Canon

WHITE PAPER

4K LENS

WHAT CONSTITUTES A HIGH PERFORMANCE 4K LENS?

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Introduction

High-end professional lenses can anticipate a long working life – of the order of a decade or more. This puts a unique context on expectations for contemporary 4K lenses. Such a lens must anticipate a wide range of productions – including theatrical motion pictures, major television dramas and episodics, commercials, and a diverse range of non-entertainment origination. Large screen portrayal will become the norm. And, it is that fact that imposes on the 4K lens a range of performance imperatives that cannot be ignored.

So what are the performance parameters that collectively define 4K optical performance? The following paper will enumerate these parameters and discuss user expectations.

4K Resolution

4K immediately invokes high resolution and the optical implications as we shall see are very significant indeed. 4K is fundamentally defined by the spatial sampling lattice of the image sensor in a 4K camera. This entails 4096 horizontal samples and 2160 vertical samples – for a total of 8,847,360 spatial samples. In sampling theory it has been long-established that a given spatial sampling frequency can only faithfully reproduce spatial frequencies that are half that number. The limit of such spatial reproduction is known as the Nyquist frequency – which is simplistically explained for 4K in Figure 1.

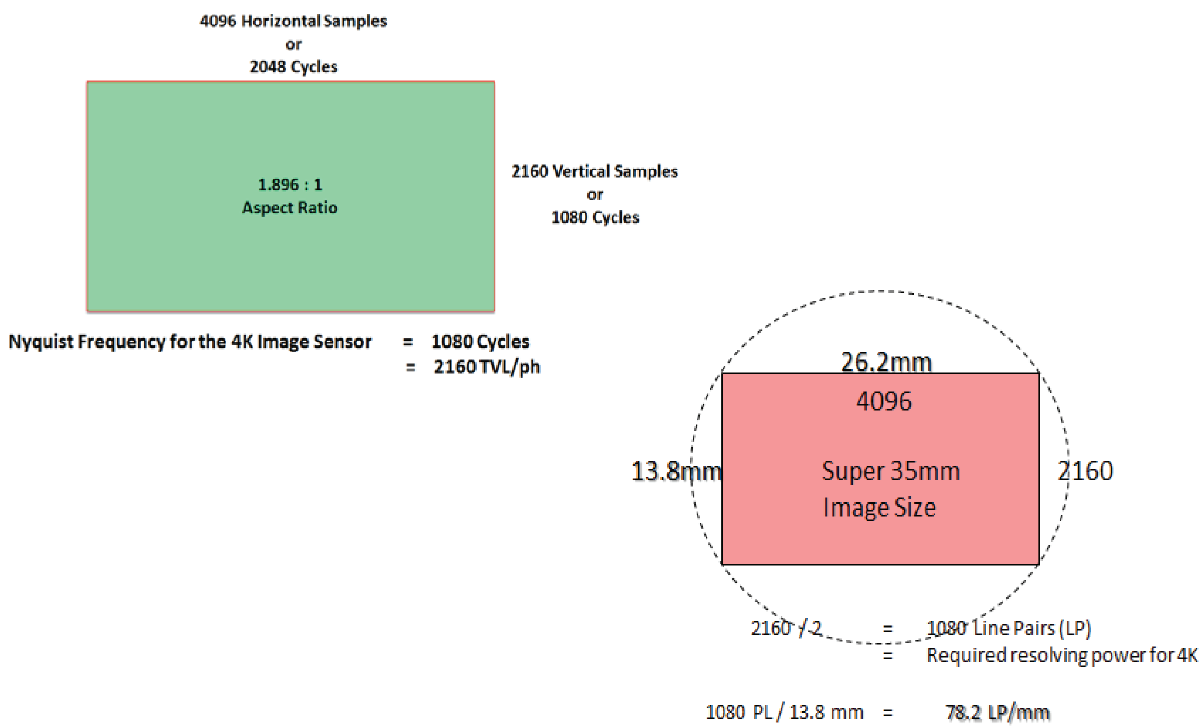

Figure 1 *Showing on top left the sampling structure of a 4K image sensor and the Nyquist frequency associated with that sampling; the bottom image represents the spatial detail of a 4K Super 35mm lens that can fulfill the resolution capability of that 4K image sensor*

4K Lens Criteria – *Optical Nyquist Spatial Frequency is 80 LP/mm for S35mm*

We have defined the optical Nyquist frequency for a 4K S35mm lens. It means that this lens needs to be able to pass through its entire optical system 80 black and white lines within every millimeter of the image size defined in Figure 1. To get a sense of the high demand of a 4K lens we show in Figure 2 below what 80 line pairs looks like. Consider what it takes to pass that through every horizontal (and vertical) millimeter of the lens output image—and to do so with *as high a contrast as possible* because it is this contrast that defines the effective image sharpness of the lens .

