drama and movie shooting.

Optical Image Aberrations

Optical aberrations largely arise from limitations imposed by fundamental optical physics, coupled with practical compromises that must be made in the overall lens design (and especially in the design criteria that relate to the very closely associated camera beam-splitting system). The degree of presence of the various aberrations is also a function of inevitable manufacturing tolerances related to each optical element.

(1) Aberrations that are Independent of Wavelength

It was long ago mathematically predicted that there are four aberrations associated with the passage of monochromatic (single wavelength) light passing through a single lens element. The geometric distortion described earlier is also an additional element within this prediction.

Defocusing Aberrations

There are four optical aberrations that can impair focusing. If a very fine point of monochromatic (single-wavelength) light is sent to a single lens element it will emerge with some degree of all of the four defocusing impairments described below.

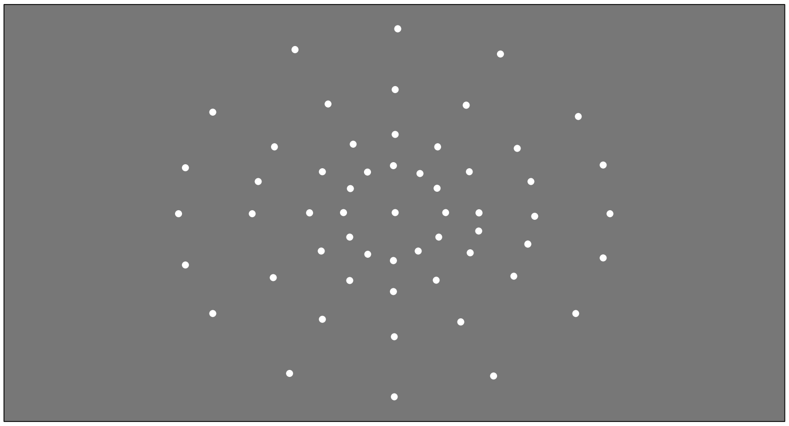

Figure 2: This dot pattern is intended to represent the light input to a lens system—consisting of an array of infinitely small point light sources that will stimulate the lens focusing aberrations.

Spherical Aberration
Relates to an aberration common to all lenses made up of spherical elements. It manifests itself as a differential focusing, with those rays (emanating from a physical point on the axis of the lens) that pass through the outer edges of the lens converging at a focal point that is closer to the lens than those rays that pass through the central optical axis of the lens.

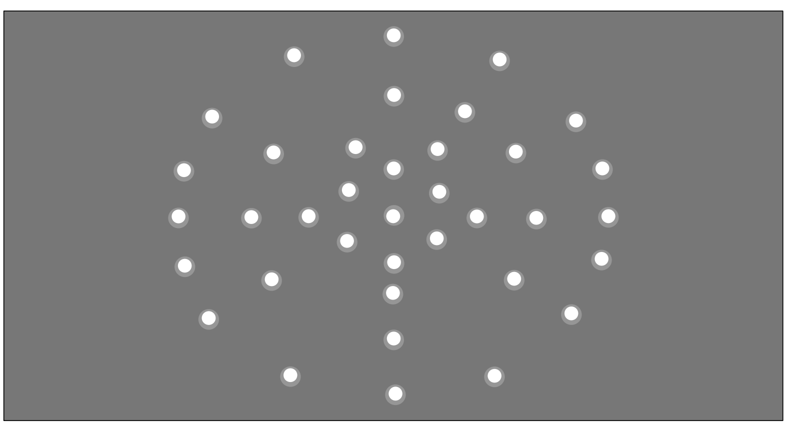

Figure 3: This shows spherical aberration (exaggerated for visibility) at the lens output.

Forming doublets of lens elements having equal and opposite spherical aberrations can considerably reduce spherical aberration. Recent aspherical lens element designs (a significant manufacturing challenge) have also contributed to reducing this problem.

Coma

When a lens is completely corrected for spherical distortion it may still create other forms of aberration on points in the scene that are off the central axis. If the rays from a point object are incident at an angle to this central optical axis they exhibit a comet-like tail instead of forming a focused point; such distortion is called *coma* or *comatic* aberration. The blur sometimes seen near the edges of the tail is often termed a *comatic* flare.

