WHITE PAPER

UHD-DIGISUPER 122
UJ122x8.2B

UHD-DIGISUPER 111
UJ111x8.3B

SECOND GENERATION 2/3-Inch 4K UHD LONG-ZOOM FIELD LENSES

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Abstract

The past twenty years of HDTV in the USA has seen no less than three generations of long zoom box field lenses. With each generation, progressive improvements saw overall image performance enhanced, optical aberrations constrained, while ergonomic advances helped make the role of the camera operator a little easier. Each generation was invariably propelled by unceasing requests for further operational enhancements -- especially longer focal ranges, and wider fields of view at the wide end of the zoom range.

It has only been four years since 2/3-inch 4K UHD camera burst on the scene and all of the major camera and optical manufacturers are now engrossed in bringing associated competitive products to the global marketplace. As always, sports coverage remains center stage in driving developments in both the field cameras and the associated lenses. Award shows, concerts, and other major outside broadcasting events are additional drivers. The stunning image quality of 4K UHD has heightened the desires within the outside broadcast production communities for even further flexibilities in operational controls. Extended focal range is paramount among these requests – with pleas for extensions at both the wide end and the telephoto end.

Early experiences with 4K UHD production has shown greater scrutiny of image stabilization capabilities as the far higher resolution imagery of 4K UHD mitigates against any degree of image unsteadiness on long telephoto shots. Equally, the unwanted "lag" that can momentarily follow a pan or tilt operational move while image stabilizations systems are engaged is drawing increased criticism. Many camera professional operators still avoid deployment of IS because of this disturbance.

In light of these new marketplace imperatives Canon decided on a major development project that can push all of the boundaries of long-zoom field lens design – operational capabilities, image performance, and image stabilization. Literally, a totally new generation of lens design was undertaken.

The special challenges posed by the high imaging demands of 4K UHD will be described in this white paper. Central to this was grappling with the fundamental physical conflicts in achieving the requisite extended focal range, optical sensitivity, highest 4K performance – while still producing a size and weight expected by those who deploy such lens-camera systems. The new optical design strategies to meet these challenges will be outlined.

An innovative new operational enhancement has been incorporated into these two new field lenses. The drop-off in light transmission common to all long zoom lens at their longer focal length settings (generally termed "Ramping") has long been the nemesis of the camera operator. A special collaboration between Sony and Canon produced a novel solution to this. This realtime lens-camera compensation is termed Automatic Restoration of Illumination Attenuation (ARIA) system and engages a gain adjustment system within the field camera that is controlled by digital information from the lens reporting on the precise focal range settings. The system also dynamically compensates for relative light illumination across the image plane based on zoom, focus, and iris data from the lens.

An important redesigned built-in image stabilization system is described. The system can increase the degree of compensation, extends the frequency range of that compensation, and virtually eliminates the lag associated with sudden cessation of panning/tilting operational actions. Digital system interfaces are identified.

1.0 INTRODUCTION

The history of HDTV long zoom field box lenses is one of relentless pursuit of focal ranges that can enhance the choreography of multi-camera coverage of all forms of sporting events, concerts, and a range of other outside broadcast events. The design constraints on achieving extended telephoto ranges while also supporting a wide field of view at the wide end have long been the dilemma for optical manufacturers. Figure 1 shows the current portfolio of long zoom lenses offered by Canon for HDTV outside broadcast coverage.

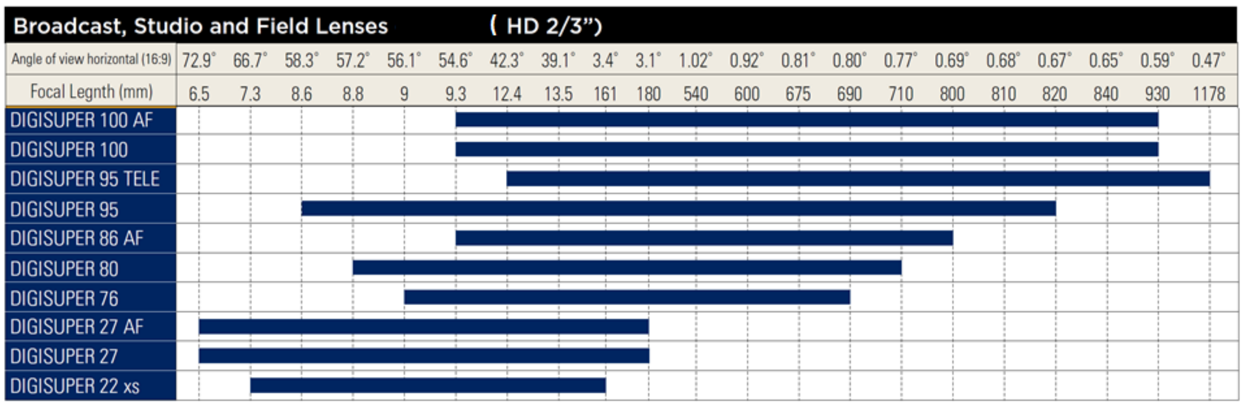


Figure 1 *Summarizing the contemporary Canon range of 2/3-inch HDTV long zoom field lenses*

Over that past half-decade growing worldwide interest in covering major sports and events in 4K UHD has propelled a highly competitive dynamic in developments of related field cameras and lenses. Major outside broadcasts in 4K UHD have been conducted worldwide during this period and especially over the past two years.