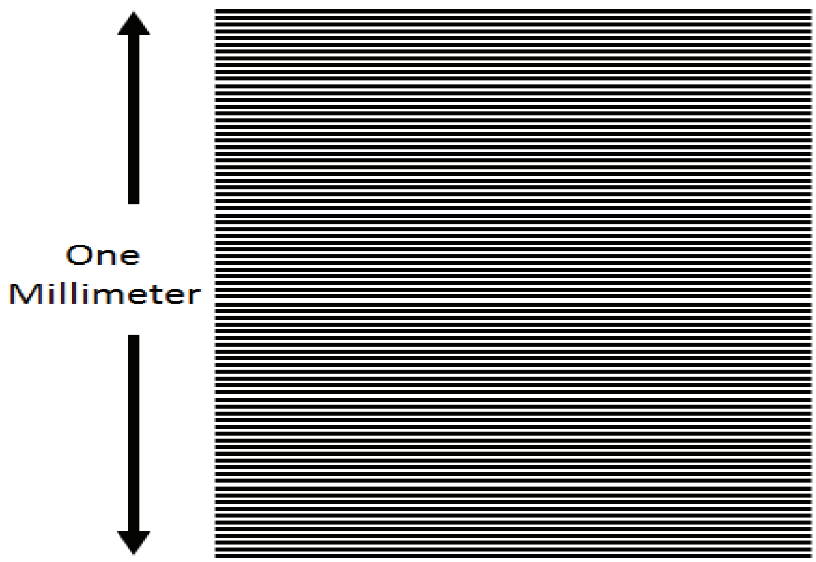

Figure 2 *Conveying what 80 line pairs within each millimeter of the output image of the 4K lens (one line pair is one black line and an adjacent white line) poses as an optical design challenge*

4K Lens Criteria – *Optical Contrast Ratio*

Cinematographers often speak of the "clarity" and "brilliance" of a specific lens and in so doing they are largely referring to the optical contrast performance of that lens. The Contrast Ratio of a lens is a formal definition of that performance. It is the ratio of the level of transmissivity through the optical system to the level of optical black contamination on the output caused by flare and veiling glare. It is sometimes likened to an optical "signal to noise". The secret to elevating lens contrast lie in the deep sciences of multilayer optical coatings that are deposited on each and every lens element surface. When a lens that does NOT employ such coatings images a black and white chart the level of transmitted white light through the optical system incurs a loss in transmissivity due to reflections at each and every air-glass surface (approximately 4% for each uncoated surface). These same reflections cause a light scattering within the overall optical system – creating flare and veiling glare that contaminates what should be zero light transmission for the black portion of the chart. The deposition of the multilayer coating creates secondary reflections that cancels the primary reflection – thus elevating light transmission through the optical system, and at the same time lowering the light scatter so that a superior black reproduction is simultaneously made possible. Multilayer coatings of different materials on each surface are required to manage all of the wavelengths across the visible color band. Associated costs are high because of the exotic nature of effective coating materials and the incredible level of sophistication and precision required in the deposition processes.

4K Lens Criteria – *Critical Linkage between Resolution and Contrast*

High emphasis is placed on the importance of an excellent contrast ratio in a 4K lens for two important reasons:

1. A high contrast lens will greatly contribute to a lens-camera capture system being able to portray vivid reproduction of scenes containing both bright and dark sections

2. Perceived picture sharpness on a large screen viewed from typical viewing distances is directly influenced by the image sharpness of the lens multiplied by the resolution characteristic of the associate camera and further multiplied by the resolution characteristic of the final display. That convolution is assessed by identifying the individual Modulation Transfer Functions (MTF) of each of these three subsystems. This leads to the need to first clarify what MTF is all about.

4K Lens Criteria – *Modulation Transfer Function (MTF)*

Modulation Transfer Function is quite a technical mouthful – and smacks of some form of mathematical terminology. And indeed it is. For simplicity, it is generally abbreviated to MTF. MTF is a powerful and practical tool for assessing the resolution behavior of individual components of a total imaging system (such as a lens, a camera, a display, a printer etc). It also allows an assessment of the overall resolution of that total system – which, is after all, what ultimately impacts our human visual system. And yes, the human visual system itself is endowed with an MTF of some considerable complexity.

Upon confronting the term Modulation Transfer Function, the question immediately arises as to what is being modulated, what is being transferred, and how does all of this bear upon resolution? It will be shown that these terms help us provide a linkage between the resolution capability of an imaging component and the contribution that component makes to the perceived sharpness seen when we look at the final reproduced image.

The terms can best be understood by starting at the front end of the imaging system – namely, the lens.

The central role of the lens is to intercept the optical wavefronts emanating from an illuminated three-dimensional object within a given scene and to transfer that into an output two dimensional object image. The lens creates an optical representation of that scene. Consider a lens imaging a very low frequency set of adjacent black and white bars (two or three pairs of lines) as depicted in Figure 2. As the lens transmits the light from that scene object there will be a modest loss of the white light at the lens output port (the transmissivity loss that is indigenous to all lenses) and there will be an elevation of the black level (due to internal optical flare phenomenon). Thus, the output optical reproduction of the black and white scene will incur a small loss of contrast – and the formal Contrast Ratio of that lens will then be as defined in Figure 3.

