

BROADCAST ENGINEERING 5/05 WHITE PAPER TUTORIAL

HEADLINE: HDTV Lens Design: Management of Light Transmission

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Broadcast engineers have a comfortable familiarity with electronic transmission (over the air or via cable). They understand related issues of channel transmission losses, interferences, reflections, ghosts, and other aberrations. The optical lens system, meanwhile, is in some sense a microcosm of the larger electronic transmission system with many direct parallels. Indeed, the optical system caters to a much higher frequency portion of the electromagnetic spectrum—visible light—than does its radio/television “cousin.”

The multi-element lens is all about light transmission. As we outlined in our previous papers, skillful management of MTF (Modulation Transfer Function) is an inherent part of contemporary lens design. So too, management of light transmission through two dozen or more optical elements is an equally complex task. In that context, two aspects of that transmission system stand out as being of primary importance: first, the amount of light that emanates from the output optical port of the lens is a measure of the sensitivity (or optical speed) of the lens in question; second, the shaping of the spectral response of that light in its passage through the many elements comprising the lens system has a direct bearing on the color gamut reproduction capability of the lens/camera system.

@Subhed:Further Optical Challenges in HDTV Studio Lens Design

In the management of the light flux passing through the lens optical system that forms the final image for presentation to the camera sensors, there are four core issues relating to light transmission that are inextricably intertwined. They are:

- 1.) *Transmittance* of the lens (the maximum amount of light it can transmit).
- 2.) *Aperture Control* (the calibrated iris mechanism to precisely control the degree of light passed by the lens).
- 3.) *Relative Light Distribution* (this refers to the inescapable limitation of an optical system; it curtails the degree of light transmitted at the peripheries of the image relative to that at the center of the lens optical system).
- 4.) *Spectral Transmittance* of the lens (the shaping of the light transmission between the blue and red wavelength extremities, which is a significant contributor to the colorimetric performance of the lens/camera system).

This examination will begin with the efficiency of the light transmission through the complex multi-element optical system that constitutes the studio lens.

Lens Spectral Transmittance

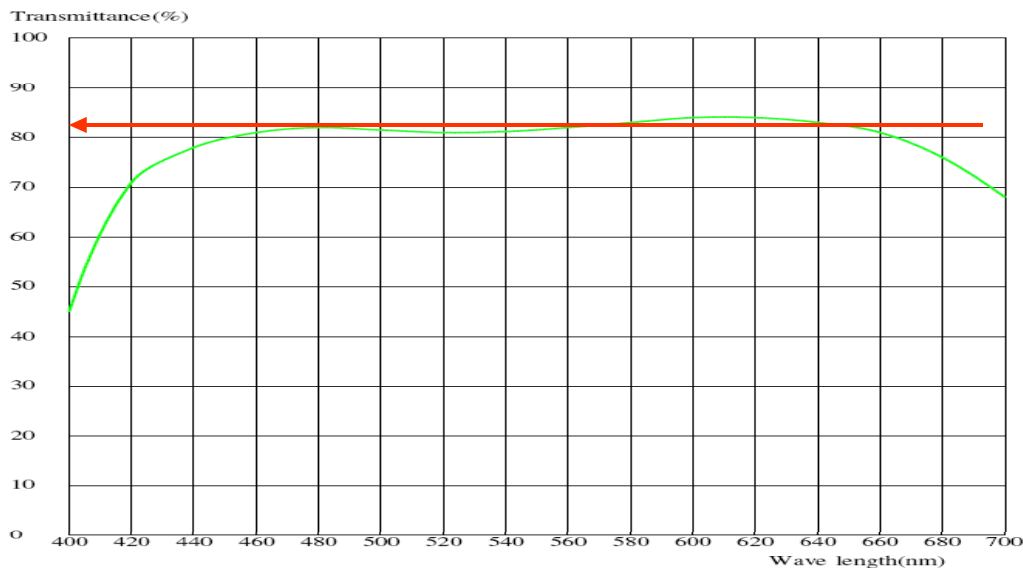


Figure 1: Spectral Transmittance of a typical HD Studio Lens, showing both the amount of light that reaches the output port and the attendant careful shaping of the spectral response.

The characteristic shown in Figure 1 is a typical high definition studio lens specification. It shows the spectral transmittance characteristic of an HD lens that exhibits an average transmittance of 82 percent. For a lens comprising in excess of 30 separate optical elements this is an impressively high number. Powerful computer-aided design, advanced optical element materials, and exotic multilayer optical coatings on each of those elements all contribute to this efficiency of light transmission.

A traditional optical measure that is used to define image brightness at the center of the lens output optical port is derived from the ratio of the lens' effective aperture (D) to the focal length (f). This quotient D/f is called the *Aperture Ratio*.