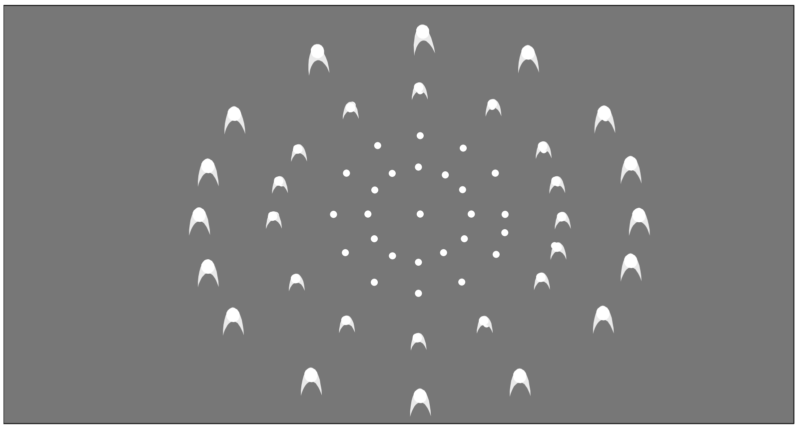

Figure 4: Illustrates (again in exaggerated magnitude) the form taken by comatic flare.

Curvature of Field

Relates to a defocusing phenomenon where the lens fails to focus a plane scene object as a plane optical image. When the center of that object plane is sharply focused the edges are out of focus. Conversely if the edges are symmetrically focused, the center of the image is out of focus. The lens, in effect, is forming the optical image in a bowl-like shape.

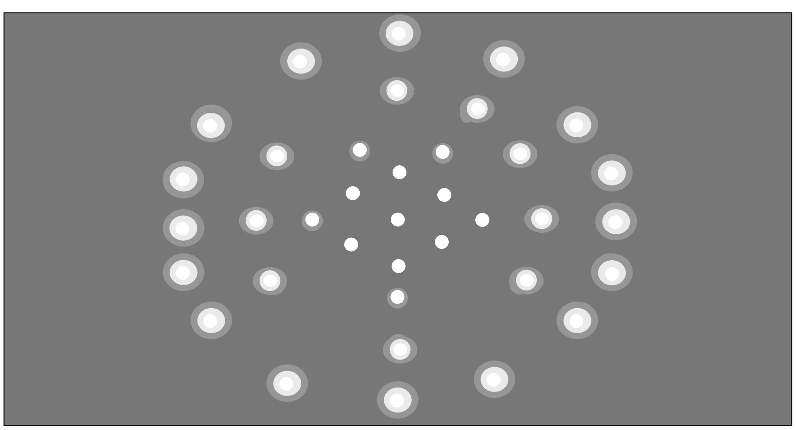

Figure 5: Note the progressive center to edge defocusing associated with curvature of field.

Astigmatism

A lens that has been corrected for spherical distortion sometimes will still not properly focus an off-axis point in the scene. Instead, the point adopts an elliptical shape or becomes a line in the lens-created image. Adjusting the lens focus, the image can change between two ellipses at right angles to each other—failing to achieve a sharp point focus. This is an aberration called *astigmatism*.

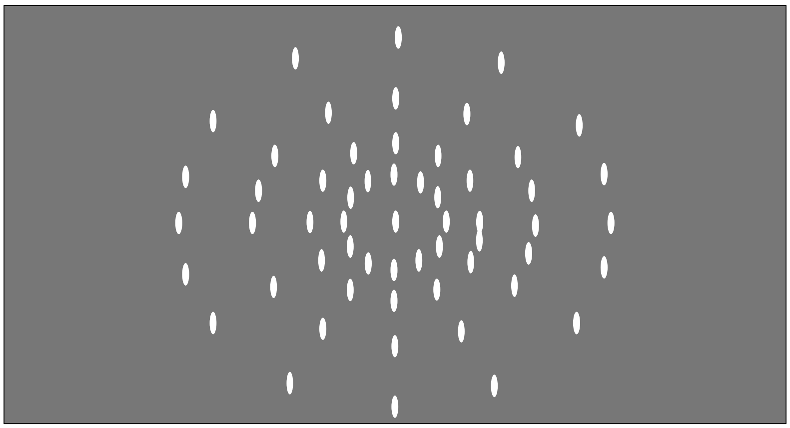

Figure 5: Showing an exaggerated case of lens astigmatism.

All of these four aberrations combine to detract from overall image sharpness. Controlling the degree of these impairments in a multi-element lens constitutes a crucially important second level of management of the MTF (Modulation Transfer Function) of the lens (the topic discussed in the article "HDTV Lens Design: Management of Light Transmission," *Broadcast Engineering*, 5/05).

(2) Aberrations that are Wavelength Dependent
In addition to the monochromatic aberrations just described there are a variety of additional aberrations associated with colored light—that is, these distortions are wavelength-dependent. They result from fundamental optical properties that vary with wavelength. These aberrations are the nemesis of the HDTV lens. But, their curtailment represents the toughest design challenge of all for the optical designer.

The Greatest HDTV Lens Design Challenge*: Chromatic Aberrations*
Different wavelengths of light encounter a different index of refraction within a given optical material. The phenomenon is referred to as *dispersion*. A single lens element will accordingly form a number of images—one for each color present in the light beam. These are technically described by two separately defined aberrations: a *longitudinal chromatic aberration* (different focus plane for constituent colors) and a *lateral chromatic aberration* (the fact that the focal length of colored light rays vary causes an associated variation in the lateral magnification, which produces an effective misregistration). Because this is an important and challenging topic within HDTV imaging it will be separately dealt with in some depth in our next article in this series.