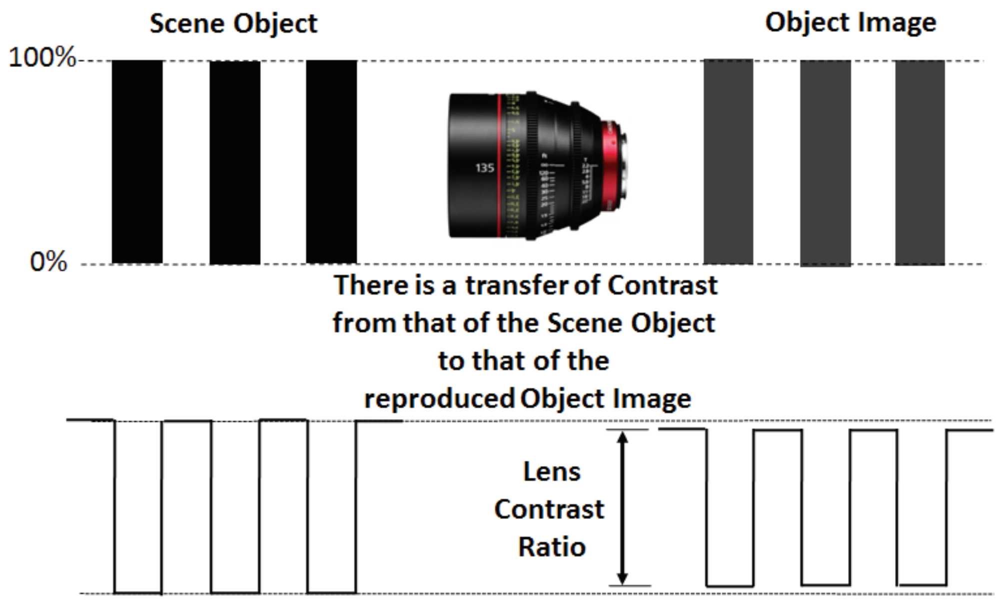

Figure 3 *The very best lenses have less than 100% transmittance and also have some degree of black contamination due to flare and internal reflections – this combination defines the lens contrast ratio*

As the spatial frequency of the black and white bars being imaged by the lens is progressively increased the contrast of their optical reproduction at the lens output lowers. This is simulated in Figure 4 below. The higher that spatial detail becomes the lower its contrast at the lens output port. Thus, there is a modulation of the transfer of contrast through the lens as a function of spatial frequency. Hence the term Modulation Transfer Function – usually abbreviated to MTF.

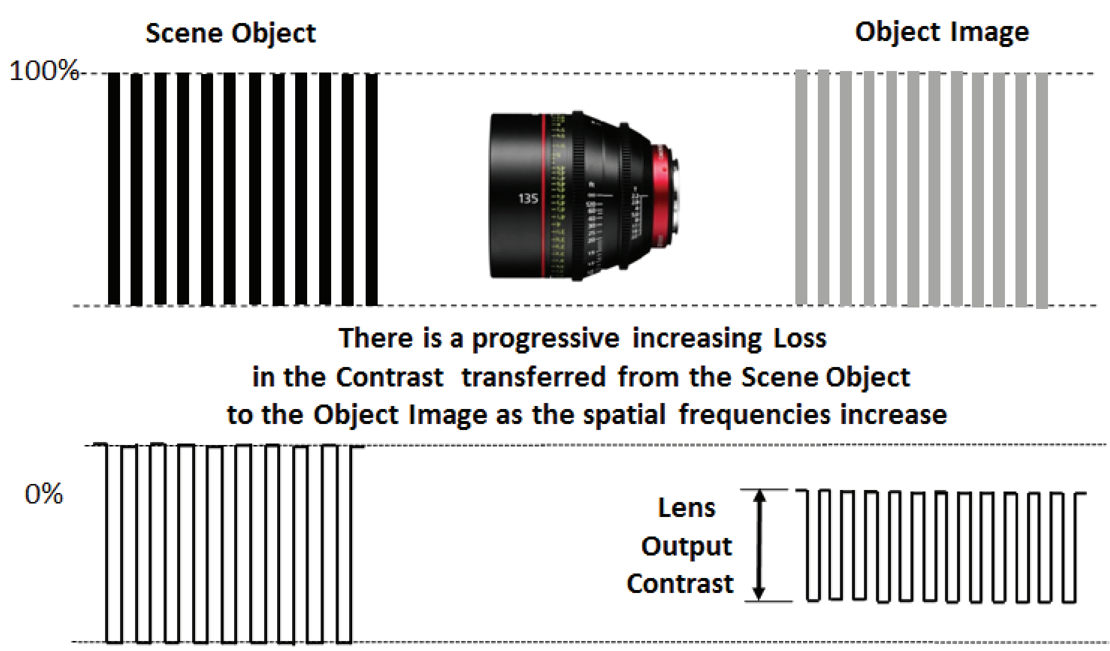

Figure 4 *Modulation Transfer Function (MTF) is the ratio of the contrast in the Scene Object to the contrast in the Object Image as a function of spatial frequency.*

If the lens output optical level relative to the level of the input scene object (100 % black and white bars) were plotted as a function of spatial frequency it would illustrate this progressive loss of contrast within the lens in the manner shown in Figure 3.

