A New HD Cine Zoom Lens for Digital Motion Pictures

By Fumiaki Usui, Jun Hosoya, Ken Ito, and Laurence Thorpe

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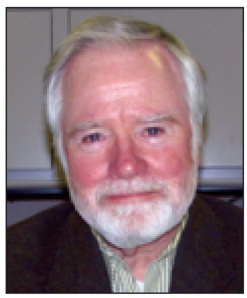

Laurence Thorpe

Digital motion picture production is expanding. Propelled by new creative flexibilities, the unceasing quest for enhancements to production workflow, and by diverse fast-moving technologies, digital program origination is clearly bound for unceasing evolution. The global standardization on the 2/3-in. image format size for high-definition (HD) production has added significant impetus to broadening technological developments in HD cameras and associated HD lenses conforming to this image format. At the same time, separate developments in the long-established and larger 35mm image format hold promise of elevating digital motion picture production to an even higher performance plane.

Portable high-definition (HD) lenses are currently being developed that today address an extraordinary diversity of production needs within the expanding mainstream 2/3-in. image format. Electronic field production (EFP) for television needs, electronic newsgathering (ENG), and cine (for digital moviemaking, prime-time television, and for television commercial production) are collectively driving separate design criteria for portable lenses that seek to optimally address the creative needs of these many different applications. These criteria encompass image performance, operational facilities, ergonomic, and physical imperatives—all uniquely tailored to their separate applications.

This paper will describe these design criteria as they apply to a new 5.5mm to 44mm T2.1 cine 2/3-in. zoom lens designed for the now increasingly popular digital 24P HD cameras (Fig. 1). This third-generation cine lens design reflects comments and suggestions offered by a number of prominent film directors of photography (DoP). The paper will outline the prioritized technical imperatives and the associated unique solutions that sought to support the recommendations of the DoPs.

Figure 1. The new 5.5 to 44mm T2.1 cine zoom lens.

Introduction

Digital motion picture production is rapidly branching into moviemaking, prime time television production, television commercial production, documentaries, independent filmmaking (in all of its manifestations), and a host of corporate, business, and industrial applications. That expansion, in turn, is broadening the development of a diversity of related digital acquisition, editing, and post-production products. It is also encouraging the emergence of a widening range of optical products related to digital motion picture production, such as cine prime lenses, cine zoom lenses, EFP videography lenses, optical anamorphic converters, and an associated proliferation of optical filters and accessories. This paper will describe the technical background underlying a new digital cine zoom lens intended specifically for high-end digital motion picture origination in the 2/3-in. image format.

Image Format Sizes for Digital Motion Pictures

Digital motion pictures ignited as a production alternative to motion picture film with the arrival of the first 24-frame digital high-definition system in 2000. That system was based on the 2/3-in. widescreen 16:9 image format and the internationally standardized 1920 x 1080 digital high-definition production standard.[1] The supporting cameras and camcorders are three-charge coupled device (CCD) imaging systems, which have since been joined by a variety of lower cost digital 24-frame systems—in the alternate high-definition 1280 x 720 standard, in a 4:2:2 standard-definition 720 x 480 system, and in a 4:1:1 standard-definition 720 x 480 system. In the space of a few years, a rapidly broadening family of 2/3-in. lenses is supporting all of these 24 frame/sec progressive scan television (24P) acquisition systems. It should be noted that the 2/3-in. image format translates to a circle having a 16.93mm diameter within which the actual 16:9 image format is centered, and this has a diagonal of 11mm. These include high-performance portable field production (EFP) lenses, as well as the emergence of cine-style lenses that are more reflective of the desires and imperatives of motion picture film cinematographers.

Large Image Format Systems

The past year has seen the birth of a higher level of digital 24P acquisition in the form of prototype digital 35mm image format cameras using single sensors (both CCD and CMOS) separately designed to variants of that image format (according to the separate 35mm styles described in the SMPTE 59 standard). The importance of these new-generation digital systems lies in their increased sensor spatial sampling, coupled with the inherently higher modulation transfer function (MTF) of the larger format lenses, thus producing an overall higher picture sharpness. In addition, there is the significant attraction of familiarity with this long-established 35mm optical format and the opportunity to continue working with the enormous existing global inventory of 35mm motion picture film lenses. However, the sheer breadth of the emerging digital production marketplace, and its many diverse tiers of budgets and creative aspirations, will likely ensure that a variety of image format sizes coexist in the long-term expansion of digital motion pictures.

The 2/3-in. Image Format as a Mainstream Digital Cine Format

While the emerging 35mm format digital motion picture systems will become increasingly attractive to the very high-end sectors of production (for major theatrical features, high-end commercials, and some television drama), it is still expected that the mainstream of digital motion picture production will continue to be based upon the high-definition 2/3-in. image format. This is due to a number of reasons. First, the enormity of the worldwide base of this internationally standardized format. Second, extensive present global inventory of 2/3-in. HD and SD lenses, and the increasing design prowess underlying ongoing developments. Third, unceasing evolution in refining the compactness of the many integrated camcorders—this collective drive on the 2/3-in. format overshadowing all other image formats. And, perhaps most important, the steadily lowering costs of these 24P cameras and camcorders, because of the substantial competitive impetus behind this format.

Cine Zoom Lens Family

Coexistence of EFP and Cine Lenses for Digital Motion Picture Production

Traditional television producers, directors, and camera operators (accustomed to video origination), as well as traditional studio producers, directors, and directors of photography (who have largely been shooting on motion picture film), in addition to the large freelance world of videographers and cinematographers, are gaining considerable experience in digital motion picture production. In turn, they are collectively driving extensive global developments in both EFP lenses and in cine-style lenses (and associated accessories). From the viewpoint of the lens manufacturer, both of these categories are equally important and require a family of related lenses. Collectively, they reflect many different production needs (optical and ergonomic), radically diverse production budgets, and a host of creative aspirations. Accordingly, new lens system designs will continue on both fronts.

It was early signaled that the adoption of digital motion picture production by the extensive community accustomed to shooting on motion picture film should be respectful of the long-established practices and craftsmanship of this community. Especially in single-camera shooting of dramas, movies, and television commercials, the techniques and production workflow on the camera sound stage and on location shoots are radically different from the separate disciplines of video shooting. The cine lens is central to that difference in being physically reflective of the collaborative working bond between the director of photography, the lighting crew, and the production director.

