

HDTV LENS DESIGN:

Management of optical aberrations

By Larry Thorpe and Gordon Tubbs

As discussed in previous editions of this article series, 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 fall into two categories:

- Distortions to the optical image in shape and size.
- Aberrations, which are image defects associated with the fundamental behavior of light rays passing through a lens element.

Ultimately, the strategy of HDTV lens design seeks to optimize all of these factors so 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

Geometric distortion 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. (See Figure 1.)

Typically, a zoom lens will exhibit barrel distortion at the short focal length (i.e., at the wide angle) and pincushion distortion 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 2/3in image format size, a

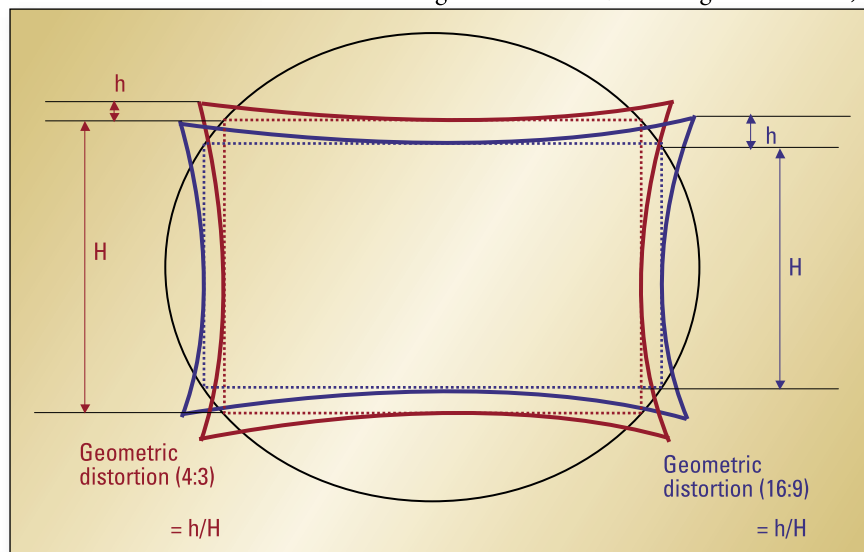


Figure 1. Shown here is the same degree of pincushion (a positive geometric distortion) for a 4:3 aspect ratio image and a 16:9 aspect ratio image. The percentage of distortion is visibly greater in the widescreen image.

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.

Focus breathing

Focus breathing is not strictly classified as a distortion. In the eyes of practitioners, however, it behaves as an image distorter. The term refers to the phenomenon of the change in image size when operating the focus control. Focus breathing is an unwanted alteration in picture angle of view that is a consequence of moving optical elements



while focusing. While traditionally accepted in ENG shooting, it is sometimes 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, especially in the design criteria that relate to the 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.

Wavelength-independent aberrations

Long ago it was mathematically predicted that there were four aberrations associated with the passage of monochromatic (single wavelength) light through a single lens element. Geometric distortion is an additional element within this prediction. If a fine point of monochromatic light is sent to one lens element (as shown in Figure 2 on following page), it will emerge with some degree of these four defocusing impairments:

- *Spherical aberration.* Spherical aberration relates to an aberration common to all lenses made up of spherical elements. (See Figure 3.) It manifests itself as 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 the rays that pass through the central optical axis. Forming doublets of lens elements having equal and opposite spherical aberrations can considerably reduce spherical aberration.

- **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. (See Figure 4.)

- **Curvature of field.** Curvature of field relates to a defocusing phenomenon where the lens fails to focus a plane

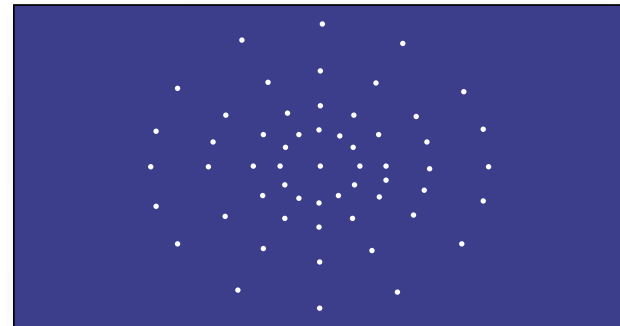


Figure 2. Light input to a lens element, consisting of an array of infinitely small point light sources that will stimulate the lens focusing aberrations