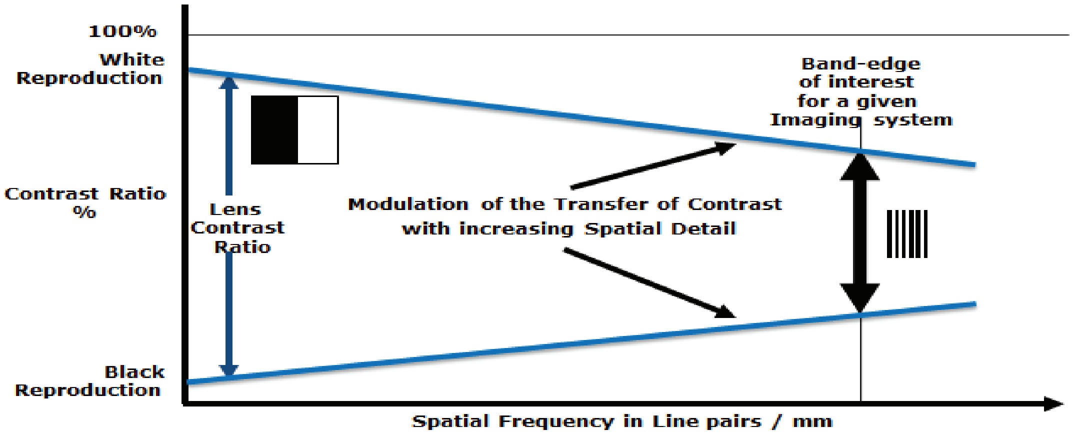

Figure 5 *Showing a representative falloff in lens contrast – spanning very low spatial detail to the highest spatial detail that defines the pass band of interest for a given imaging system*

If this contrast characteristic of a given lens is plotted as a graph with spatial frequency as the horizontal axis we have the portrayal of the MTF of that specific lens. In the optical world, the unit of spatial frequency is typically in lines per mm – that is, the number of black and white line pairs passed through each millimeter dimension of a lens. The spatial frequency at which the MTF has dropped to a level below 10% is referred to as the *Limiting Resolution* or the *Resolving Power* of the lens.

4K Lens Criteria – *Importance of the Lens MTF Characteristic*

Extraordinary advances in optical designs have taken place over the past twenty five years. There have been the steady advances in Super 35mm lenses (and larger formats) used in motion picture film production over many decades. The 1990s saw the arrival of production HDTV systems based largely upon the small 2/3-inch image format which was to spur highly competitive worldwide developments in HD studio, field, EFP, and ENG lenses. A decade ago saw the emergence of Super 35mm single sensor digital cameras – that started at the 2K/HD level – but which has rapidly advanced to the broadening array of 4K systems we see today. The advantage of this larger image format size is the increase in horizontal and vertical millimeter which directly contribute to elevating the total line pairs the 4K lens can resolve.

The lens optical MTF is multiplied by the camera electronic MTF (largely determined by the sampling mechanism of the image sensor and its associated optical low pass filter) to produce the effective MTF of the lens-camera imaging system. The imperatives of achieving as high an MTF as possible in the digital 4K camera must be balanced by the necessity of shaping the roll-off of the camera MTF characteristic to avoid an undue level of aliasing (a consequence of the horizontal and vertical sampling mechanism of the image sensor). The larger onus thus falls on the 4K lens to sustain as high an MTF as possible across the 4K passband to effectively elevate the composite Lens-Camera MTF because of the relative more rapid roll off of the camera – see Figure 6.

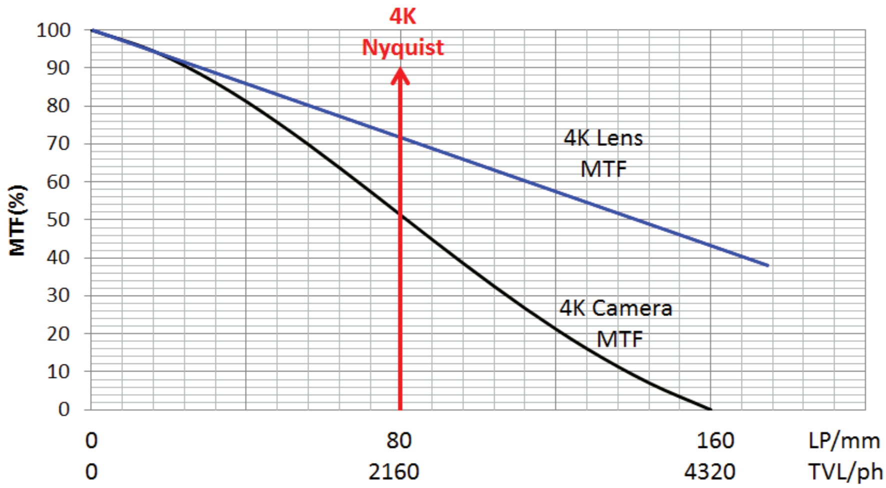

Figure 6 *Showing the natural falloff of resolution at Picture center of a hypothetical 4K lens in comparison with the more rapid MTF falloff of the hypothetical 4K camera*

That overall lens-camera MTF curve greatly affects the faithfulness of the video representation of the scene being imaged. The accumulated subjective experience around the world has shown that what we actually see on the large screen (television or theater) – what is termed *Perceived Picture Sharpness* – is directly related to the square of the area under the composite Lens-Camera MTF curve [1].

