White Paper
#2

HDTV Lens Design

Broadcast Studio Zoom Lens

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Introduction

This second paper will begin an examination of the requirements and expectations for a series of distinct categories of high definition lenses presently used within the larger broadcast and production industries. The broadcast studio lens – long considered the “flagship” of high performance lens – will constitute this initial discussion. The HD studio lens will be scrutinized in some detail from two aspects: first, to illustrate the highly exacting science of contemporary high definition lens design, and second, to form the basis for the later discourse on some of the other key production lens categories.

The modern high-end studio lens is a marvel of optical science. In the case of high definition (HD) lenses it is a technological triumph. The lens designer must cope with an enormous number of variables in maximizing all of the important attributes that collectively contribute to the high imaging performance of the lens and—ultimately—to the final picture made by the HDTV camera with which it will be used. These picture attributes were described in our first paper in this series: sensitivity, contrast, color reproduction, and picture sharpness. Lens designers also face an unceasing struggle to minimize a variety of picture impairments that are a consequence of the nature and limitations of optical physics. They must control multiple optical aberrations that are inherent in any complex real-world lens system.

Right or wrong, it was decided long ago to radically simplify published specifications for broadcast studio cameras and their associated studio lenses. While this has probably saved the sanity of many a chief engineer perusing competitive specification sheets, it has also obscured intractable realities that still *must* be confronted by lens and camera designers. The contemporary studio lens is a very complex optical system, comprising – in the case of Canon’s HD studio lens – no less than 34 separate optical elements.

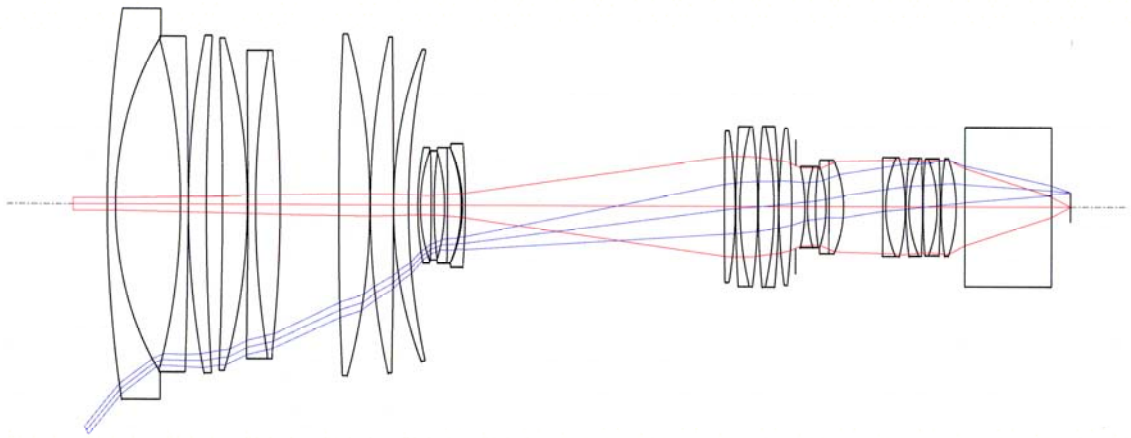

Figure 1 A typical HD studio lens – showing the concatenation of many optical elements required to implement all of the desired contemporary operational requirements

User requirements for a Contemporary Studio Lens

The modern television studio lens embodies three operational attributes that are of high interest to the broadcast program producer, and especially to the camera operator. They are:

- Image performance expectations
- Operational performance expectations
- Digital control of lens functions

Image Performance Expectations

The choice of a specific studio lens revolves around the user's assessment of the collective attributes of the lens that contribute to a superb picture performance (often a result of detailed competitive testing) while, at the same time, judging the degree to which the lens design has also minimized a multiplicity of inherent lens limitations and optical aberrations. End-user assessment can vary widely, which is why careful lens testing is essential prior to any purchase commitment.