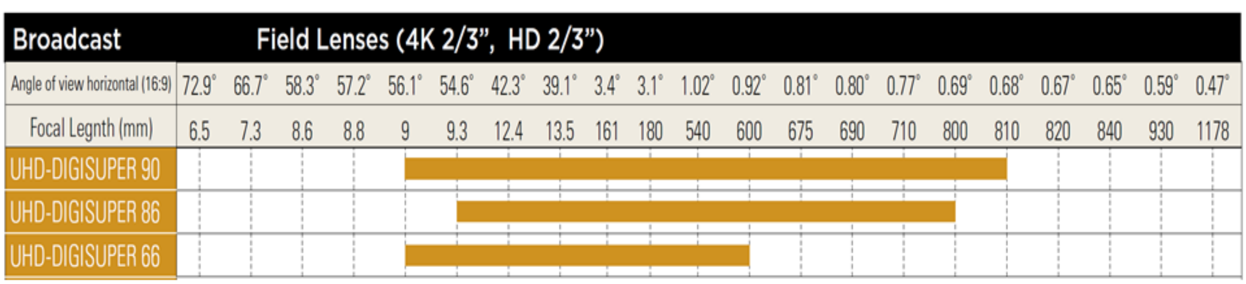


Figure 2 *Summarizing the contemporary Canon range of 2/3-inch 4K UHD Long zoom field lenses*

In numerous discussions with producers and camera operators in the sporting world many of them have challenged the optical manufacturers to "go for" the 1000 mm goal. However, many also insisted that the wide angle field of view could not be compromised in pursuing that quest.

2.0 REQUESTS FOR SECOND GENERATION 4K UHD FIELD LENS

Canon recognized that 4K UHD was being increasingly adopted worldwide to cover major sporting events, concerts, and other major outside broadcast events (royal weddings, papal visits etc.) [1]. The extraordinary image quality of 4K, the consumer trend to migrate to ever larger home displays, and the competitive dynamics in 4K UHD camera and lens developments spurred consideration of a major development project, having a goal of producing a second generation 4K UHD field lens that would qualify for the highest profile events. This project would simultaneously push the boundaries of all three core specifications of a field lens – as illustrated in Figure 3.

