

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. A given 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 sampling lattice of the image sensor in a 4K camera. This entails 4096 horizontal photosites 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.

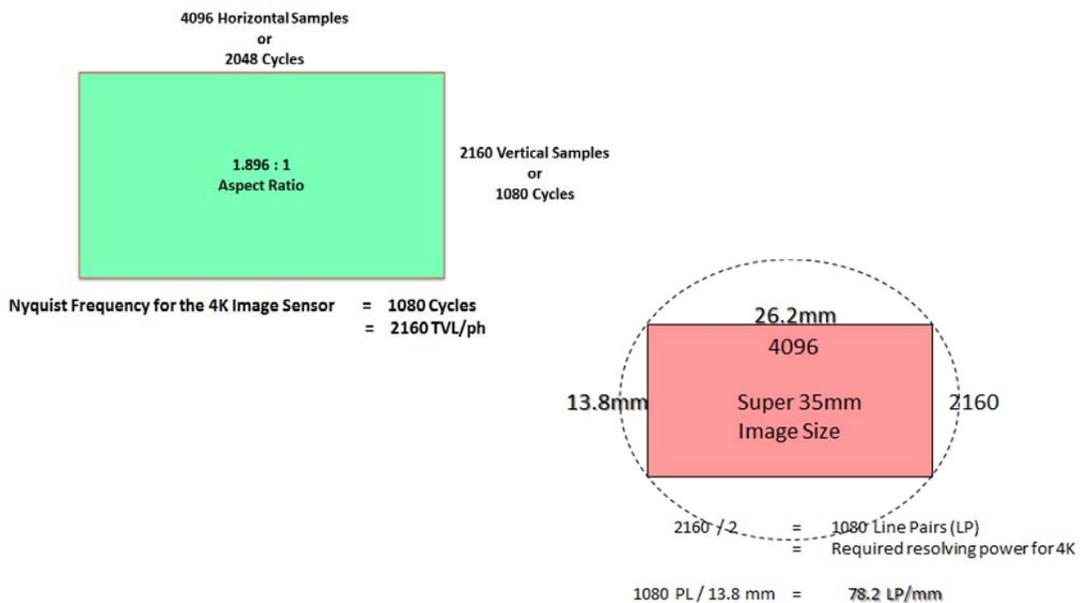


Figure 1 Showing on top the sampling structure of a 4K image sensor and the Nyquist frequency associated with that sampling; the bottom image represents the spatial detail of a 4K Super 35mm lens that can fulfill the resolution capability of that 4K image sensor

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*.

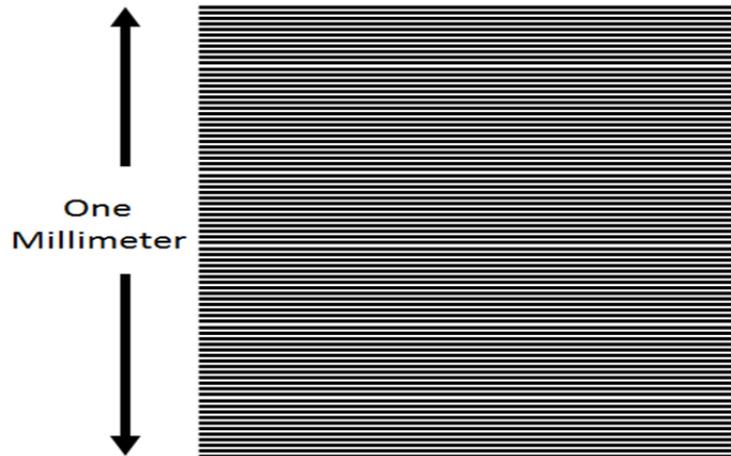


Figure 2 Conveying what 80 line pairs within each millimeter of the output image of the 4k lens (one line pair is one black line and an adjacent white line)

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.

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 an established method of measuring the resolution behavior of lenses, cameras, and displays –namely, the Modulation Transfer Function (MTF) of each of those systems.

4K Lens Criteria – *Modulation Transfer Function*

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 and there will be an elevation of the black (due to internal 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.