Operational Performance Expectations

Operational performance expectations refers to the user's specific requirements in the context of the studio in which the lens will operate, such as the physical logistics associated with the studio set, the lighting levels anticipated, the desired angles of view and zoom range commensurate with the nature of the studio sets and shows, and possible other additional specific desires of the camera operator and director(s)

Digital Control of the Lens Functions

The Digital control of lens functions has seen continual progress with the evolution of remote-control systems for such primary operational functions as zoom, aperture, and focus, which have greatly empowered camera operators. Sophisticated high-speed servo systems have become highly refined and lens control greatly augmented by digital microcomputer technology. Precision adjustment of many of the separate interpretative lens controls further empowers camera operators by allowing management not only of the separate "dimensions" of image construction, but also of the speed, range, and optional nonlinear control characteristics of individual real-time adjustments. This further enhances creative control in news and drama studios, as well as for documentaries and live-event coverage.

Image performance

As stressed in our first paper the picture performance of a lens/camera system is largely predetermined by the optical image the lens presents to the camera's image sensors. Contrast, color reproduction, and picture sharpness have been optically defined and it is now the task of the HD camera to transform these (and other picture dimensions) into the digital representation dictated by the desired HDTV production standard (SMPTE 274M, SMPTE 296M, or the international ITU 709). No aspect of HDTV picture performance captures attention to the same degree as image resolution. As will now be examined, the role of the HD lens within the lens/camera system is of primary significance here.

Resolution and Picture Sharpness

While lens resolution is the most oft-discussed topic relating to HD lens performance, it is also the least understood. It is an extraordinarily complex topic. The perceived subjective sharpness of any television image is a complex convolution of the separate sharpness characteristics of the lens, the television camera, the display system – and finally, the human eye-brain system itself. Within this total system, the modern zoom lens represents, by far, the most challenging design task.

Camera Resolution

Before the advent of the contemporary solid-state CCD imager the HDTV television camera employed photoconductive pickup tubes. These imagers carried a great deal of technical "baggage" in terms of their picture impairments, and especially the vagaries of many of those impairments over the entire picture raster. The arrival of the CCD imager in 1992 [1] brought an entire new order to this former technical chaos, primarily because of the constancy of the image quality it produces all over the raster – from picture center to the corner extremes. This represented a tremendous advance in HD imaging. Regrettably, however, the constancy is *not* true of even the very best studio lens, as will be discussed below.

The modern television camera traditionally describes its contribution to picture sharpness with a specification for its "horizontal resolution", and sometimes, a separate specification for "vertical resolution" – but with little correlation between the two. This is a legacy of a long history in the evolution of broadcast studio camera specmanship. Today, for example, the typical HD camera will specify a depth of modulation at an agreed-to reference frequency – being 800 TVL/ph spatial frequency, or the related 27.5MHz electrical frequency (for the 1080-line system). Some HD cameras will separately quote a horizontal *limiting resolution* (the highest horizontal spatial frequency having a depth of modulation of at least 5%).

While very important in facilitating an easy method of measurement that establishes whether a given HD camera is meeting its resolution performance specification, these published numbers tell little about the actual picture sharpness performance of the camera. Instead, it was long ago established that visual picture sharpness must be correlated with the Modulation Transfer Function of the lens-camera system [2].

Modulation Transfer Function

The Modulation Transfer Function is a curve that describes the behavior of the *contrast* of different spatial frequencies – that range from low frequencies up to the highest spatial frequency that the lens-camera can reproduce.

The contrast of a low frequency black-to-white square wave (perhaps of the order of 50 TVL/ph) on a chart being imaged by the lens-camera system will be faithfully reproduced with no attenuation and will produce a full amplitude video level on a video waveform monitor. That becomes the reference contrast level.

As additional higher-frequency black to white square waves are imaged the level of the corresponding reproduced contrast will decrease relative to that reference level.

A multiburst chart that contains square wave frequencies ranging from that 50 TVL/ph reference all the way up to, say, 1000TVL/ph will produce a corresponding video envelope on the waveform monitor. It is as if the contrast level over this frequency range is being “modulated” by the lens-camera reproducing system. If this characteristic is graphed with spatial frequency as the horizontal axis (this can be in Line-pairs per millimeter as preferred by the optical engineer, or it can be in Television-lines per picture height as preferred by the video engineer), and with contrast as the vertical axis then the representation becomes a form of “transfer function” for this contrast modulation. Hence, the title Modulation Transfer Function (MTF) – see Figure 2.