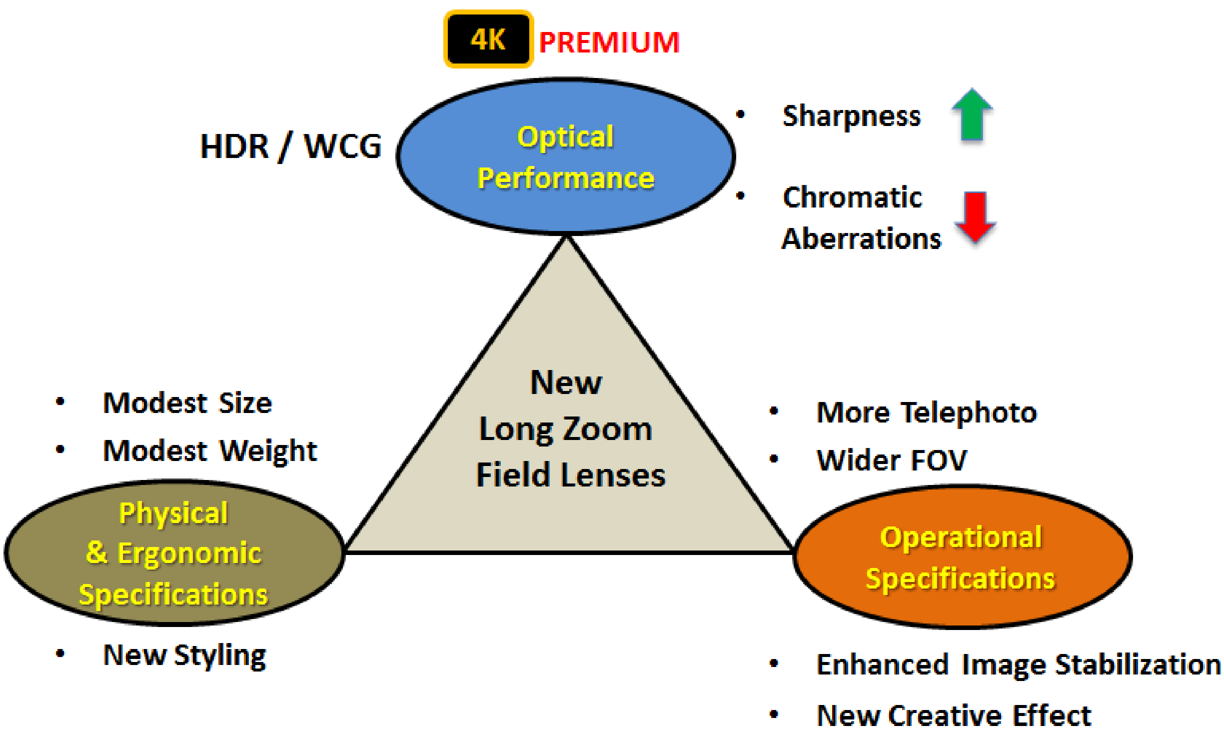


Figure 3 *Summarizing the three core specifications underlying long zoom field lens design – optical performance, operational specifications, and ergonomics*

2.1 Extending Operational Specifications

Central to the new lens design was the very specific goal to extend the focal range in both directions – targeting greater than 110:1 zoom range while simultaneously widening the field of view at the wide extremity to at least 60 degrees' horizontal.

Sports coverage continues to broaden in scope and today encompasses diverse venues posing greater challenges to the focal range capabilities of the field lens. The polo playing field – with its length of 900 feet – is an excellent example of this as shown in Figure 4. The ability to fully frame a horse and rider from a field extremity is particularly attractive to the sports director.

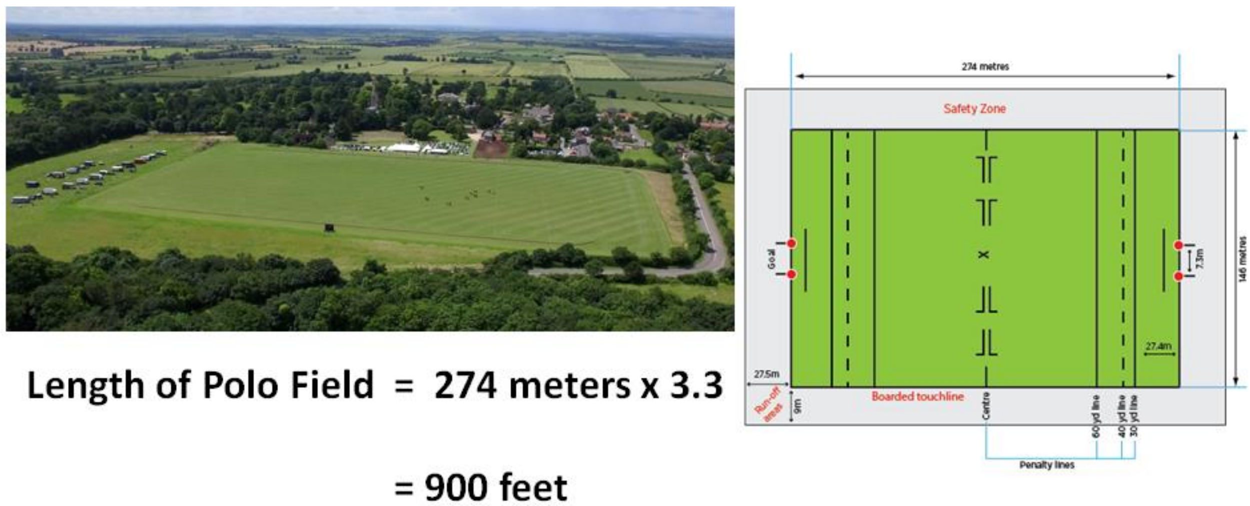
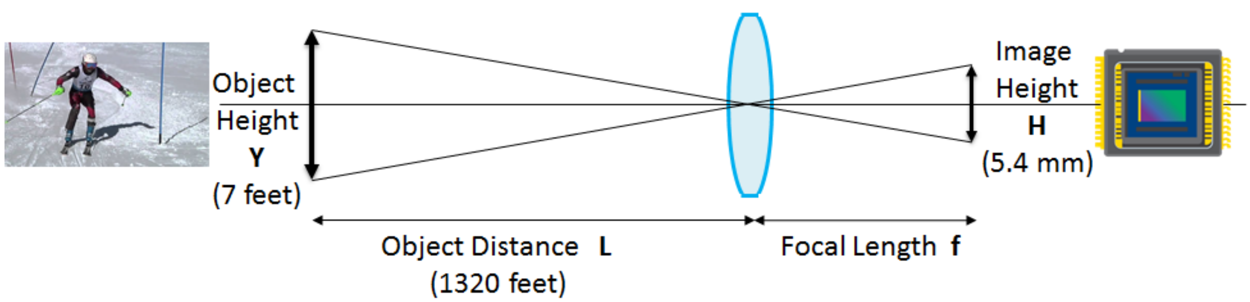