@Subhed:Aperture: Both Geometric and Photometric

The studio lens has a built-in mechanical iris system that facilitates remote control of the amount of light transmitted by the lens. This is a mechanically variable opening--or *aperture*--that alters the diameter of the group of light rays passing through the lens. This allows a known degree of control over the brightness of the image being formed at the lens output port. This important operational control is calibrated to facilitate the precise management of the light transmitted by the lens to the HD camera image sensors. This, in turn, facilitates the management of the lens/camera dynamic range when imaging scenes that have enormous contrast ranges. In the traditional television or video world these calibration steps are termed *F-Numbers*, and the nature of this control is known

as a *Geometric Aperture* system. The actual value of the F-number is the inverse of the Aperture Ratio--in other words, f/D .

@Subhed:*Geometric Aperture*

The F-number expresses the optical speed of the lens on the assumption *that 100 percent of the incident white light is transmitted through the lens*. This is impossible in the real world of lens design, as indicated in Figure 1. For video shooting this is of no great importance. The true merit of the F-number calibration is its quite accurate depiction of *changes* in light level for a given lens system. F-number values are expressed as a geometrical series starting at 1 with a common ratio of square root of 2 as follows:

1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8.0, 16.0, 22.0, 32.0

Each doubling of the number indicates a precise halving of the previous amount of light exiting the lens-output port. This relationship has long served the broadcast studio operation very well. It is very important to bear in mind, however, that given that the spectral transmittance of lenses made by different lens manufactures invariably will *not* be the same, any two such lenses having the same F-number may actually have different optical speeds. This needs to be carefully accounted for in any side-by-side test between different lenses (using appropriate *light meters*).

@Subhed:*Photometric Aperture*

The moviemaking world has always been cognizant of the true amount of light passed by the lens, and accordingly, lenses for film cameras have long employed an alternate calibration system known as *Photometric Aperture*. The new cine lenses for digital cinematography cameras also employ this method of calibration--one that is described by what are called T-numbers. T-number values take into account the reality that 100 percent of the incident light is not passed through the lens. It carefully factors in the transmission efficiency percentage of the lens. Accordingly, any two lenses having the same T-number *will* have identical optical speed. This calibration will be further examined in a later paper dealing with cine lenses for digital motion picture cameras.

@Subhed:*Relative Light Distribution*

This is a term familiar to optical designers and it refers to a physical phenomenon that is sometimes called *peripheral illumination*. The specified lens F-number indicates the brightness of a lens at the *center of the optical axis*. The brightness at the *edge of the image* is invariably less (due to the unavoidable vagaries of optical physics), and is expressed as a percentage of the center illumination. This peripheral illumination is affected by (a) by the 4Cosine law, and (b) by optical *vignetting*.

The 4Cosine Law--so familiar to optical designers--states that the rate of light fall-off in peripheral areas of the image (peripheral illumination) increases as the angle of view increases. This is true even for a perfect lens (if such could be

built). The amount of this fall-off is proportional to the Cosine of the angle (at which the light rays are entering with respect to the optical axis of the lens) raised to the fourth power.

Vignetting (caused by the physical fact that the lens mechanical barrel eclipses part of the peripheral light, which causes a 360-degree darkening of the edges of the optical image) can be eliminated if the diameter of the lens optics is sufficiently increased. Accordingly, it is less a challenge with the larger studio lens than it might be with the necessarily smaller diameter portable EFP/ENG lenses. Vignetting also decreases as the lens is stopped down (this also improves the relative light distribution problem).

Specification of Light Distribution

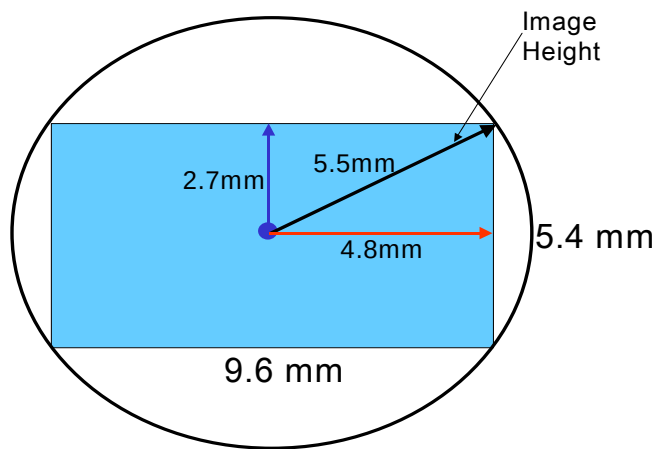


Figure 2: Shows the 2/3-inch HDTV optical image and how the light distribution is measured relative to the light level at picture center.

Relative Light Distribution is expressed as a percentage ratio between the center image brightness and that of off-axis points; this is traditionally specified along the radial termed “image height” as shown in Figure 2 above. A typical published specification for this optical brightness distribution is shown in Figure 3.