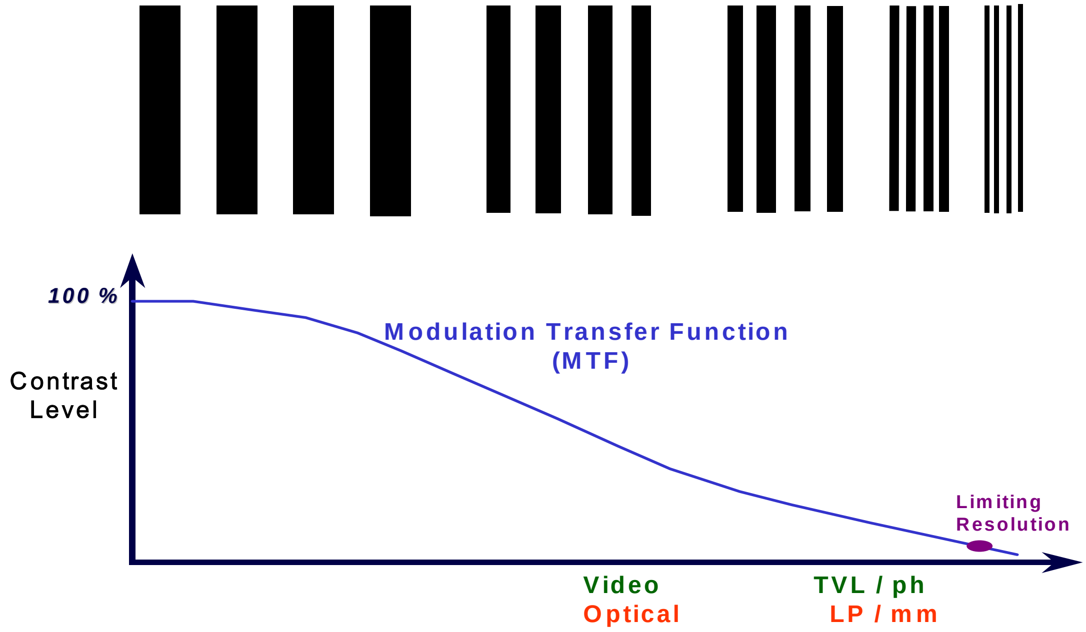

Figure 2 MTF is a representation of the behavior of the contrast level of increasingly higher spatial frequencies as they pass through an imaging system

Relationship between Lens-Camera MTF and Picture Sharpness

Reference [2] is one of the seminal works in the science of imaging. The tremendously important result of that work was the revelation that visual picture sharpness for any system involving distant viewing (such as television or cinema) is *proportional to the square of the area under the system MTF curve.* The implication of this is that the *shape* of the MTF curve over the useful passband of the camera is of vital importance to perceived picture sharpness. Indeed, it is much more important than the limiting resolution specification.

The picture sharpness of a given HD camera system is ultimately determined both by the shape of the MTF curve of the lens, multiplied by the shape of the camera MTF curve. The shape of that composite MTF curve below 800 TVL/ph – in the all-important range of 200-600 TVL/ph – is, in fact, the greatest determinant of the visual picture sharpness of that lens-camera system. The design of a studio lens must always factor this in by including optical innovations that enhance the effectiveness of reproducing contrast over this spatial frequency range–as outlined in Figure 3, below.

Because MTF is all about spatial frequency contrast levels, it is important to also note that the inherent optical *contrast performance* of the lens (the degree with which the lens can distinguish between different brightness levels and its ability to reproduce a true "black" with no light contamination) is inextricably bound up in the overall lens/camera picture sharpness performance.

Canon HD lenses utilize a variety of design techniques to produce both excellent contrast and as high an MTF as possible over this critical frequency range. These include the basic lens element design, the physical materials used to implement that design, and the all-important multilayer optical coatings used for each element of the lens.