In 1996, a 2/3-in. cine style lens, the 5.2mm to 47mm zoom, was introduced. This was followed in 2001 by a new family of five high-definition 2/3-in. prime cine lenses and two cine-style zoom lenses (one wide angle ranging from 4.7mm to 52mm, and a second long zoom ranging from 7.5mm to 158mm). These products were used on many 24P HD digital acquisition systems across a range of productions. Many comments, criticisms, and suggestions spurred a major new development program that produced an entirely new family of second-generation prime lenses (comprising six separate lenses from 5mm to 55mm), and a companion new cine zoom lens in 2004. The latter is an entirely new addition to the family, being a 5.5mm to 44mm cine zoom lens, and embodies some novel new design concepts.

Basic New HD Cine Lens Design

The essential optical operational aspects of this new lens were chosen in the context of the two cine zoom lenses already available: the very wide-angle 4.7mm to 52mm and the long zoom 7.5mm to 158mm. Directors of photography suggested that a third cine lens system offering a broad attractiveness to the film cinematographer should be more modest in its zoom capability, have a wide-angle capability, and seek a high optical performance closely matching that of the new cine prime lens family. The design of the new lens was unique, compared to the earlier two cine zoom lenses.

Specific Performance Goals

The overall performance of the new lens placed high priorities on the essential optical attributes that directly bear on superior picture quality: contrast, spectral transmittance, and picture sharpness, while simultaneously seeking to ameliorate the impact of optical distortions that form an inescapable part of any optical design. Prominent among the latter are focus-related aberrations (such as spherical, comatic, and chromatic), geometric distortions, and relative light distribution. Among these design goals, the primary challenge lay in quantifying those attributes of picture sharpness and color reproduction that are especially appealing to the film cinematographer.

The incredibly close tolerances to which contemporary lens elements can be machined and polished endows the modern lens designer with the ability to mobilize more elements in a given lens system, and this, in turn, provides broader degrees of freedom in more effectively addressing multiple design parameters. This was exploited in this new lens design. Figure 2 provides an idea of the number of elements used.

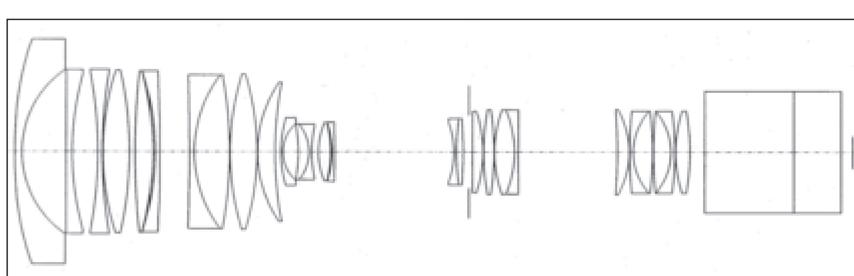

Figure 2. A profile of the more than two-dozen optical elements that constitute the new 5.5 to 44mm T2.1 cine zoom lens.

Image Resolution and Issues of Picture Sharpness

In all the protracted debates on imagery between the video and motion picture film communities, the topic of picture sharpness has long garnered the highest attention. This is not surprising. Certainly, 35mm film has long reigned as the yardstick of high-resolution imagery, as well as embodying other core attributes of high picture quality such as superb tonal and color reproduction. This excellent and long-established reference was inevitably destined to become the goal of any high-definition digital system aspiring to cine production. Both the HD lens and the HD camera must contribute to achieving that goal.

Video Resolution

While the video world has always spoken of resolution (and further segregated this into separate examinations of horizontal and vertical resolution) the film world has long used the term picture sharpness. The latter is a particularly pertinent term that speaks to the totality of the two-dimensional presentation of resolution. It also better infers the psychovisual stimulation of a viewer who is invariably some distance away from the theatrical screen or the home television set.

Quite different attributes of the detail information within a given image are at play within the inherent distant viewing encountered in the cinema theatrical environment or entertainment television viewing. This form of viewing is distinctly different from that involved in close scrutiny of a computer screen or the searching scrutiny of photographic imagery from a satellite. At any given viewing distance, the eye-brain system can only resolve a quite finite level of detail. The scientific community uses the term acuity to define this human visual capability. The average human can discern an object that subtends an angle of approximately one minute of arc. The viewing ratio defines the ratio between a given screen height and the distance of that screen from the viewer.

In video, spatial resolution is formally described as the maximum number of alternate black-and-white lines that can be distinguished in a dimension equal to the height of the image, with both the white and black lines being counted. The resolution is termed Television Lines per picture height (TVL/ph). It applies to both horizontal and vertical resolution. In optical terms, spatial resolution is used in terms of cycles per millimeter or Line-pairs per millimeter (Lp/mm).

Optical Resolution

The precision of detail reproduction within an optical image is determined by the intensity and the diameter of reproduction of the theoretical input point image. In practical terms, a tiny bright light point in the scene will incur some degree of blurring as it passes through a glass element, exhibiting a bright center surrounded by a light disk with radially decreasing intensity. Certain optical aberrations can compound this affect. The well-known spherical aberration (mathematically predicted by Seidel in 1856) produces a small hazy disk surrounding a point image. Comatic aberration (also Seidel) adds further flaring around a bright point image, but one having a defined tail pointing inward or outward. These aberrations can obscure extremely fine detail and significantly detract from overall image quality when they reach a certain level. This has been referred to as image unsharpness. As will be discussed in the paper, what was traditionally viewed as an imaging limitation, would be turned into a novel creative advantage.

Lens Contrast and Its Effect on Picture Sharpness

The term contrast refers to the ability of a lens-camera system to faithfully reproduce the blackest portion of an object scene being imaged, the very brightest portion of that same scene, and all of brightness levels between these two extremes. The challenge to faithfully do so starts in the lens. The many optical elements that comprise a lens can technically conspire to contaminate the black level by the introduction of flare (spawned from other brighter portions of the scene) and veiling glares. Highlights outside of the field of view can enter the lens as stray rays and create light interferences that can also invade black areas of the scene being imaged. At the other extreme, the peak highlights in the scene, those overexposed portions (sunlight glare off walls and glass in outdoor shooting or car headlights in night scenes) can create strong stray light rays and internal reflections that may introduce a variety of picture impairments.

Especially important, the primary exposed area of the image—that grayscale comprising all of the critical brightness levels between capped black and reference white (the 89.9% reflectance white chip on the standard gray scale chart)—must be faithfully reproduced if high picture quality is to be ensured.