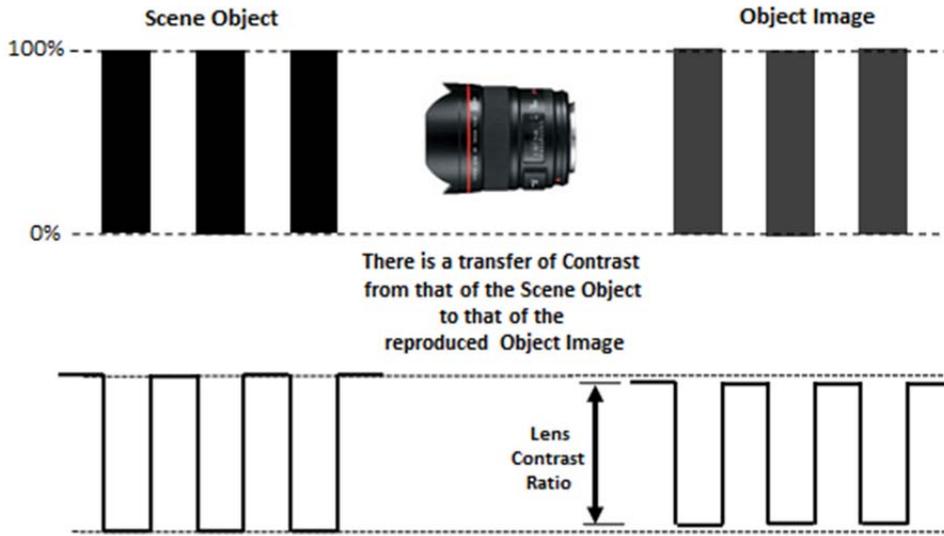


Figure 3 *The very best lenses have less than 100% transmittance and also have some degree of black contamination due to flare and internal reflections – the combination defining the lens contrast ratio*

As the spatial frequency of the black and white bars being imaged by the lens is 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.

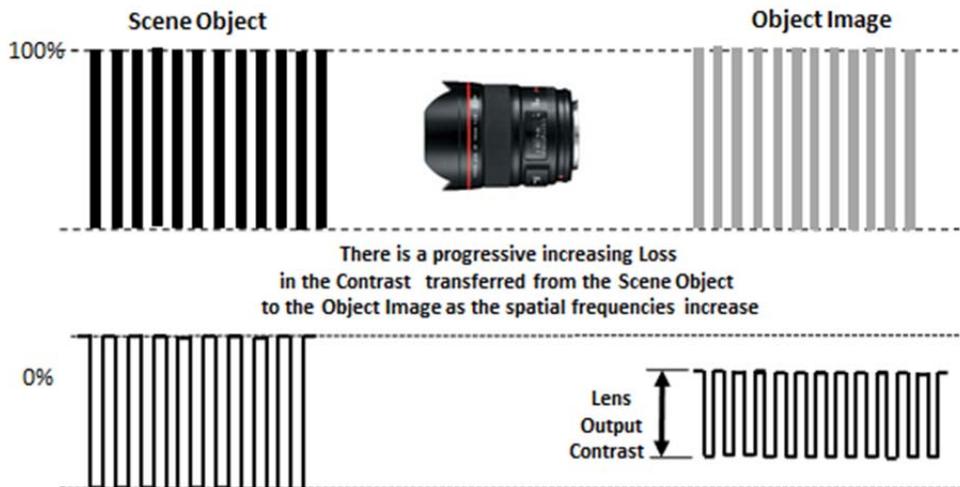


Figure 4 *Modulation Transfer Function is the ratio of the contrast in the Scene Object to the contrast in the Object Image as a function of spatial frequency.*

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 plot this progressive loss of contrast within the lens in the manner shown in Figure 3.

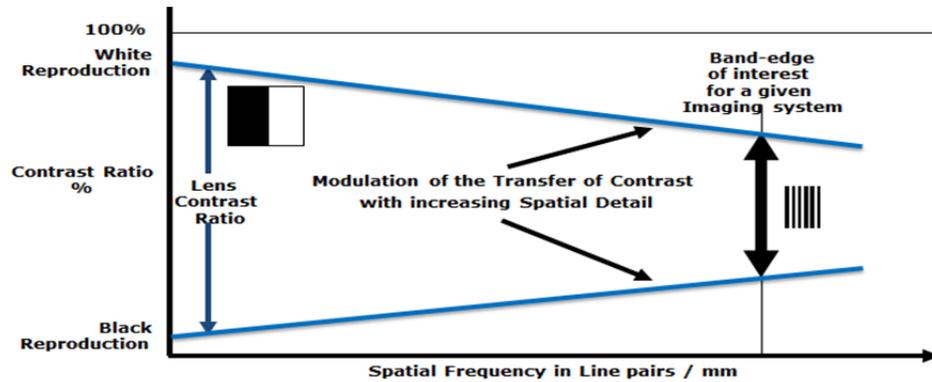


Figure 5 Showing a representative falloff in lens contrast – spanning very low spatial detail to the highest spatial detail that defines the pass band of interest for a given imaging system

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 Half Nyquist Frequency

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. Significant and sustained optical developments were necessitated by that competitive drive – to a level where the latest generation of high-end HD lenses has quite extraordinary optical performance.