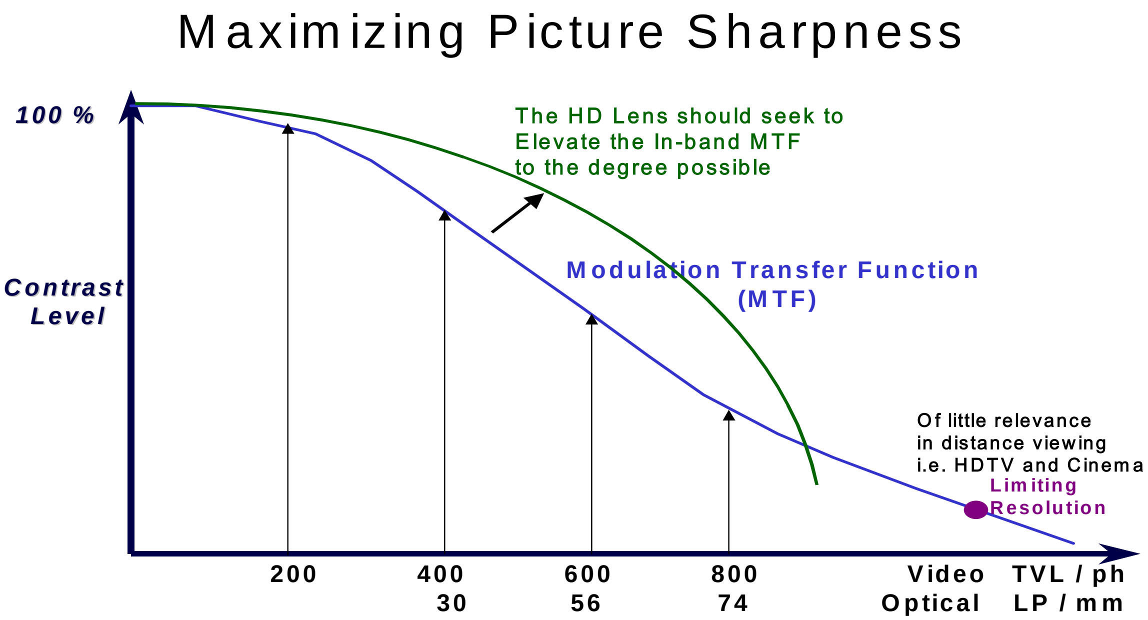

Figure 3 Generic HDTV Lens-Camera MTF curve – emphasizing the importance of an HD lens design that optimizes the MTF over the critical 200-600 TVL/ph range

A Look at the 1080-line and 720-line HDTV Studio Cameras

HD lenses do not distinguish between different HDTV production standards. They are all high definition – and similar MTF criteria apply. Figure 4 depicts a typical MTF curve of a 1920(H) x 1080(V) HDTV studio camera operating with a typical high performance HD studio lens. Contemporary 1080-line HD camera specifications generally specify a depth of modulation in the 40-45% range at the accepted reference spatial frequency of 800 TVL/ph (as depicted in Figure 3 below) – quoted as using a “typical” HDTV lens. But, these camera specifications make no reference whatever to the all-important depth of modulation at spatial frequencies of 200, 400 or 600 TVL/ph.