Figure 4 *The polo playing field (900 feet long) poses a unique challenge to the telephoto field lens*

Major sporting events like skiing entail considerable distances and challenges for strategic field lens-camera placements. The focal length requirement to fully frame a skier (assuming an approximate overall height of 6 feet) on a 2/3-inch image sensor (having a 5.4mm height) from a distance of one quarter mile (3210 feet) can be calculated as outlined in Figure 5.



Focal Length $f = H \times L / Y$

$= 5.4\text{mm} \times 1320 \text{ feet} (\times 12 \times 25.4)\text{mm} \;/\; 7 (\times 12 \times 25.4)\text{ mm}$

$= 1018 \text{ mm}$

Figure 5 *Showing the calculation of requisite focal length to fully frame a skier from a distance of one quarter mile*

With these considerations in mind, Canon set a target of 1000 mm for the maximum focal range of one of the new field lenses.

The zoom servo speed was also considered important for an ultra-telephoto lens and a goal of achieving 0.5 second to cover the total focal range was set.

2.2 Extending Optical Performance Specifications

The critical image performance parameters of the contemporary 4K UHD lens-camera system are illustrated in Figure 6. The lens applies the first performance footprint on the image within any lens-camera acquisition system and in that context lens optical performance is critical to the three core image quality parameters circled in red.

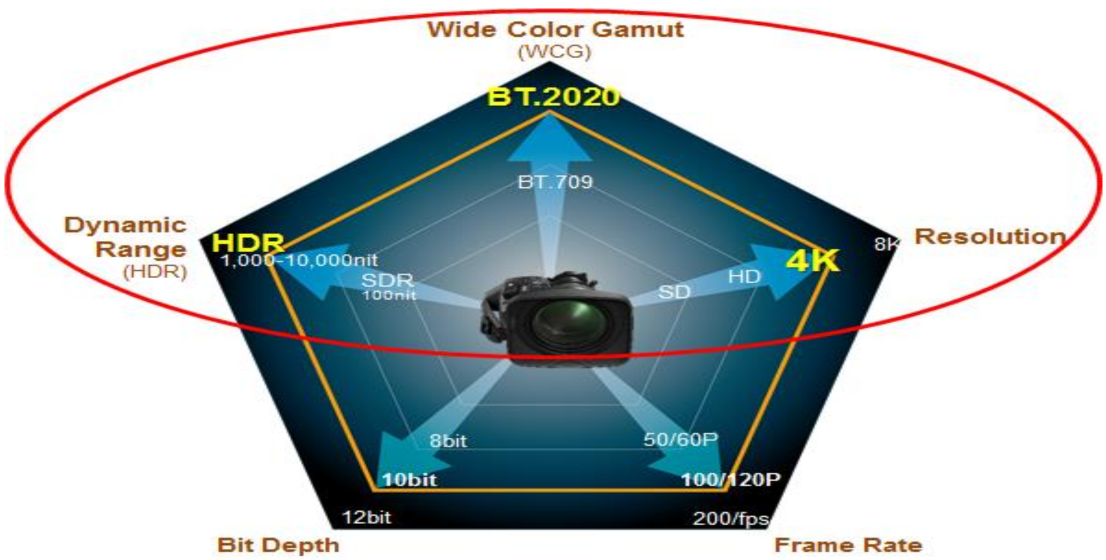


Figure 6 *The critical image performance parameters required for high quality 4K UHD lenses*

For 4K UHD motion imaging the image sensor deploys four times more spatial samples than HDTV. That elevates the challenge of minimizing chromatic aberrations as the sensor can now "see" even small degrees of this. While High Dynamic Range (HDR) and Wide Color Gamuts (WCG) can significantly enhance the subjective appeal of many images there is a negative aspect to these attributes. They further enhance the visibility of these chromatic aberrations – placing an even higher onus on the optical design to suppress them to where they become subjectively invisible.

Canon set high goals for the overall optical performance of the new field lenses. The resulting overall 4K UHD optical performance is such that the lenses are defined as **4K Premium.** Elevating the design aspirations to the 4K Premium level placed the highest priority on maximizing the 4K sharpness – especially at picture edges – while simultaneously minimizing the visibility of chromatic aberrations. In addition, considerations of image enhancements from HDR and WCG were also folded in as summarized in Figure 7.