The higher that composite MTF curve is around the half Nyquist spatial frequency 1080 TVL/ph in video terms and 40 LP/mm in optical terms) the sharper the most important elements of an image will appear to the viewer [2]. Edge sharpness is critically important to close-ups and to very wide-angle scenes. Textural reproduction (facial, hair, clothing, materials etc) is also a key element in high-resolution reproductions.

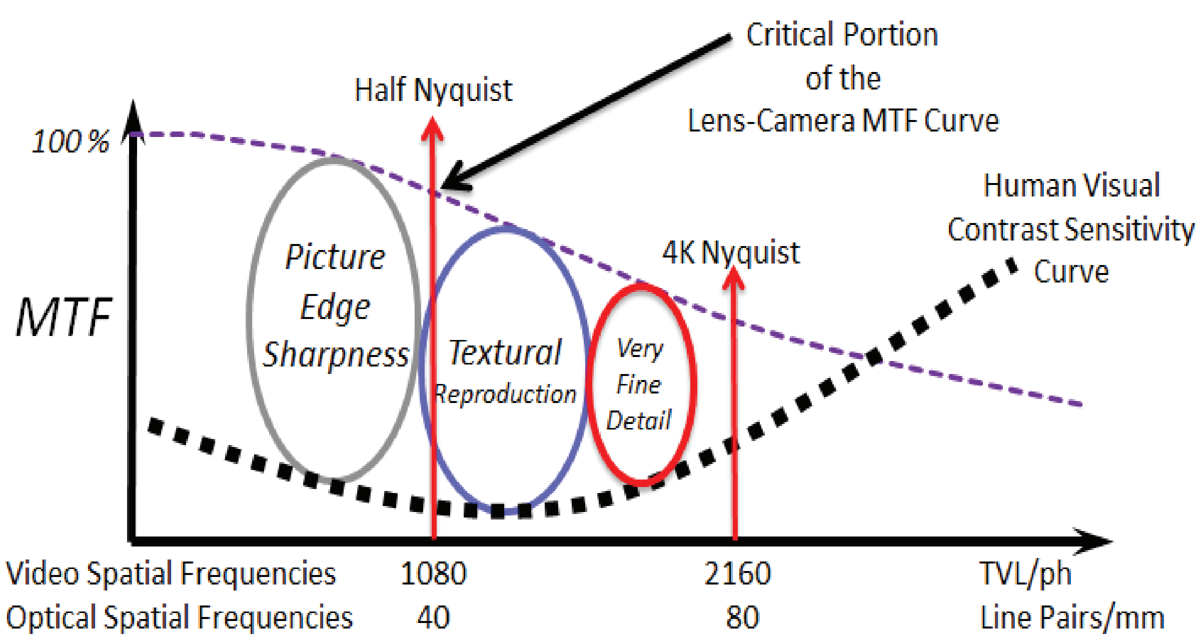

Figure 7 *Emphasizing the importance of achieving a high lens-camera MTF at the half Nyquist spatial frequency*

4K Lens Criteria – *Resolution across the Image Plane*

So far we have discussed issues relating to 4K resolution at the all-important picture center –the "sweet spot" in all lenses. However, it is a fundamental optical behavior that MTF will falloff from its peak at picture center toward the image extremities. This has long posed a challenge to optical designers, and over the decades many ingenious optical strategies have been developed to counteract this falloff. It is an important quest because our human perception of picture sharpness assimilates the resolution of the image across the total image plane. This acquires an even higher importance with the superb picture sharpness of the 4K imaging system – especially on a large cinema screen. Recognizing the impossibility of achieving a totally constant MTF across the image plane, the optical designers define two circular zones – based upon years of collaborative experiences with cinematographers – where they make every attempt to maintain close to constant MTF.