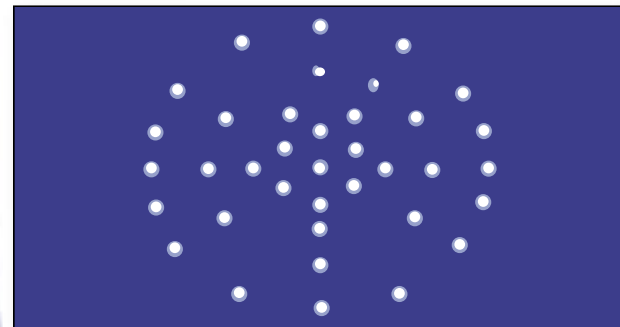


Figure 3. Spherical aberration (exaggerated for visibility) at the lens output

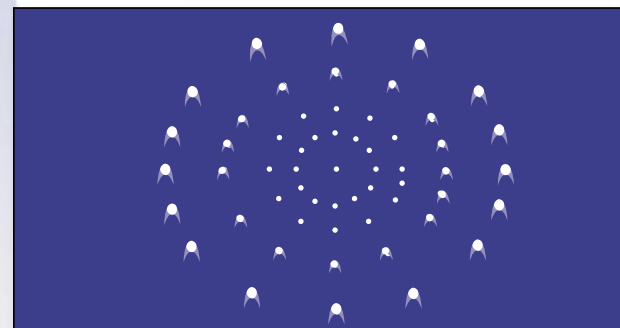


Figure 4. Comatic flare (exaggerated for visibility)

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. (See Figure 5.)

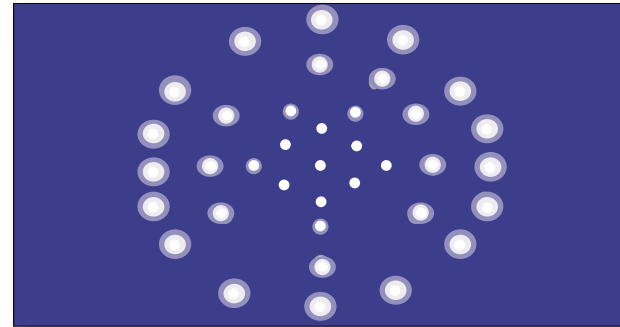


Figure 5. Note the progressive center-to-edge defocusing associated with curvature of field

- **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. (See Figure 6.)

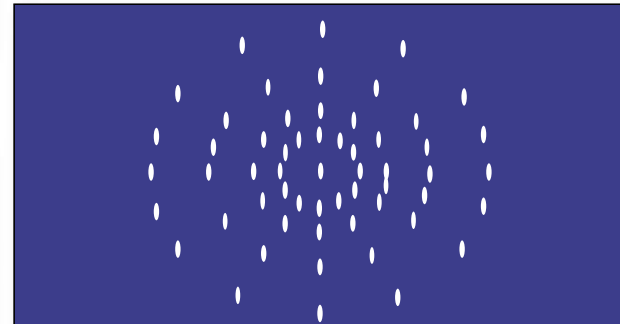


Figure 6. Exaggerated case of lens astigmatism

All four of these 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 modulation transfer function (MTF) of the lens.

Wavelength-dependent aberrations

In addition to monochromatic aberrations, there are a variety of additional aberrations associated with colored light; these distortions are wavelength-dependent. They result from fundamental optical properties that vary with wavelength. These aberrations are the nemesis of HDTV lenses. And, their curtailment represents the toughest design challenge for optical designers.

Different wavelengths of light encounter a different index of refraction within a given optical material, 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 aberrations: a *longitudinal chromatic aberration* (different focus plane for constituent colors) and a *lateral chromatic aberration* (focal length of colored light rays vary, which causes an associated variation in the lateral magnification, producing an effective misregistration). This complex topic of chromatic aberration will be treated in-depth in our next article.

Aberrations of light transmission

As light passes through the lens, it is subject to a variety of impairments that can contaminate the darker portions of the optical 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 and, consequently, the 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.

In severe cases, ghosting can show up as multiple images.

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, 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.

Additional degrees of freedom in managing the multiple variables inherent in lens design are facilitated if more lens elements are used. 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.

- **Flare.** Flare 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 to 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, the iris blades or even the camera sensor itself. The advent of exotic multicoatings on each lens element 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 lenses 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.** Veiling glare is an unwanted diffuse stray light that can abruptly fog across the image plane under certain imaging conditions, consequently detracting from the image contrast. 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 cause veiling glare. 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.** 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 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 ghost-like appearance). In severe cases, it can show up as multiple images. Depending upon the effectiveness of the lens design, these images may be monochrome or separate color reproductions. The ghost image can be introduced by the highlight source even when it is outside the picture area. To reduce such impairments, special coatings are applied to lenses.

Summary

By now it is recognized that the 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 technically disciplined. 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. The specific application of lenses determines the priorities assigned by the designers as they seek the best performance for each category.

Our next article will examine the most vexing lens aberration — chromatic aberrations. 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 — especially within the small 2/3in image format — chromatic aberrations are the most daunting image impairment.

Larry Thorpe is the national marketing executive and Gordon Tubbs is the assistant director of the Canon Broadcast and Communications Division.