The accuracy in reproduction of the reference low-frequency black-and-white burst on the resolution chart shown in Appendix 1, is directly a measure of the contrast capability of the lens and the associated camera. As discussed in the Appendix, the MTF[2] of the system is the modulation of the reproduced contrast level of successively higher black-and-white sets of bursts. Thus, contrast performance is inextricably tied to perceived picture sharpness.

A specific design goal for the new cine lens was to maintain that high contrast across the entire image plane, as this considerably augments the apparent picture sharpness in the corner extremities of the image.

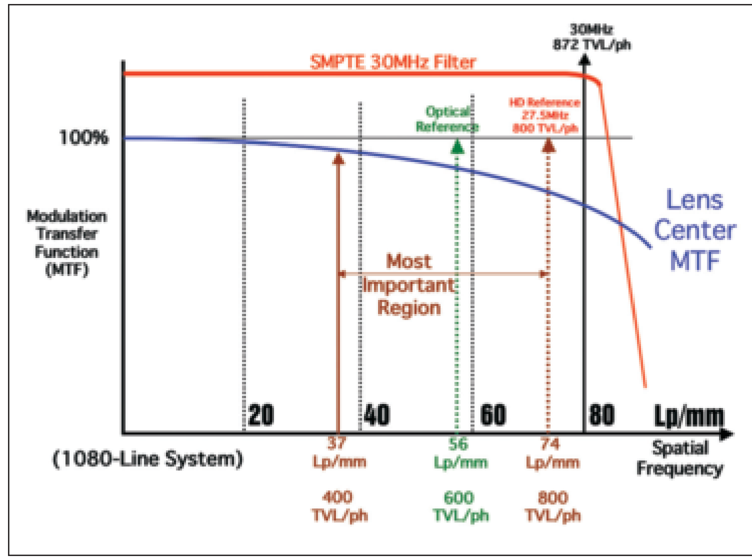

Figure 3. The tests revealed that the MTF characteristic in the region between 35 to 75 Lp/mm had the greatest effect in determining a given picture sharpness.

Picture Sharpness Imperatives as Defined by Film Directors of Photography

There is little doubt that those long accustomed to shooting with motion picture film cameras have acquired personal built-in subjective preferences on perceived picture sharpness that are often quite different from those of the videographers and studio camera operators who shoot exclusively with video cameras. Quantifying that difference into design criteria for digital motion picture systems has helped sustain a lively industry debate for decades, and represented a special challenge to lens design engineers.

Because of this challenge, and following the experiences of the earlier cine zoom lenses (some of which encompassed film directors of photography), it was elected that manufacturers work closely and collaboratively with chosen DOPs to attempt a more definitive establishment of criteria on a desired picture sharpness characteristic for the new generation digital cine lenses (primes and zoom). The discourse opened with a general agreement among the consulting DoPs that current cine lenses, in combination with contemporary HD camcorders, produced a visual perception of sharpness on the HD monitor that was "too hard." This was noted especially on close-ups of the human face with the lens aperture set close to wide-open (a popular setting for most DOPs). The task was to translate such a subjective verbal term into meaningful technical specifications.

It was initially believed that the differences in visual preferences could be effectively addressed by considerations of MTF, because MTF deals squarely with picture sharpness as actually perceived by the viewer at normal viewing distances (for television or cinema). The examination began with some initial test shooting using a digital HD 1080-line camcorder with the digital image enhancement systems entirely disabled. Thus, the fixed MTF of the camera itself remained an invariable throughout the series of tests, with a wide range of cine zoom and cine prime lenses. In some instances, optical filters were used in front of the lenses to further explore image sharpness criteria.

A considerable amount of viewing, on a large screen, followed the shooting tests. There was general agreement that the MTF characteristic of the HD lens-camera system in the 35 to 75 Lp/mm region was especially important to the look of the imagery, when viewed on a large screen. Paradoxically, some of the lenses having less MTF over this region, proved subjectively more pleasing to the DoPs. This region is shown in Fig. 3 in horizontal spatial resolution terms (also shown in relation to the bandwidth of the 1080-line HD system). This provided impetus to search for a technique that might somehow modify the effect of the high MTF in this lower portion of the passband, while preserving the desirable high MTF in the upper spatial frequencies (desirable because of the increasing MTF fall-off of the HD camera in this region).

Guidelines to a Desired Picture Sharpness in the Cine Lens

From this body of work, overall design guidelines were developed that collectively related to the sought-for subjective picture sharpness. These guidelines were outlined to the optical designers as follows:

(a) As high an MTF characteristic as possible—over the image plane.

(b) Criticality of achieving flat focus across the entire image plane.

(c) High contrast that is not compromised by flare or veiling glare.

(d) Contrast that is even across the image plane.

(e) Elimination of lateral chromatic aberrations (that blur and color detail transitions especially at the extremities of the image plane).

In terms of specific optical design parameters, these requirements translated into the following design tasks:

(1) Achievement of an effective picture sharpness characteristic—the central quest—per the guidelines established by the DoPs.

(2) Minimization of curvature of field—one of the classic optical aberrations that contribute to corner defocusing.

(3) Careful control of spherical and comatic aberrations.

(4) Minimization of lateral chromatic aberration.

(5) Minimization of flare and veiling glare optical interferences.

(6) Optimization of relative light distribution.

The Search for Acceptable Picture Sharpness for Digital Motion Pictures

The consulting DoP's description of the HD camera picture sharpness as being "too hard," required careful examination. MTF considerations alone would not produce the desired result. Appropriate optical pre-filters employed on the lens input port could be used to curtail the midband spatial MTF contributing to this excessive sharpness (Fig. 4). Experimental shooting quickly showed, however, that this takes an undue toll on the higher spatial frequencies, removing important textural detail.