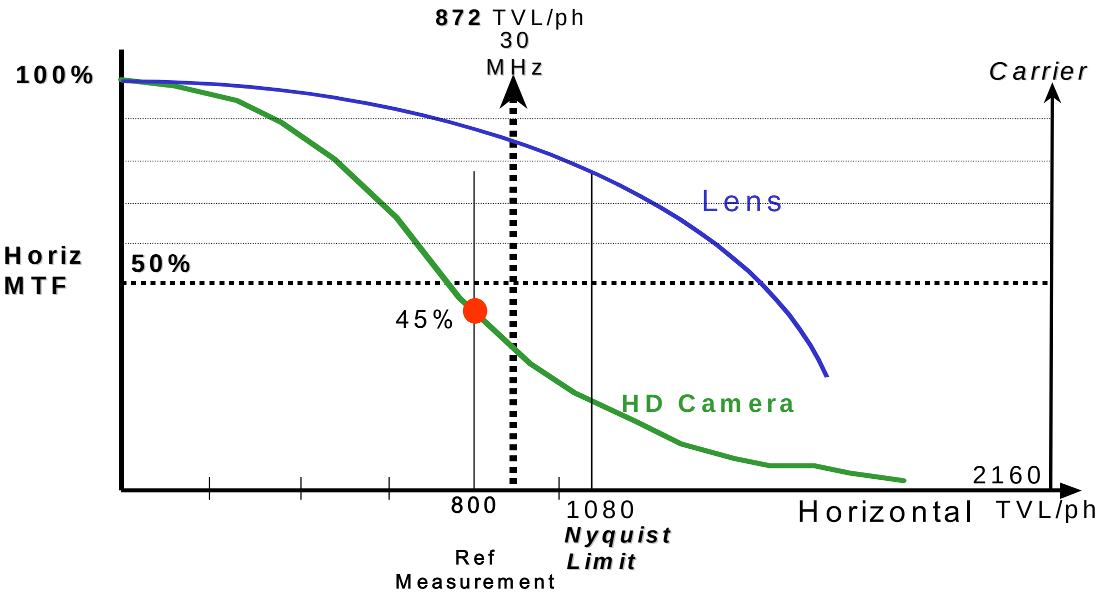

Figure 4 MTF measured at picture center of a 1080-line HD camera in with a typical HD lens. Generally, only the specification at the reference 800 TVL/ph spatial frequency is published.

The situation with the 720/60P system is more benign because of the trade-off of spatial resolution for the enhanced temporal resolution of the 60-progressive frame capture inherent to that system. As shown in Figure 5 the lens MTF will be high across the horizontal passband of this HD system – which is why a typical 50% depth of modulation is achieved at the reference spatial frequency of 530 TVL/ph (or 27.5 MHz in the video domain). Thus, the 720-line 60P system exhibits good subjective picture sharpness.

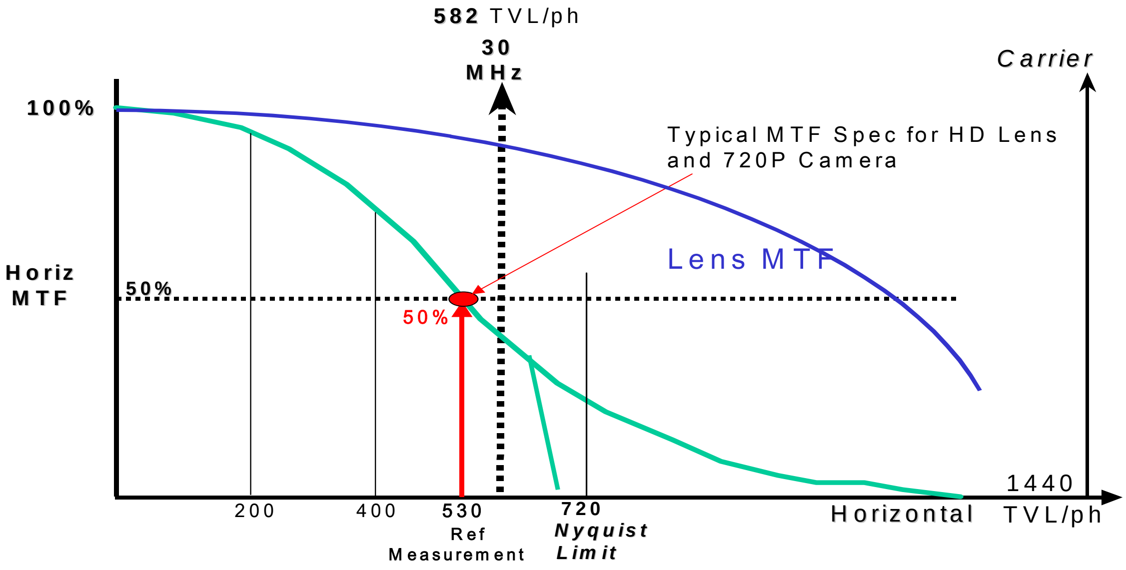

Figure 5 MTF measured at picture center of a 720-line@60P HD camera with a typical HD lens. Only the specification at the reference 530 TVL/ph spatial frequency is published

Enter Lens Realities into the Domain of MTF

The real picture performance of the camera system cannot be effectively established without fully encompassing the associated high definition lens. And here, the technical plot thickens considerably. While the HD camera resolution performance remains essentially constant all over the picture raster (being irrevocably determined by the spatial sampling of the imager, the optical low pass filter, and the electronic filtering employed prior to the camera A/D converter), the very nature of optical physics within the modern zoom lens system dictates that its resolution performance *is highly dynamic.* It is dynamic in three respects:

1. Optical design constraints, manufacturing tolerances, and the complexities associated with the concatenation of multiple optical elements within the studio lens system produce an MTF behavior that cannot be constant over the picture raster. There is an inevitable falloff in MTF from picture center out to the four picture corners.