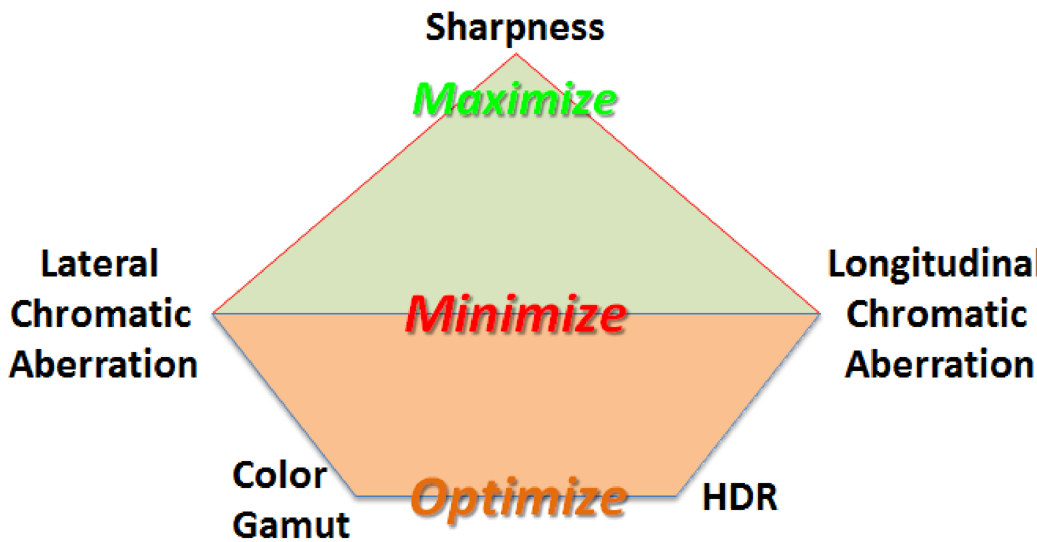


Figure 7 *Summarizing the pivotal design goals in producing a 4K Premium lens*

This paper will discuss those performance specifications in some detail.

2.3 Extending the Physical Specifications

Long zoom field lenses are typically large. Of necessity, many of the optical subgroups within the lens are large in order to achieve the operational and performance specifications demanded in such lenses. Surface tolerances of all of the glass elements are in the fractions of a nanometer for 2/3-inch 4K UHD optical systems – to ensure specified performance levels. Given the wide range of environmental conditions these lenses encounter over the course of a year the supporting optomechanical system must be unusually robust and incorporate a variety of mechanical strategies to compensate for the differential temperature coefficients of glasses and metals. The new lenses incorporate the most sophisticated mechanical strategies in terms of precision alignment of the dozens of glass elements – critical to sustaining 4K performance – and maintaining that alignment over a broad environmental temperature range.

Outside Broadcast lens-camera systems are vulnerable to a variety of physical perturbations (platform vibrations, wind blowing, etc.) that can cause image blur. Even a small degree of blur can mar the excellent sharpness of the 4K image. A particular priority was placed on improving the performance of the built-in image stabilization system in recognition of the ultra-sensitivity of the very high 4K resolution image to even the tiniest physical perturbation.

3.0 DEVELOPMENTS IN OPERATIONAL SPECIFICATIONS

3.1 Extension of Focal Range Specifications

The operational parameters of the two new lenses are summarized in Table 1. It is immediately apparent that a major breakthrough in focal ranges has been achieved. With the UJ122x 8.2B the 1000 mm barrier has been breached at the telephoto end. Simultaneously, the angle of view at the wide extremity of the two lenses has been opened – to more than 60 degrees' horizontal.

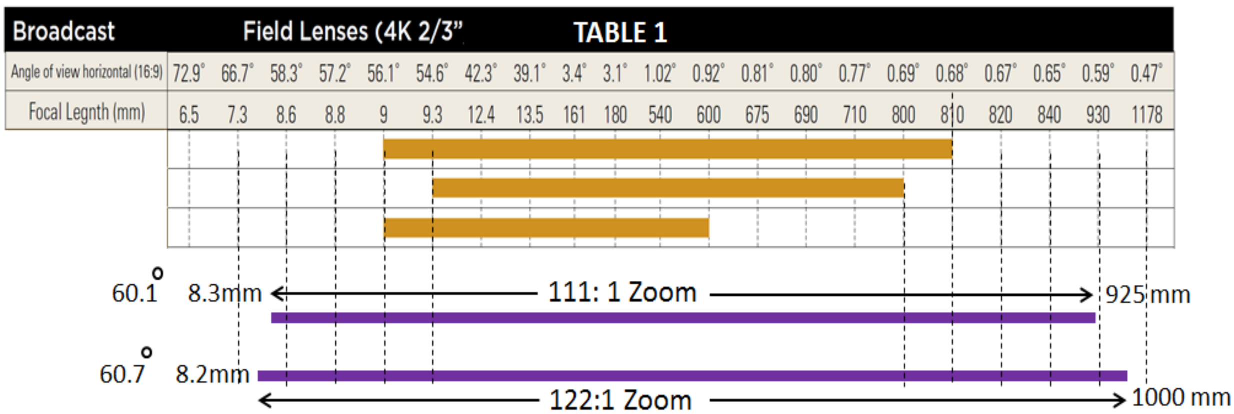


Figure 8 *Summarizing the focal ranges of the two second generation 4K UHD field Lenses*