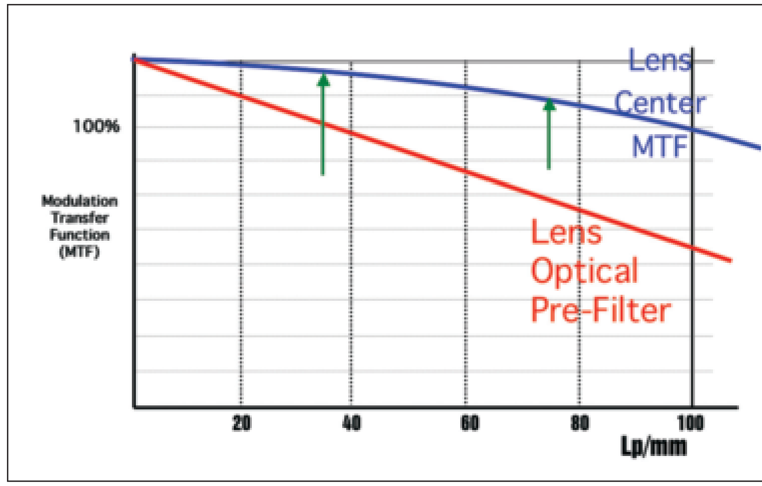

Figure 4. Optical prefiltering on the lens to adequately lower the MTF in the 35 to 75 Lp/mm region introduced too high a loss in the 75 to 100 Lp/mm region, because of the high rate of HD camera roll-off in this region.

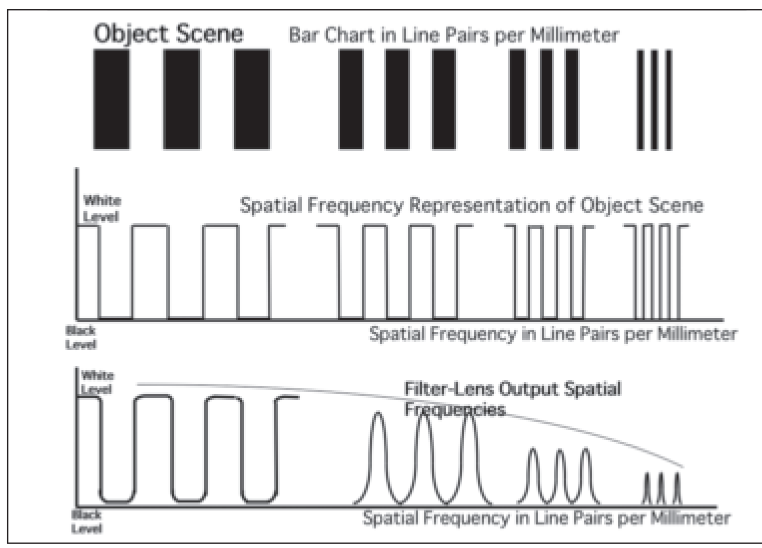

Figure 5. The drastic toll exacted on the higher spatial frequencies in terms of attenuated amplitude and significant spread-function are outlined by a traditional optical filter on the lens input port that seeks to curtail MTF in the lower 35 to 75 Lp/mm spatial passband.

Such a pre-filtering approach produces undue spreading of the image point function and significantly lowers the amplitude of the higher frequency detail signal (Fig. 5).

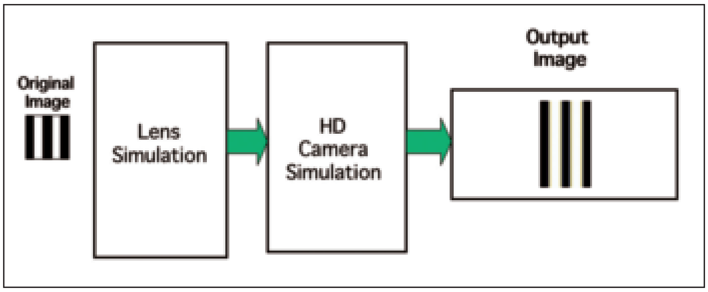

Figure 6. The principle of the computer simulation system employed, simulated both the lens and the HD camera, and presented the convolved results on a screen.

Computer-Aided Design of the Cine Lens

Computer simulation has advanced today to where lens designers can closely examine the various trade-offs involved in the optimization of MTF across the image plane, while also precisely controlling the balance between various lens focal aberrations. In particular, the simulation has advanced to where precise prediction of spherical, comatic, and chromatic aberrations is possible. This degree of design prowess offered a novel opportunity to address the task of designing a lens that, in combination with a digital HD camera, might come close to achieving the "look" desired by the DoPs.

From the viewpoint of picture sharpness, the design quest became a fourfold task:

(1) Maximize the MTF over the HD spatial frequency range of 0-100 Lp/mm.

(2) Minimize lateral chromatic aberration as this directly impairs lens MTF.

(3) Minimize comatic aberration to remove a visually objectionable form of image distortion.

(4) Optimize the level and the profile of the spherical aberration to synthesize an image point-spread function that would produce the desired subjective picture sharpness (when this is convoluted with the known MTF characteristics of both the lens and the HD camera).

The last point is the critical challenge in that it, of necessity, encompasses the HD camera. That unique picture sharpness, sought by the DoPs, involved the convolution of the camera MTF characteristic with the final adjustments made to the picture sharpness attributes of the lens. Fortunately, over recent years the simulation system has been progressively developed to do just that while allowing the overall HD lens-camera system color reproduction to be explored (Fig. 6).

The lens simulation system is highly sophisticated in terms of the number of design variables it can process. The output produced is sent into the HD camera simulator, which can accurately simulate the optical low-pass pre-filter, the beam-splitting prism, and the MTF of the CCD imagers. That analog output is passed through an analog to digital (A/D) conversion process, and relevant digital RGB camera processing is then simulated in the digital domain. The digital output of the simulator is then passed through a digital to analog (D/A) for final viewing. It is important to note that this image was projected onto a large screen so that final optimization could be viewed in the manner preferred by the DoPs.

The simulation design process involved three sequential steps:

(1) Optimization of lens MTF over the entire image plane.

(2) Minimization of chromatic lateral and comatic aberrations.

(3) Optimization of spherical aberration.