2. Operation of the lens iris to control its aperture for different scene lighting conditions produces a variation in MTF – a fundamental of optical physics associated with diffraction phenomenon

3. Most important of all – the alteration of the lens focal length during zoom operation further alters the lens MTF

To manage these immense technical challenges, Canon's design optimization takes into consideration nine separate spatial reference points that are precisely defined within the 16:9 image plane – termed picture center, middle (four points) and corner (four points) – as shown below in Figure 6.

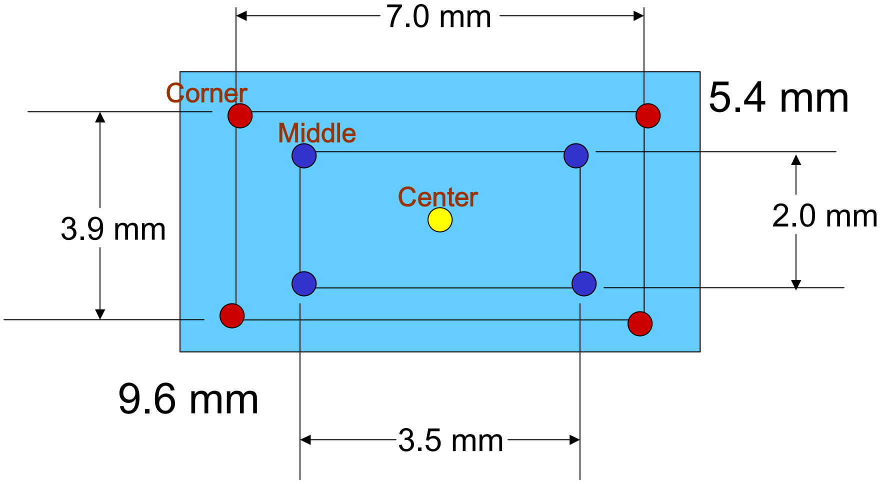

Figure 6 The three zones where computer optimization searches to achieve the best distribution of MTF during the design phase

Powerful computer optimization programs are harnessed to achieve the highest total MTF possible at all nine points for the overall thirty-four separate optical elements that comprise the studio lens system. This task is greatly escalated in complexity given that this optimization must also seek the highest MTF when the lens iris is being operationally exercised to alter the lens system's optical aperture. Further, system optimization is again sought when many of these optical elements are being moved in position relative to each other while altering the lens focal length during a zoom operation. The sheer number of variables involved in this design optimization is staggeringly large. Only an optimum overall compromise is possible under such conditions. It is testament to the prowess of modern computer-aided design techniques that a quite excellent performance in spatial MTF (with special attention to the 200 – 600 TVL/ph region) is the final achievement.

This dynamic nature of MTF is an inescapable technical reality for *all* lenses – regardless of manufacturer. Multiple optical physical constraints are in play here and they are all central to this universal optical reality. With respect to this daunting design challenge, the different lens manufacturers make their own proprietary design optimizations. Accordingly, there are certainly systemic differences in the necessary compromises made by each lens designer. *These differences are what should be explored in any HDTV lens testing prior to a purchase decision.*

Summary

Picture sharpness looms large in any assessment of high definition imaging performance. As has been emphasized, the lens plays a major role in this sharpness reproduction. It also predetermines the lens-camera contrast performance and plays a significant role in the system color reproduction. Given the extensive number of variables entailed in the HD studio lens optical system, the overall high performance of current lenses – at the price points seen today – is reflective of formidable engineering design prowess and superb manufacturing tolerance control.

The next paper in this series will continue with our examination of the HDTV studio lens – paying particular attention to the MTF distinctions between the HDTV and SDTV lens – and how MTF is technically managed as the various lens operational controls are exercised.

References

Ref 1 “HDVS CCD Camera – A Significant Advance in Real-time High Definition Imaging”
L.Thorpe, Y.Morioka, S. Kurita, N.Kawada
NAB Proceedings 1992

Ref 2 “Image quality – A Comparison of Photographic and Television Systems”
Otto H. Schade, Jnr.
SMPTE Journal, June 1987 Pages 567 – 595