TABLE 1 Operational Specifications of the two Second Generation 4K UHD Field Lenses

	4K Premium Canon UJ122x8.2B IESD		4K Premium Canon UJ111x8.3B IESD	
Extender	1.0x	2.0x	1.0x	2.0x
Focal Length	8.2 – 1000 mm	16.4 – 2000 mm	8.3-925mm	16.6-1850mm
Zoom Ratio	122x		111x	
Maximum Relative Aperture (F number)	1:1.7 (8.2 - 340 mm) 1:5.0 (1000 mm)	1:3.4 (16.4 - 680mm) 1:10.0 (2000 mm)	1:1.7(8.3-340 mm) 1:4.65 (925 mm)	1:3.4 (16.6-680 mm) 1:9.3 (1850 mm)
Angular Field of View	60.7° x 36.5° (8.2mm) 0.55° x 0.31° (1000mm)	32.6° x 18.7° (16.4mm) 0.28° x 0.15° (2000mm)	60.1° x 36.0° (8.3mm) 0.59° x 0.33° (925mm)	32.3° x 18.5° (16.6mm) 0.30° x 0.17° (1850mm)
M.O.D.	3.0 m*		3.0 m*	
Shooting Range at M.O.D.	314.8x177.1 cm* (8.2 mm) 2.7x1.5 cm (1000 mm)	157.4x88.6 cm* (16.4 mm) 1.4x0.8 cm (2000 mm)	311.6x175.3cm* (8.3 mm) 2.9x1.6cm (925 mm)	155.8x87.7cm* (16.6 mm) 1.5x0.8cm (1850 mm)
Approx. Size (w x h x l)	approx. 9.9 x 10.1 x 25.1 in./ approx. 250.6 x 255.5 x 637.4 mm		approx. 9.9 x 10.1 x 25.1 in./ approx. 250.6 x 255.5 x 637.4 mm	
Approx. Weight	approx. 58.6 lbs / 26.6 kg		approx. 58.6 lbs / 26.6 kg	

3.2 New Optical System

As a consequence of the significant elevation of the operational capabilities of these lenses – and ever cognizant of the goal to achieve 4K Premium performance level across the extended zoom ranges – a total redesign of the optical system was undertaken. Powerful computer simulation was extensively used. The redesign entailed the all-important input floating focusing optical group and the separate optical subgroups involved in the lens zooming system. The optical team explored latest glass materials, optimum number of elements, element shapes, element groupings, use of aspheric elements, while the optomechanical team explored mounting strategies for the lens elements that could withstand extreme environmental conditions envisaged for these lenses.
Optomechanical considerations also guided the design of the optical subgroups that implement the zooming action – with high attention paid to their individual size, weight, and stroke distances – to help ensure the desired high zoom speed.

Ultimately a central optical design emerged that embodied two core areas of new optical innovations:

- New Input Floating Focusing Group
- New Multigroup Zooming System

Figure 9 outlines the optical system of these two lenses. The rectangles indicate lens element groups (numbers in red are the number of individual lens elements within that subgroup. The relative sizes of the rectangles are indicative of the actual sizes of the lens elements in each subgroup.