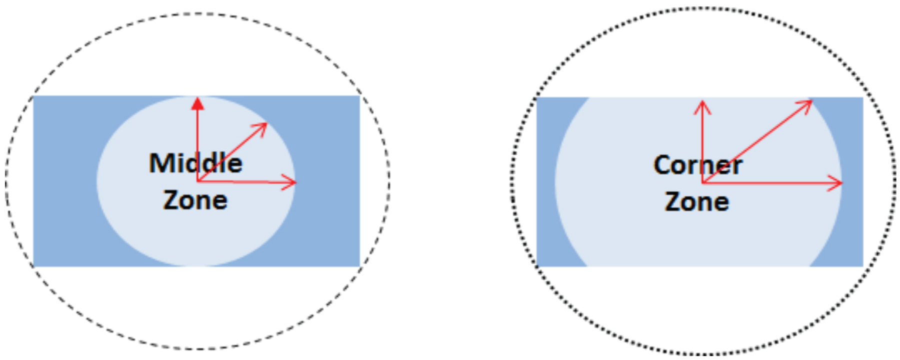

Figure 8 *Showing the two zones used to separately specify MTF behavior in the Canon 4K Super 35mm cinematography lenses*

These spatial zones are related to the interest of cinematographers who seek a constant sharpness across the most important middle zone that typically will encompass a facial close-up or a medium shot as shown in the left of Figure 9. The outer zone encompasses the greater portion of a wide angle scene –and here there will be a well-controlled roll-off of MTF at the outer portions.

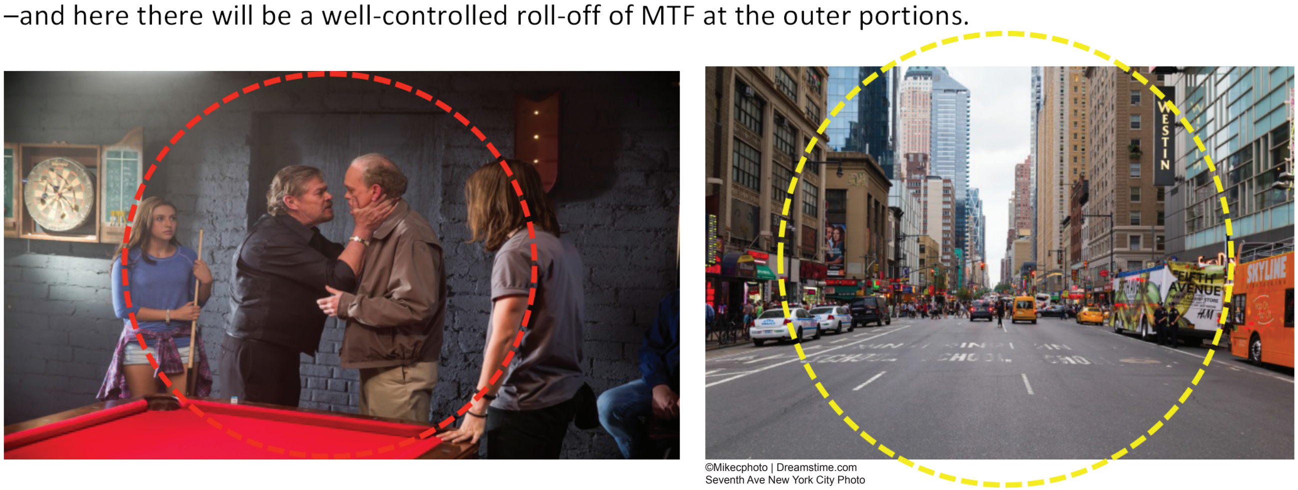

Figure 9 *Showing the picture content implications of the two zones that are used to manage MTF characteristics across the image plane*

4K Lens Criteria – *Maintaining 4K Resolution over the Total Focal Range*

The challenge of tightly controlling lens MTF is further elevated in zoom lenses – because it is also an optical reality that MTF changes over the focal range of the zoom lens. And again, the optical designers must mobilize further innovative optical design strategies to minimize these changes. The demands on 4K lens design are higher than that of HDTV lenses – because of the anticipated very high bar in image resolution expectations.

It is customary to show the variations in MTF across the image plane and its variations with focal range in one chart – as depicted in Figure 10