Lens Light Distribution

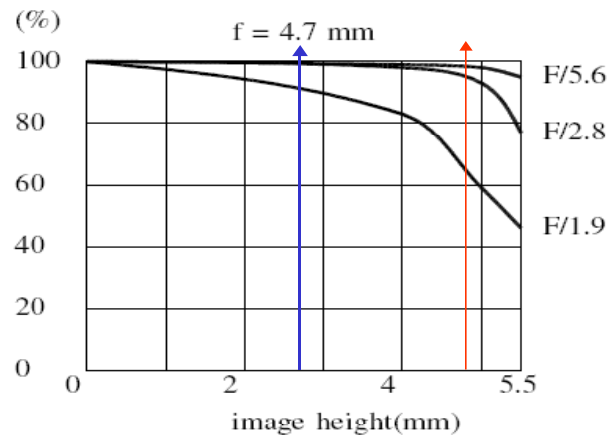


Figure 3: Shows the relative light distribution behavior for a typical HDTV studio lens at one specific focal length.

As is clear from Figure 3, the light-distribution shortfall is more acute when the lens operates at maximum aperture (iris wide open). The light distribution characteristic will alter when the focal length is changed (another totally unavoidable vagary of optical science) and the effect will increase toward the wide-angle setting.

@Subhed:Spectral Response and Color Reproduction

The goal of the lens-design team is to achieve a lens design that transmits the maximum amount of light, or, in other words, to minimize the attenuation of the amount of light entering the front port of the lens as this flux passes through all 30-plus optical elements. At the same time, those many elements that comprise the lens system must be optimized so that working in concert they shape the spectral response of the output light flux, predetermining, as it were, the color reproduction of the system. It does this by closely correlating with the separately specified spectral response of the camera prism beam splitter and the spectral response of the camera's CCD (or CMOS) imager.

The lens spectral transmittance curve is designed in close collaboration with the major camera manufacturers, because it must accommodate subtle variations in their respective shaping of their camera optical beam-splitter characteristics, the spectral response of their individual CCD (or CMOS) imagers (and associated IR cutoff filters), and the final design of their respective linear matrix circuits (that ensures that the overall lens/camera system colorimetric response meets the published standards of SMPTE 274M/296M and ITU 709)--as outlined in Figure 4.

While attempting to meet the nominal specifications contained in the standards (which incidentally, have no published tolerances) the lens designer also seeks to implement a spectral characteristic that will maximize the total

range of colors that can be reproduced by the lens/camera imaging system. The proprietary design techniques used by each optical manufacturer will invariably produce variances in this color gamut capability--and this can only be evaluated by careful subjective testing (a topic of a later paper).

Digital Motion Picture Color Reproduction

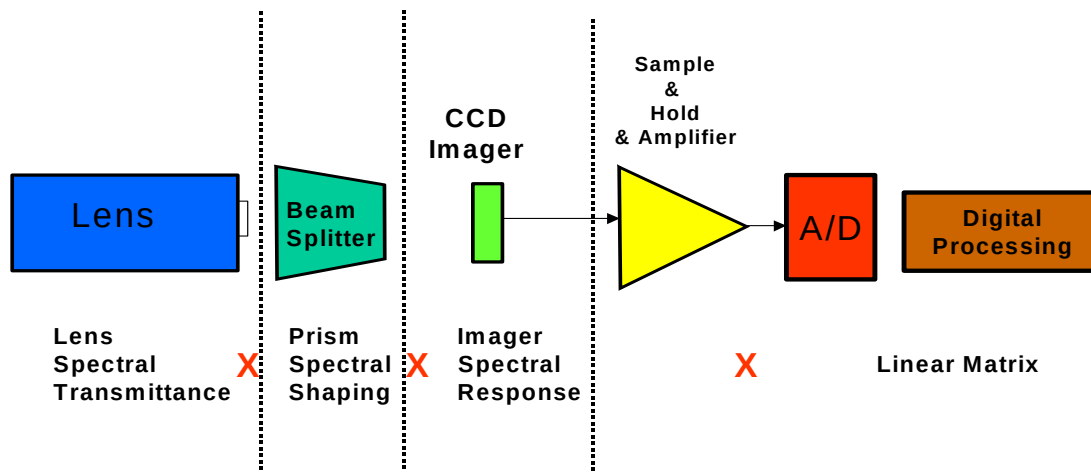


Figure 4: Outlines the four core elements of the HD Lens/Camera system that determine the colorimetry prescribed in the ITU-709 HDTV Production standard.

@Subhed:Summary

As stated in our second paper in this series, the contemporary lens is an engineering marvel. Our previous papers exposed the challenge posed to the optical designer in the all-important domain of preserving high image sharpness while the camera operator is exercising zoom, iris, and focus operational controls. At the same time as these factors are being optimized the designer is preoccupied with eking out every degree of transmission efficiency possible to raise the optical sensitivity of the lens. And, at the same time, the careful shaping of that spectral transmission characteristic must be crafted in concert with the separate design optimizations being wrought by different associated camera manufacturers. But, the challenge does not end there. As we will see in our next paper, while managing all of these design variables, the designer must simultaneously wrestle with an extensive list of optical aberrations and distortions that also vary--sometimes in a quite contrary manner--when the lens operational controls are exercised.

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