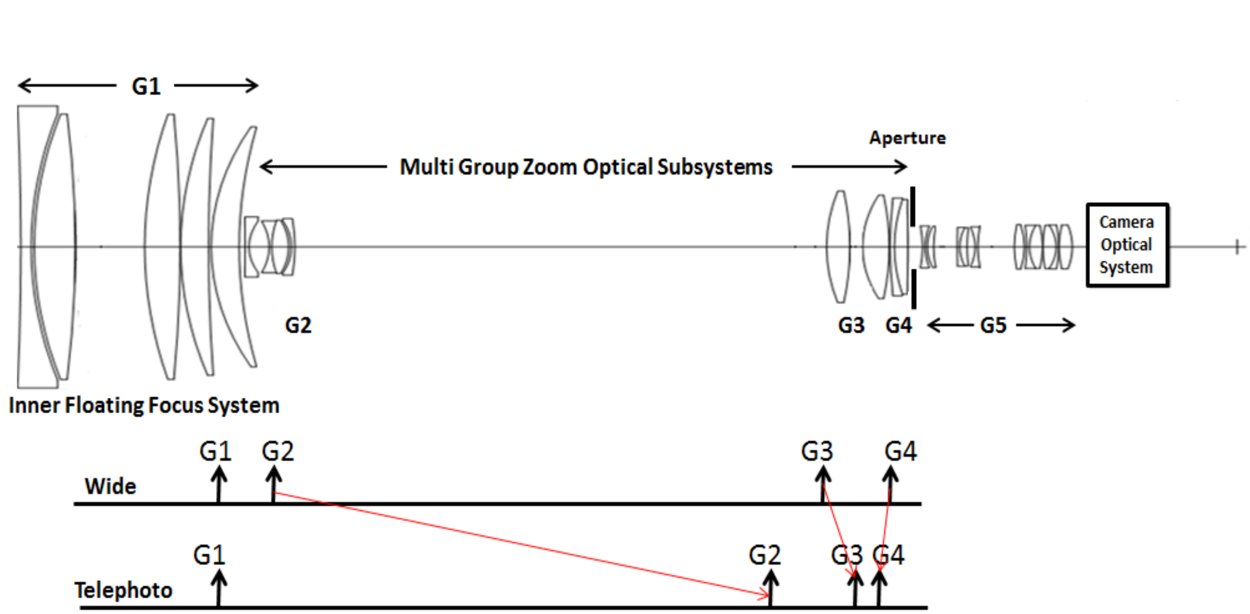


Figure 9 *Redesign of the optical subsystems for Focus and Zoom were critical to matching the size and weight of the new 4K UHD lenses to the former HDTV long zoom lenses*

3.2.1 New Input Focusing Group

The input focusing system is comprised of three separate lens element groups with a differential movement of the two groups within G1 implementing the focusing action.

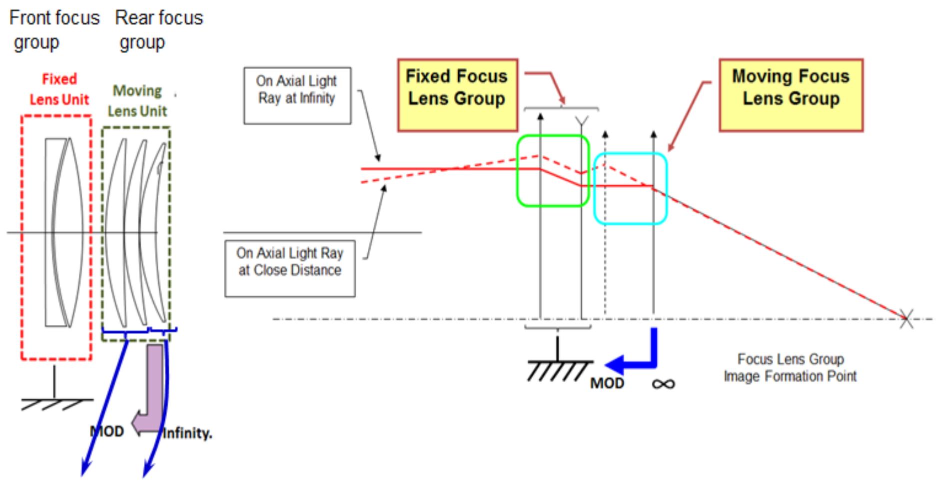


Figure 10 *A newly developed Floating Focus Group helped to minimize focus breathing and helped to ensure UHD optical performance*

3.2.2 Multigroup Zooming system

The earlier generation of studio and field zoom lenses utilized a traditional dual group zooming system comprising the Variator optical group and the Compensator optical group as typified in Figure 11. Zooming action entails the differential movement of these two optical subsystems as shown below.

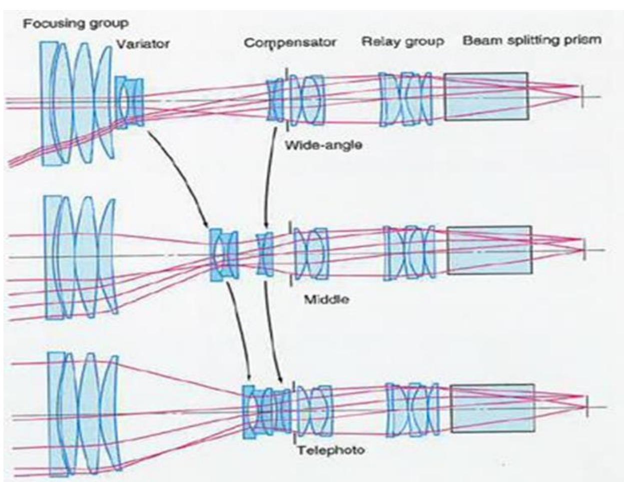


Figure 11 *Two optical groups that implement the zooming action in the ENG or EFP zoom lenses*

Within this two-group zoom system the Variator has the longest trajectory. The zoom torque associated with a given lens group that must be overcome by the drive unit is determined by the mass of that group times its zoom stroke distance. The mass of a given lens element is proportional to its diameter cubed – thus, if the diameter of a lens element is reduced to 80% its mass is approximately halved. This became a key consideration in this second generation lens design.