Computer Simulation Step 1—Maximizing Lens MTF

The final MTF optimization produced the lens performance shown in Fig. 7. It achieved an impressively

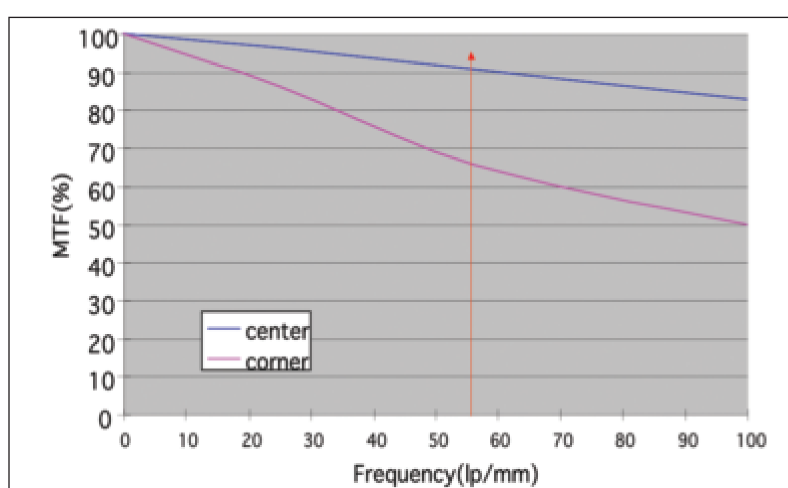

Figure 7. The MTF characteristic of the new 5.5 to 44mm T2.1 cine zoom lens.

high MTF (exceeding 90% at 54 Lp/mm, or 600 TVL/ph) at picture center over the entire 0 to 90 Lp/mm of the HD spatial frequency passband. The attendant success in maintaining that high MTF over the zoom range of the lens, and at different aperture settings, was accompanied by the inevitable MTF compromise in the image extremities. But, even here, a very respectable MTF of almost 70% at 54 Lp/mm was achieved in the picture corners.

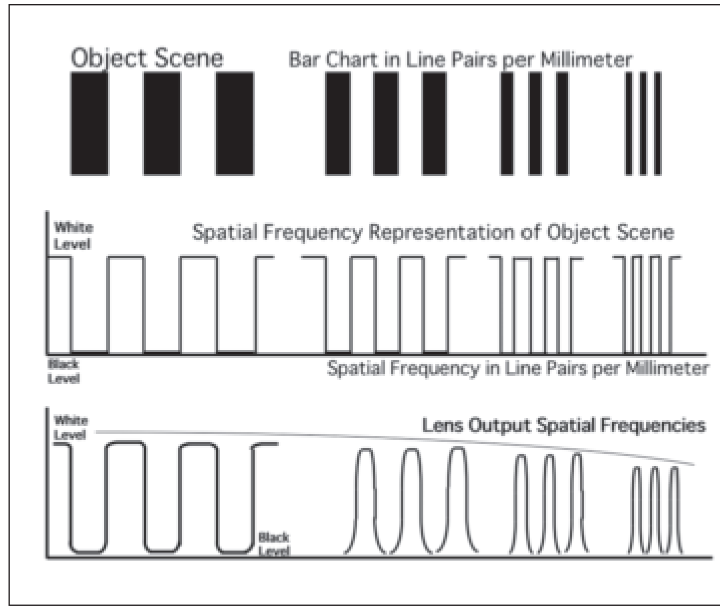

Figure 8. A simplistic illustration of the principle of synthesizing a lens point-spread function by maximizing the HD lens-camera MTF (producing high-amplitude reproduction of detail across the spatial passband) while simultaneously shaping the spherical aberration characteristic to introduce a carefully controlled spreading in the lower amplitude portion of the transition.

Computer Simulation Step 2—Minimizing Undesirable Distortions

A large amount of simulation effort underlay the quest to minimize the focal aberrations known as coma and chromatic. Elimination of comatic distortion (to the degree possible) was especially critical in achieving a point image profile (essentially removing the comet-tail characteristic of coma) that would support the final stage of optimization of overall picture sharpness. This simulation took into account the optical characteristics of a range of available optical materials, aspherical lens design options, groupings of lens elements, and associated degrees of manufacturing tolerances that would be required to minimize this aberration. A final result was achieved that virtually eliminated coma.

Lateral chromatic aberration involved a great deal of similar searching of optical materials, aspherical techniques, and the use of doublets, and manufacturing tolerances. And, again, quite excellent results finally emerged.

Every attempt was made to deal with the inevitable barrel and pincushion geometric distortion that accompanies the widest-angle setting of the lens focal length. Geometric distortion is especially daunting in the widescreen image format (a 1.5% level of pincushion or barrel distortion in a 4:3 image translates into almost 2.2% in the 16:9 format). The collaborating DoPs all urged as precisely accurate image geometry as possible, especially at the short focal lengths where a great deal of close-up shooting remains popular in contemporary filmmaking, and geometrical distortions tend to appear most visible.

A variety of optical technologies were mobilized to lower geometrical distortion, especially new aspherical lens-element designs, and the use of new materials for some of the more critical optical elements within the lens.

Computer Simulation Step 3—Achieving the Desired Picture Sharpness

Having maximized the MTF of the lens, and minimized the critical distortions, the next stage of the HD lens-camera system simulation focused on searching for a point-image profile that would hopefully produce the final “creative” portion of the simulation: a secondary modulation, as it were, of the MTF characteristic over the 35 to 75 Lp/mm spatial frequency region that would result in the special image sharpness look.

Spherical aberration, by nature, produces a small disk instead of a defined point from an object point image that is off-axis. This aberration is a consequence of those off-axis rays converging to focus at a point longitudinally before the focal point of a corresponding central optical-axis light ray. The quest for highest MTF in a lens design traditionally sought minimization of this aberration. The computer simulation, however, had become refined to where this effect could be controlled to a fine degree. This, in turn, allowed adjustments to the level and profile of the spherical aberration. In effect, it facilitated synthesis of a carefully defined point-spread function that could be adjusted to produce the desired "softening" of the spatial frequencies over the critical 35 to 75 Lp/mm spatial passband (when its effect was convoluted with the combined lens-camera MTF characteristic). The principle of this optimization is shown in Fig. 8.

The harnessing (and careful control) of the classic spherical aberration indigenous to all lens elements in the manner described is a novel innovation in cine lens design. It most effectively transformed perennial image impairment into an unexpected ally. It helped produce an HD lens-camera picture sharpness remaining faithful to the desired preservation of high-definition detail while simultaneously implementing a novel methodology to curtail the excessive sharpness in the visually sensitive 35 to 75 Lp/mm spatial passband. The optimization involved here remained empirical in the sense that the final design decisions were made on the computer, while results were subjectively judged on a large projected simulated image.

The final result achieved was to effect a lowering of the degree of sharpness—only when the lens aperture is set close to wide-open—to synthesize a look that produced an approximation to that of a 35mm positive release film when projected on a large screen.