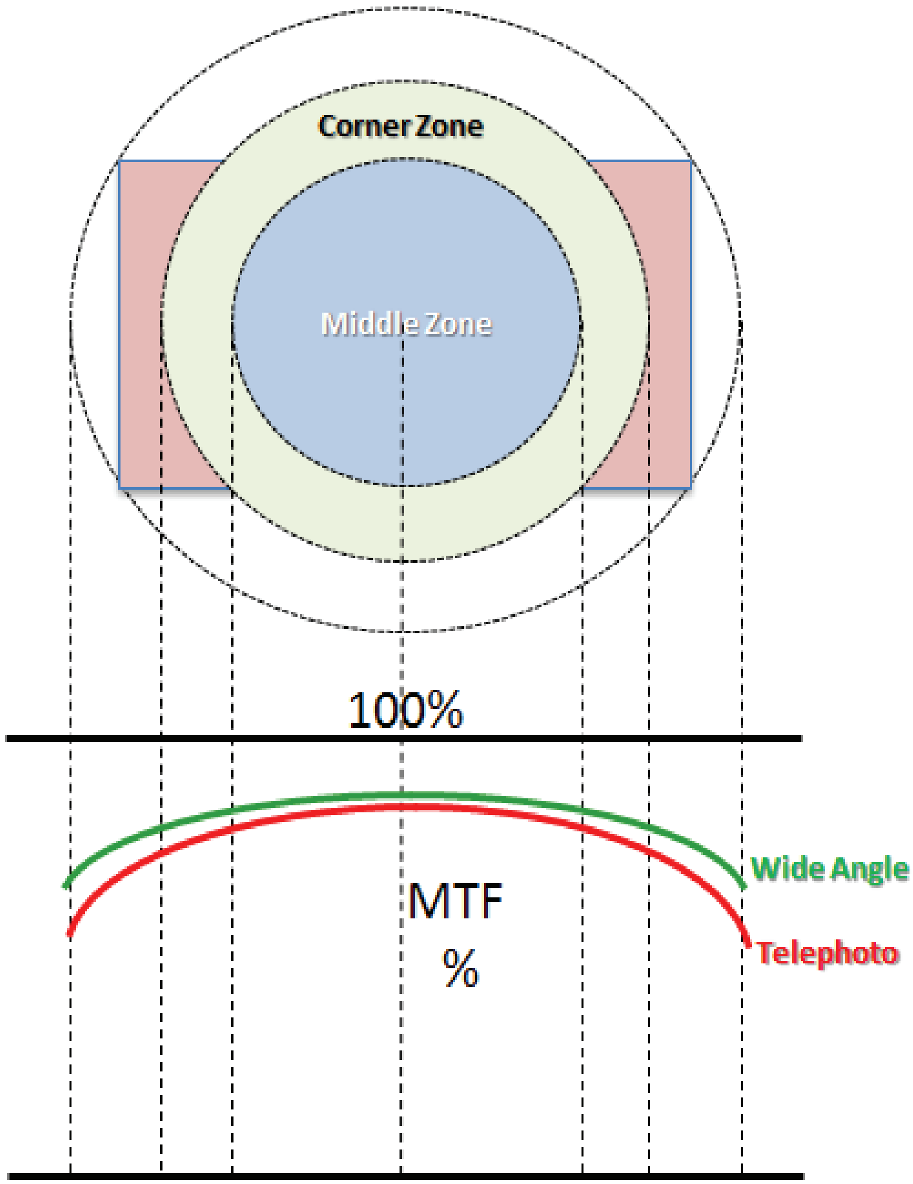

Figure 10 *Showing the hypothetical MTF characteristics of a 4K lens as a function of both the two spatial zones and the total focal range*

The design goal is to achieve minimum falloff in MTF across the middle zone while also minimizing that falloff across the total focal range of the 4K zoom lens

4K Lens Criteria – *Lateral Chromatic Aberration*

All lenses have optical aberrations. There are the famous four monochromatic (independent of wavelength) aberrations known respectively as astigmatism, coma, curvature of field, and spherical aberration. There are two additional aberrations that are both wavelength dependent – lateral and longitudinal chromatic aberration. The former is the most difficult to contend with in optical design and is a consequence of each wavelength of light having a different magnification. The image sensor in the camera can read this as misregistration between the various wavelengths which can cause color fringing on image transitions, and when added to the four monochromatic aberrations, this constitutes what are collectively called the aggregate defocusing distortions that impair lens MTF – especially at the wider aperture settings (shown for a hypothetical 4K lens in Figure 11).

Because the 4K image sensor can see four times more spatial detail than an HD image sensor it becomes imperative to more tightly control optical aberrations in a 4K cine lens –and most especially to curtail, to the degree possible, the lateral chromatic aberration.

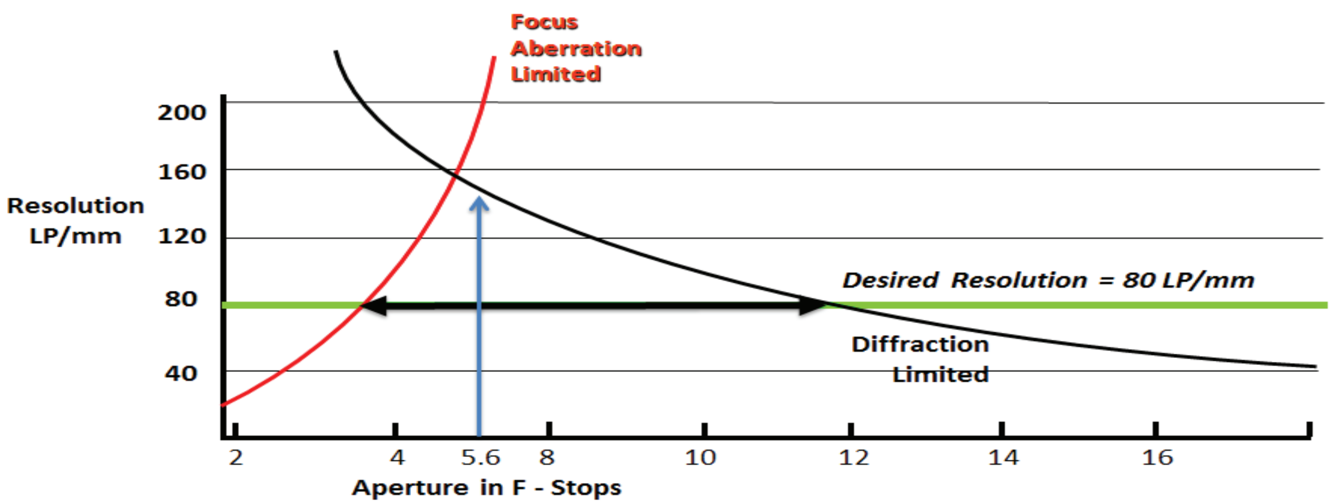

Figure 11 Showing the two boundaries to resolution in all lenses (this is a generic curve shown here)