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 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 level of contrast at HALF of the Nyquist frequency than at the Nyquist limit itself.

So, for the 4K lens our optical designers focus on elevating the MTF at 40 LP/mm as high as possible as shown in Figure 6 below.

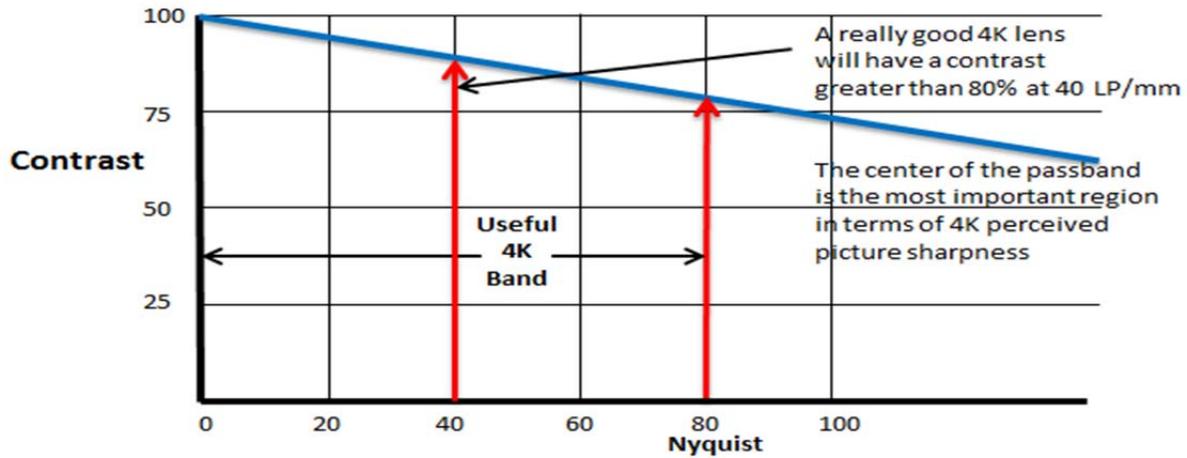


Figure 6 *Showing the natural falloff of resolution at Picture center of a 4K lens*

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 – as shown in Figure 7. That overall MTF curve greatly affects the faithfulness of the video representation of the scene being imaged. 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. 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.

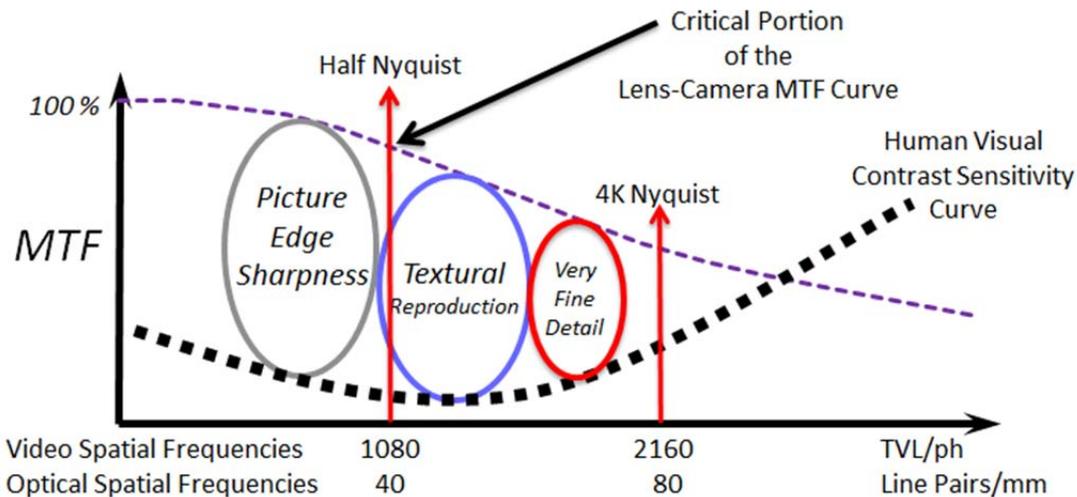


Figure 7 *Emphasizing the importance of achieving a high lens-camera MTF at the half Nyquist spatial frequency*

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.