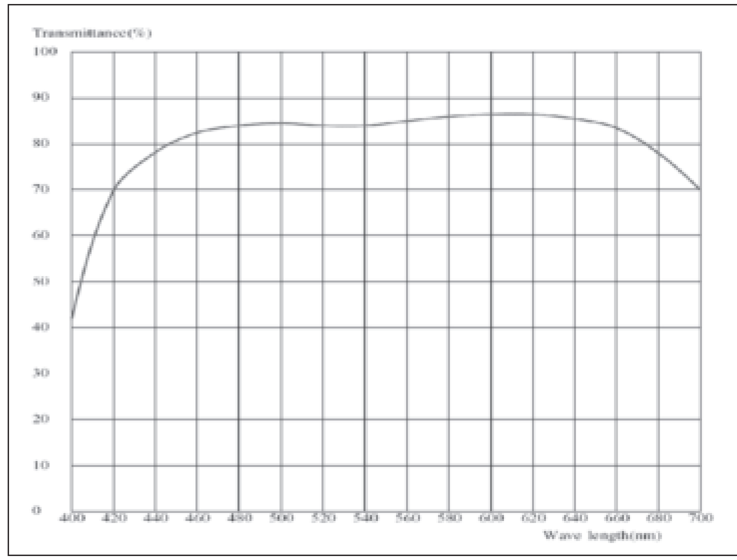

Figure 9. The final spectral transmittance of the new cine lens, achieving a 85% overall transmittance and careful shaping of the two extremes of the spectrum.

Spectral Transmittance

All of the cinematographers expressed a desire for the fastest lens possible, but consistent with some other important imaging attributes. These included a more subtle color reproduction of "soft" colors that the standard HD lens-digital camera did not seem to achieve. Maintenance of flat illumination across the image plane, especially at wide apertures was another expressed desire. All of these requirements relate directly to the spectral transmittance and the relative light distribution attributes of the lens.

Lens Optical Speed

All optical elements of a lens attenuate the light flux that passes through them. It is always, however, a question of degree. The larger the entrance glass port, the more light that can be transmitted, but size and weight rise rapidly with lens diameter. This particular new cine lens was intended to be very portable, so a final lens diameter of 95mm was settled upon at the outset.

Modern optical materials and the exotic coatings available today, ensure that the light attenuation can be very effectively minimized. Multilayer coatings were used on all elements of the lens. Still, the fact that the cine zoom lens comprises a multiplicity of such elements does define a certain overall attenuation that is difficult to reduce. This bears directly on the sensitivity, or the photometric aperture-specification of the lens.

The final transmittance achieved in the new cine lens was of the order of 85% across most of the visible spectrum (Fig. 9). This endowed the new cine lens with a photometric aperture specification of T2.1, which holds throughout most of the zoom range, dropping off slightly to T2.2 at the zoom extremity. The photometric aperture (using the lens iris control) control range is T2.1 to T16. It should be noted that the advantage of the T-number versus the traditional video F-number specification is that the latter is an accurate method of calibrating changes in light levels but is not an accurate absolute measurement because it assumes 100% light transmission through the lens. The T-number, on the other hand, factors in the actual transmission efficiency of the lens and produces an accurate absolute measurement of optical sensitivity. The F-number and T-number are mathematically related according to: F-number = T-number x square root of transmission percent/10. As an example, for this T2.1 lens, Fig. 9 indicates an average transmission of 85% and, accordingly, the equivalent F-number calculates as 2.1 x 9.2 (square root of 85) divided by 10 = F 1.9.

Color Reproduction

The lens designer is simultaneously preoccupied with shaping the overall spectral response of the multi-element lens system. The shape of that curve (at the blue and red end of the visual spectrum) works in concert with the RGB spectral separation of the digital camera beam-splitting system, the spectral characteristics of the image sensors, and the linear matricing strategy employed by the camera manufacturer to implement the final digital camera system colorimetry (Fig. 10).

DoPs collectively expressed a desire for a more accurate reproduction of soft colors than that experienced with the standard HD lenses and HD cameras. They generally concluded that the ITU R 709-BT colorimetry standard produced too high a saturation on such colors. They also placed great emphasis on having a close color reproduction match between the new zoom lens and the six cine prime lenses. This became a key design goal.

Computer simulation allowed an examination of a total imaging system that started with the spectral response of 3200° LC infrared studio light, and the various HD camera elements such as the infrared cutoff filter, the RGB separation curves of the prism, and the spectral response of the CCD imagers, as shown in Fig. 11. The simulation system was the same as that described earlier in Fig. 6.

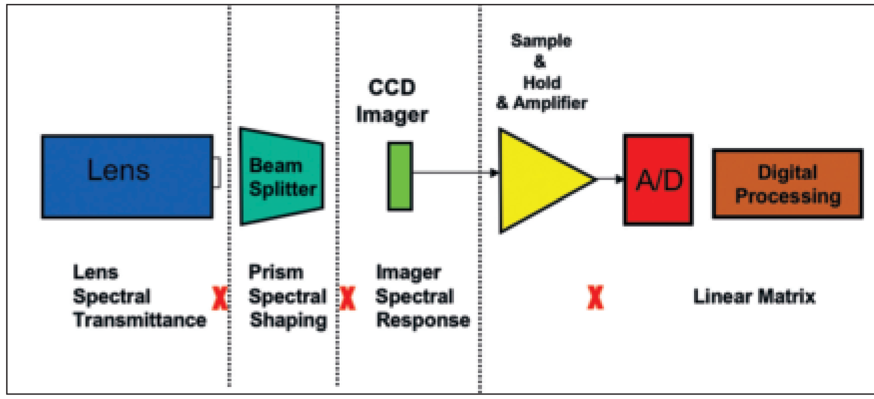

Figure 10. The convolution of the four key system elements that contribute to digital motion picture color reproduction (the display must also be taken into consideration).