In Figure 11 above the curve labelled Diffraction Limited – is a fixed curve for all lenses of a given image format size. No optical design ingenuity can counteract that limitation which imposes a progressive lowering of MTF as the lens aperture is stopped down. The red curve on the left – the aggregate of all of the lens aberrations is, to quite a degree, under control of the optical designer. If enough optical strategies are mobilized (number of lens elements increased, adroit combinations of different glass materials deployed, selective shaping of the individual lens elements, and selective use of aspheric lens elements) then this red curve can be driven to the left which opens up the range of aperture stops that can deliver the full 80 LP/mm and more. However, it is one of the intractable realities of lens design that these strategies do not come cheaply, which is one reason that high performance 4K lenses are not inexpensive. In 4K lens design you really do get what you pay for – especially with respect to minimizing optical aberrations..

4K Lens Criteria – *Variation of MTF with Object Distance*

It is not over yet! It is also an optical fundamental that the distance of the scene object to the lens front face also affects the MTF behavior of the lens. But, this too can be controlled to a degree with strategic optical design. The imperative to do so is that much greater in a 4K lens than in an HD lens because of the anticipated broad use for theatrical motion pictures. On those very large screens a rack focus between two subjects at different depths within a given scene that entails a change in image sharpness is likely to be seen more readily than on a 50 or 60-inch HD home viewing display.

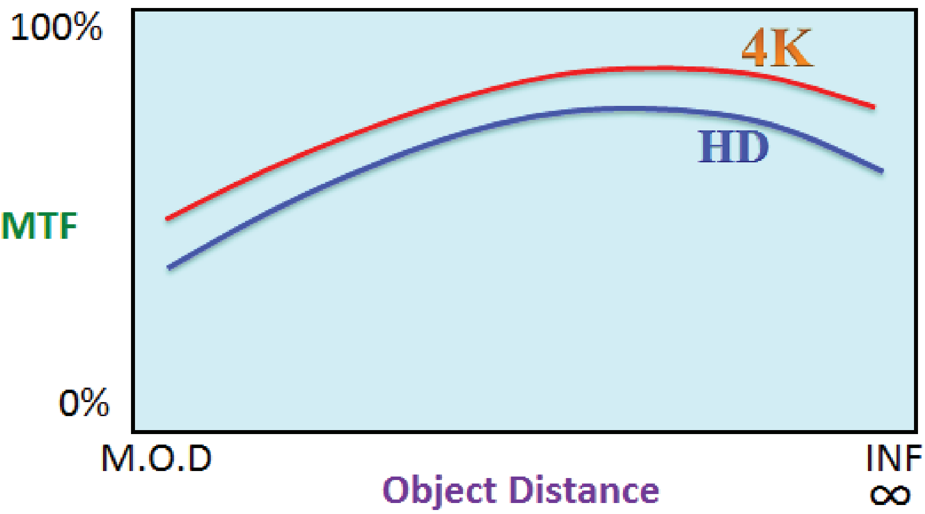

Figure 12 *Showing in generic fashion the tendency of lens MTF to vary as a function of object distance – and the desire to better control this in a high performance 4K lens.*

The 4K High Performance Lens – *a Summary*

It has been shown that the 4K lens confronts a much higher bar of overall image quality than any high performance HD lens. 4K cameras are evolving with extraordinary rapidity and the escalating global competition continues to drive their performance to ever higher levels. The recent CES show saw many manufacturers with 84-inch diagonal 4K consumer displays and a few topping 100-inch diagonal. Competitive forces are clearly spurring ever-larger consumer 4K display sizes. Separately, 4K digital projectors for large screen cinema viewing are steadily proliferating and they exhibit excellent image sharpness.

It is this anticipation of stellar 4K imagery being portrayed on such large screens that places a special onus on the performance of that which originates that imagery – namely, the 4K lens. Shortfalls in MTF and visibility of optical aberrations become more apparent on large screens. There is no circumventing the extraordinarily powerful optical design tools, innovative optical materials and technologies, highly sophisticated manufacturing techniques, and the all-important precision assembly practices that combine to make a true full performance 4K lens.

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[1] Otto H. Schade, Sr. "Image Quality: A Comparison of Photographic and Television Systems" *Reprinted in J.SMPTE, Page 567 – 573, June 1987.*

[2] Brian Caldwell, Wilfried Bittner, Winston Ip, and Dan Sasaki. "High-Performance Optics for a New 70mm Digital Cine Format" *J. SMPTE, Page 49 – 54, March 2104*