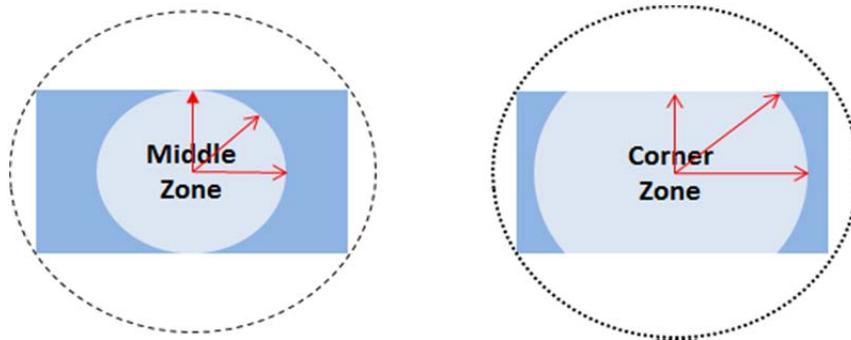


Figure 8 Showing the two zones used to separately specify MTF behavior in the Canon 4K Super 35mm cinematography lenses

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 close-up 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.

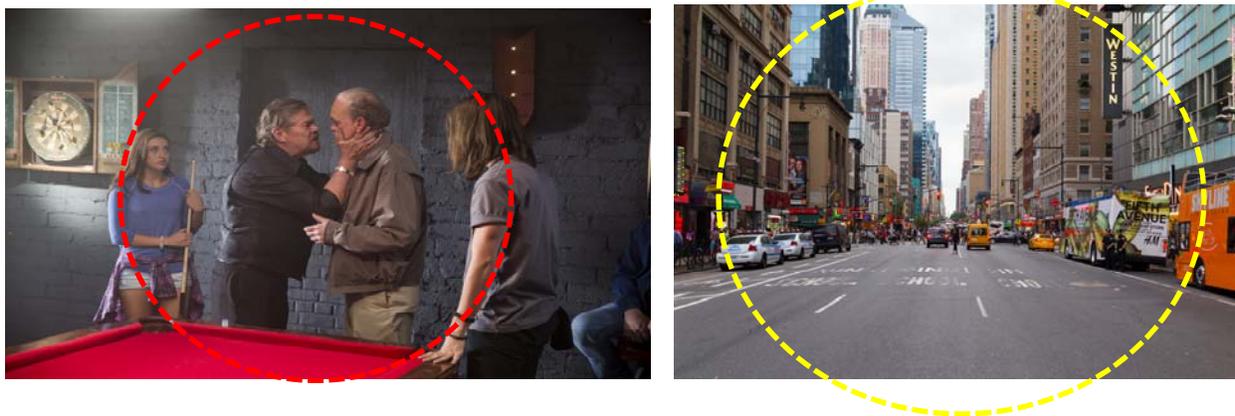


Figure 9 Showing the picture content implications of the two zones that are used to manage MTF characteristics across the image plane

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

The challenge of tightly controlling lens MTF is further complicated 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 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. 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 (NOTE – these are the final computer simulations of the lenses).

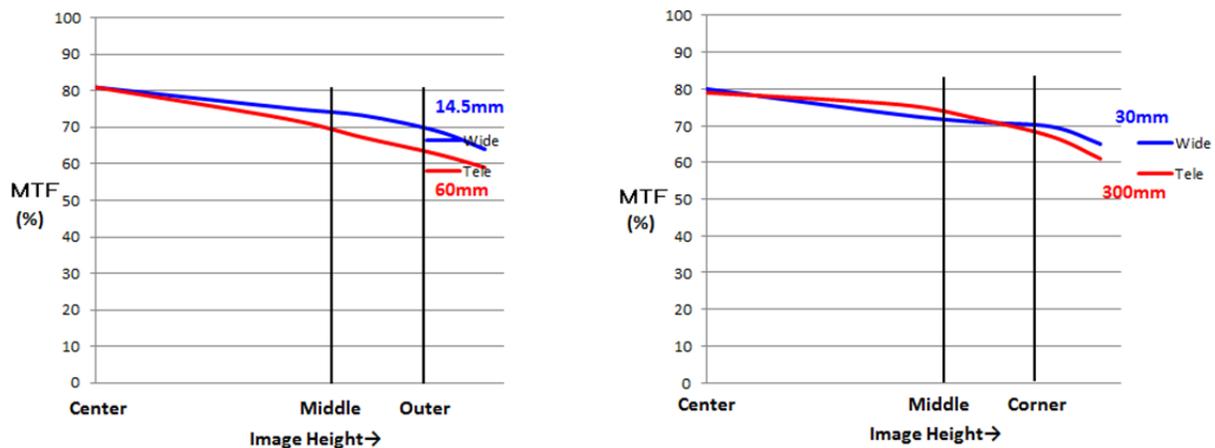


Figure 10 Showing the MTF characteristics of the Canon CN-E14.5-60mm and the CN-E30-300mm 4K lenses as a function of both the two spatial zones and the total focal range

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.