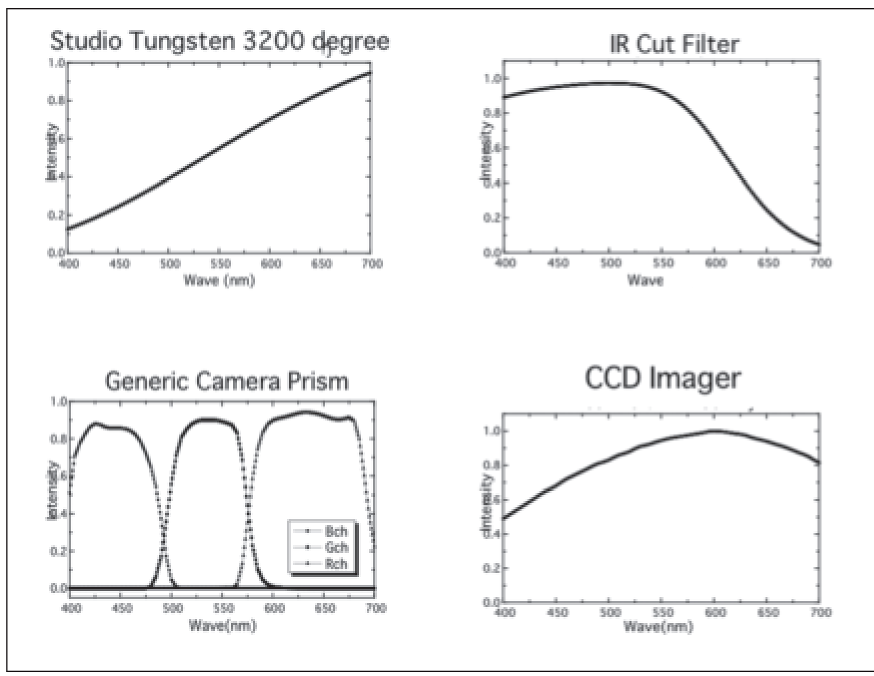

Figure 11. Typical spectral responses of a total HD imaging system, within which a suitable lens spectral transmittance curve needed to be appropriately shaped.

The simulator employed the principles of the Color Contribution Index (CCI),[3] which indicates the amount of color variation within a specific digital HD imaging system (or a film imaging system), caused by different lens transmittance characteristics. Three numbers in the form a/b/c express the index; these numbers being relative values expressed as logarithms of lens transmittance at the three chosen RGB primary wavelengths. Color balance is assessed by comparing the three values to ISO specified reference lens values (this reference having been pre-established by averaging a very large number of lenses from multiple optical

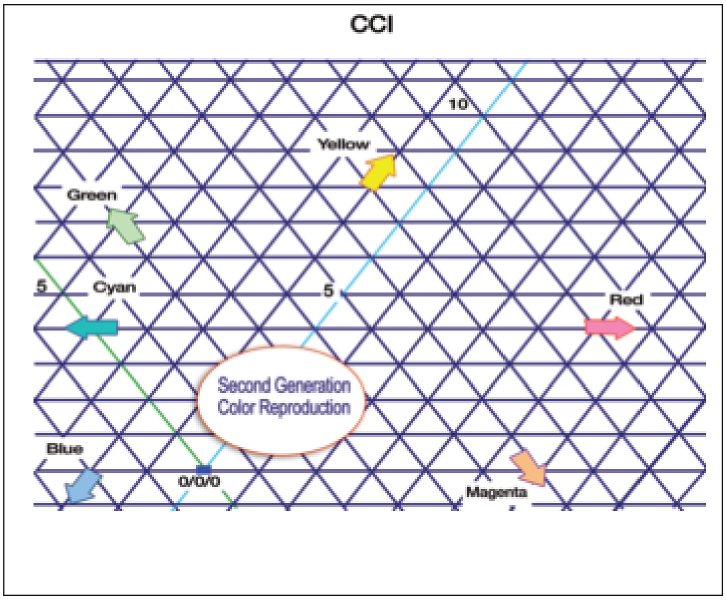

Figure 12. The ISO tolerance range mapped on the Color Contribution Index (CCI) trilinear coordinates.

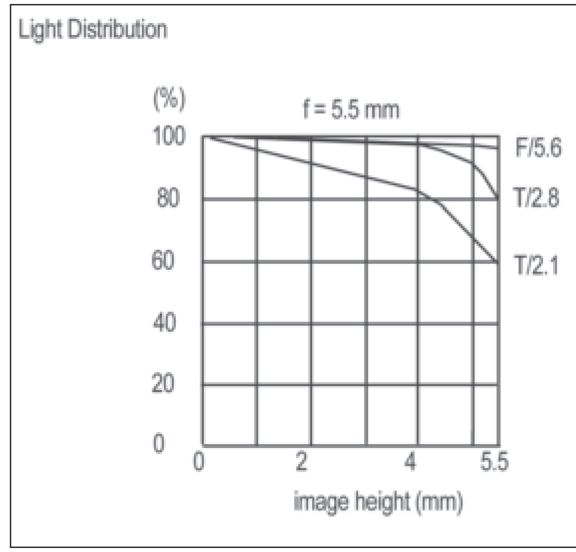

Figure 13. The relative light distribution characteristic of the cine lens at short focal lengths, and with different aperture settings.

manufacturers). This methodology was especially useful in achieving the close color reproduction match between the new zoom lens and the companion six cine prime lenses, as shown in Fig. 12. This was deemed very important by the DoPs, who expressed considerable reluctance to adjust white balance of the HD cameras when exchanging lenses during a given production shoot.

Separately, the simulation was used to produce an overall color reproduction that proved more subjectively pleasing to the DoPs. This ultimately involved trimming the blue-violet spectral response in the manner shown in Fig. 9, producing a slightly warmer look.

Relative Light Distribution

The T-stop number quoted for a given cine lens is a direct measure of the light transmittance of the lens, at the center of the image plane. It is one of the perversities of optical science that this light flux cannot be uniform across that plane. Two inescapable physical phenomena conspire to lower the light level as one moves from picture center toward the corners: one is an aberration of intensity called vignetting, and the second is termed in optical circles, as the Cosine 4th Power Law.

Both contribute to a fall-off in light intensity with view angle. This effect is called peripheral illumination or relative light distribution and is generally specified as a curve showing the light-level shortfall from picture center along a radial termed picture height, as shown in Fig. 13. This shortfall worsens as the photometric aperture is progressively opened. It cannot be avoided, but can be minimized by innovative optical techniques.

A variety of optical compensation techniques have been developed over the decades to progressively ameliorate the degree of this aberration. Increasing the len's aperture efficiency, the ratio of the area of the on-axis entrance pupil to the area of the off-axis entrance pupil being one such technique. Reducing relative light distribution became another primary design goal in this new lens design. As a consequence, the new cine zoom lens achieved an impressive degree of control over this relative light distribution, as shown in Fig. 13.