(3) Aberrations in Light Transmission
In our previous article ("The HDTV Broadcast Studio Zoom Lens," *Broadcast Engineering* 1/05), we described the challenges of managing the amount of light flux transmitted through a lens, the spectral shaping of that light flux, and its distribution from center to picture extremities. We compared the *transmission* task of the multi-element lens system to a counterpart electronic-transmission system. Each has similar challenges in producing a final high-quality signal output

with minimum attendant impairments resulting from passage through their respective transmission systems.

As that light passes through the lens it is subject to a variety of impairments that can contaminate the darker portions of the optical object image. Such contamination of the black portions of an image can severely detract from the contrast performance of the lens, which, in turn, impairs the lens MTF (Modulation Transfer Function) and consequently, overall picture sharpness. The overall optical image can also be impaired with unique optical interferences created by the passage of strong light sources from the object scene.

These transmission impairments are, in a sense, an *optical "signal-to-noise"* issue. Just as the design of a digital HD camera system struggles to enhance all of those attributes that collectively ensure the highest quality video output while simultaneously attempting to submerge noise and other electronic artifacts (such as aliasing, shading, flare, etc.), so too, a similar technological struggle is inherent in the design of an HD lens system. Here, the *collective* of all of these light-transmission aberrations is analogous to the optical "noise" of the system.

As discussed in our previous article, additional degrees of freedom in managing the multiple variables inherent in lens design are facilitated if more lens elements are utilized. This does, however, increase the number of air-to-glass surfaces and this increases the total amount of reflected light from these boundaries. This reflected light will impact the camera image sensors in a variety of forms—as discussed below.

Flare

This is an impairment that can arise from strong highlights in the scene and is most obviously manifested in dark regions of the image. The highlights can interact with the multiple optical surfaces within the zoom lens, causing light-spread around sharply defined highlights. These highlights may even originate from regions of the object scene that lie outside of the specific picture being imaged. The highlights may also reflect off the interior lens barrel, or the iris blades, or even off the camera sensor itself. The advent of exotic multi-coatings on each lens element has provided a powerful means of alleviating these impairments. These coatings are thin transparent film materials deposited on the optical surfaces to reduce reflection and to increase transmittance. Multilayer coatings in high-performance have become more popular because of their increased protection. High-quality optical materials, extremely tight control of manufacturing tolerances, and carefully blackened internal mechanical surfaces must all be mobilized to lower this aberration.

Veiling Glare

This is an unwanted diffuse stray light that can abruptly "fog" across the image plane under certain imaging conditions, consequently detracting from the image contrast. It can be caused by scatter from optical element surfaces (usually the front elements), or reflections from the surfaces of iris shutter blades and the internal surface of the lens barrel. Again, precision optical design, special materials, exotic coatings, and tight manufacturing tolerances are all harnessed to control such interference. The appropriate use of a lens hood when shooting in strong sunlight is also an important protection against the possibility of out-of-image strong light interference.

Ghosting

Refers to the creation of a sharply defined reflection—caused by the sun or other unusually strong light source in the scene—that can stimulate a very complex series of reflections among the multiple lens surfaces. It often manifests itself as an image of the mechanical diaphragm that constitutes the iris control—and it usually appears in a position symmetrically opposite that light source (thus, manifesting a ghostlike appearance). In severe cases it can show up as multiple such images. Depending upon the lens, these images may be monochrome or separate colored reproductions. The ghost image can be introduced by the highlight source even when it is outside the picture area. To reduce such impairments, lens surfaces have special coatings applied.

Summary

By now it will be recognized that the very nature of the multi-element HDTV lens system is a far more complicated and unyielding system than a modern digital HD camera. The digital camera is quite technically disciplined (by virtue of precision fixed sensor structures and precision digital processing). In comparison, the lens is—by the very nature of optical physics—highly dynamic in its management of many parameters when dealing with a wide range of light levels and a wide range of focal lengths. As a consequence, design optimization strategies must vary considerably between categories of HD lenses (such as the larger long-zoom field lens, studio lens, and the portable EFP, ENG, and cine lenses). The specific application of these lenses determines the priorities assigned by the designers as they seek the best performance for each category.

Our next article will remain on the subject of optical lens aberrations and will examine perhaps the most vexing aberration of them all—the chromatic aberrations. These stem from the most fundamental of optical physics associated with any transparent material. Managing them to an acceptable level within the physical dynamics of a zoom lens has tasked optical designers for decades. In the context of the highly challenging imaging goals of HDTV—within the small 2/3-inch image format—the chromatic aberrations remain the most daunting image impairment of them all.

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