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.

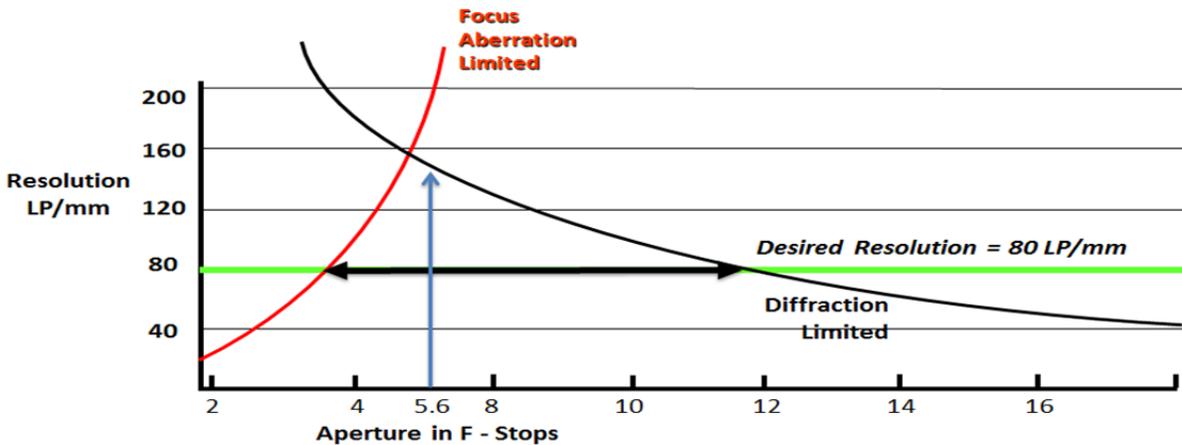


Figure 11 Showing the two boundaries to resolution in all lenses (this is a generic curve shown here)

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. 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.

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.

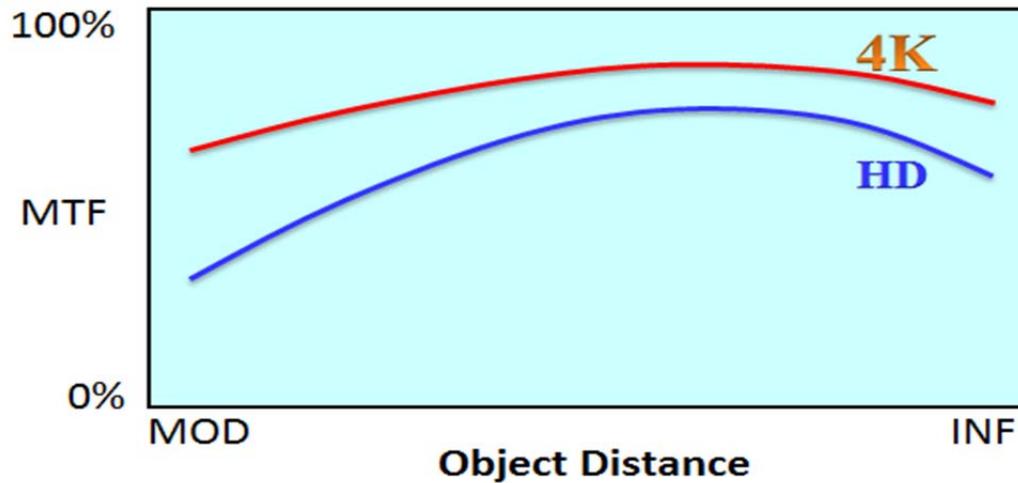


Figure 12 *Showing in generic fashion the tendency of lens MTF to vary as a function of object distance – and the desire to better control this in a high performance 4K lens.*

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 a 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 have 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 advanced technologies, highly sophisticated manufacturing techniques, and precision assembly practices that combine to make a genuine full performance 4K lens.

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