Lens Focus Breathing

The convergence between traditional videography and film-style cinematography presently being driven by the new digital motion picture acquisition systems has elevated an optical issue long known technically, but not widely acknowledged in general television shooting. This relates to an interaction between a normal lens focusing action and an attendant undesirable zooming action. The phenomenon, known as focus breathing, is seen as an undesired change in image size (an angle of view alteration due to the unwanted zoom action) as the focus control is actuated.

In movie and television drama shooting (historically on motion picture film), the use of rack focusing between a foreground and a background exploits depth of field to visually translate a 3-D effect onto the 2-D palette of imaging. Focus breathing is anathema to the director of photography implementing such a delicate creative focus move.

The problem was addressed with an optical innovation[4] in the 1970s. This has since become known as the "Three Group Internal Focusing Method." It was formally introduced in broadcast EFP lens in 1985 and since that time has been progressively included in a range of studio and EFP/ENG lenses. This solution was described in a later paper.[5] Ongoing refinements to the technique have continued with every new generation of lens design. In 2001, this optical system was introduced into the new high-definition 4.7mm to 52 mm T2.1 wide-angle cine lens. The latest refinements to this technique are also incorporated into the new 5.5mm to 44mm T2.1 cine zoom lens discussed in this paper.

Conclusion

This second generation design of a high-definition cine zoom lens reflects an increasing collaboration between the directors of photography (who have had a long experience in cinematography using motion picture film) and the various global manufacturers involved in developing products and systems in support of digital motion picture production. This can be seen in the latest generation of digital motion picture cameras, and now in the associated cine lenses. It will never cease.

The cine lens design discussed in this paper is a testament both to the dialog between users and manufacturers, and to the awesome prowess of contemporary computer simulation techniques that allow deep exploration of numerous aspects of imagery. The true power of this simulation lay in the ability to closely probe the total lens-camera combination.

The intent of this paper is to (a) outline the novel technical approach employed in this latest generation lens design to solve what initially appeared as an irreconcilable conflict of requirements regarding picture sharpness; and (b) to show how computer simulation helped gain a consensus among a number of DoPs on the highly subjective topic of color reproduction. The degree of marketplace acceptance of the subjective results will likely constitute a second paper downstream, as experience is gained on a variety of productions.

The fact that a new design strategy that exploits spherical aberration to achieve a special subjective picture sharpness, works as well as it does, is perhaps not surprising when the motion picture film system model is examined. Here, the first point image from the lens is reproduced as an expanded image on the negative film (due to light diffusion in the photographic layer).[6] The second point image is further increased in size and its intensity distribution altered by the diffusion of chemical constituents during film processing. Successive point images are created, as the process passes through the interpositive and internagative process and then the final positive release print, with each succeeding point image being an effective aperture scanning the previous image.[2] This unavoidable technical imperfection inadvertently produces a picture sharpness portrayal on the cinema screen that has been technically reported over the years;[7,8] one that has long been beloved within the creative community. This long-established film imaging system produces an image point-spread function that the new digital motion picture systems were challenged to match.

Based on this work, a prototype model of the new 5.5mm to 44mm T2.1 zoom lens was ultimately built and subjected to shooting tests by some of the DoPs involved earlier. The many comments included a general approval that an important step had been taken in realizing an HD cine lens and HD camera that produced perceived picture sharpness and color reproduction more pleasing to the film cinematographer. The match between the six prime lenses and this new cine zoom lens proved very close.

Finally, it should be pointed, considerable merit is seen in continued development of HD lenses for HDTV broadcast production (for sports, studio, news, and field production), while separately expanding the cine lens family to directly address the different creative requirements of the motion picture production communities.

Appendix I

Lens Modulation Transfer Function

The most defining attribute of an image that is viewed from some distance is the contrast that is perceived between dif-

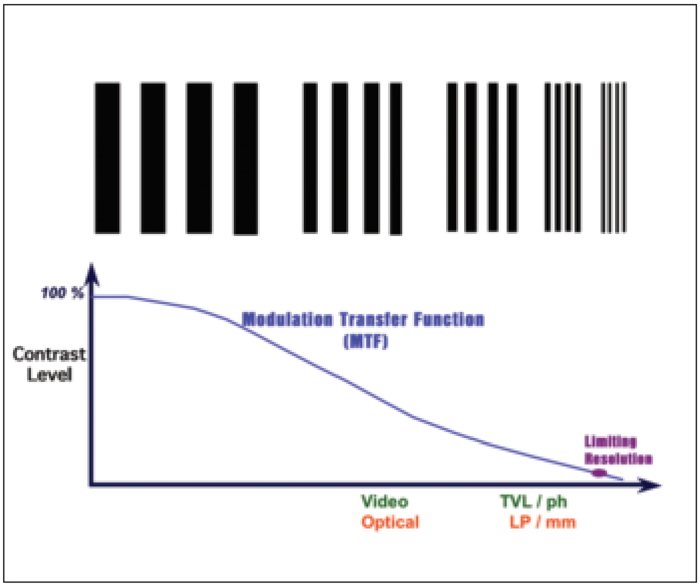

Figure 14. The MTF for an imaging system is defined as the relationship between contrast reproducibility over the spatial frequency range of interest.

ferent portions of that image. Indeed, in vision research circles there is a formal parameter known as contrast sensitivity function (CSF) that is used to analyze small variations in visual perception. This, in turn, has a direct bearing on perceived picture sharpness. This is because there is a close relationship between contrast and the ability to resolve fine detail. For a lens, a camera, and a lens-camera combination, this topic is best examined using the concept of modulation transfer function (MTF).[2]

A low-frequency set of adjacent black-and-white bars will appear to the viewer (sitting some distance from the image screen) with a high contrast. As a consequence, its perceived picture sharpness is high. A very-high-frequency set of such bars, on the other hand, will appear as a gray area with no discernible detail; picture sharpness will have virtually disappeared. Between these two extremes, a range of sets of such black-and-white bars at increasing frequencies will display diminishing contrast as their frequency increases. Their picture sharpness has been "modulated" by the lens, and, quite separately, by the camera. These intermediate frequencies provide the most useful measure of sharpness.

MTF is a mathematical term used to describe the behavior of the contrast level of black-and-white bars of increasing frequencies that are being imaged by a lens-camera system. It is generally described for a given system by a curve that plots contrast reproducibility (vertical axis) against spatial detail (horizontal axis) (Fig. 14).

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