In seeking longer focal ranges for these new lenses the challenges in achieving the requisite zooming speeds while also achieving UHD performance were escalated. This called for a new design approach to the zooming optical subsystems. The central goals were to achieve greater control over multiple lens aberrations to help ensure full 4K performance while at the same time expediting an increase in the speed of the zooming action (when the digital drive unit is set to maximum zoom speed).

Referring to Figure 9 – the Multi Group Zoom Optical Subsystems are comprised of G2 (known as the Variator) and the two groups G3 and G4 (collectively known as the Compensator) that move differentially with respect to each other during the zooming operation. This is a sophisticated system whose overall design was critical to minimizing the movements of system MTF during zooming and to curtailing both monochromatic and chromatic aberrations. It was important to reduce the weight and stroke distance of the G2 group (having the largest stroke) while also reducing the stroke distance of the G4 group (having the largest weight).

Th***e*** Rear Group (G5) design is critical to the compensation for various lens aberrations.

The following summarizes the high level design strategies required to achieve the leap forward in focal range and the enhanced 4K UHD optical performance:

- New advances in optical design theories aided by powerful computer simulation capabilities
- New multi-group moveable lens elements for reduction of zoom fluctuations in MTF
- New Inner floating focus system design contributing to optimization of the falloff of MTF across the total image plane
- Greater use of aspheric lens elements
- Fluorite, Super-UD, and UD glass elements in new configurations to help significantly tighten control over chromatic aberrations
- First use of Air Sphere Coatings (ASC) in a broadcast lens
- Advances in material technologies, processing technologies and polishing technologies

3.3 ARIA – Automatic Restoration of Illumination Attenuation

3.3.1 Lens Ramping – A Longstanding Challenge

While most directors and camera operators have accepted that long-zoom broadcast field lenses exhibit the onset of a progressive loss in light output when a certain focal length is reached and exceeded – often termed the "ramping" behavior – they have always felt hampered by this. They do understand the trade-off between focal range and lens size and weight and that lens manufacturers make the best pragmatic choices for a given lens – but this unwanted attenuation in illumination on the camera image sensor at best remains an irritant and at times (in certain low light situations) it can be a serious impediment. The associated sudden onset of a drop-off in camera output video level during a lens zooming action remains the nemesis of the camera operator's activities during live broadcast coverage of sports and other outside broadcast events.

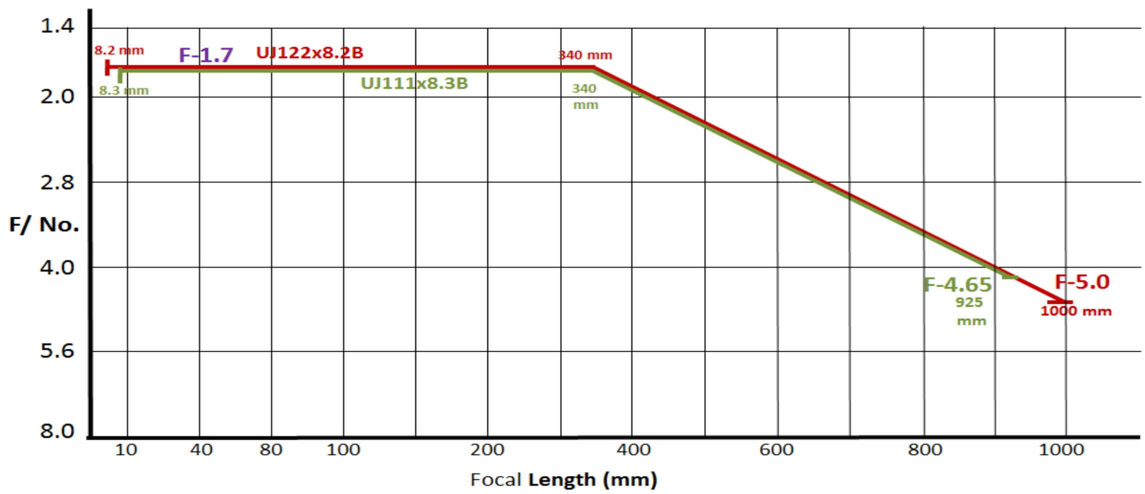


Figure 12 *Showing the ramping characteristics of the UJ122x8.2B and the UJ111x8.6B lenses*

3.3.2 The Solution – Compensation System for Ramping

A Sony-Canon collaboration created a relatively simple – but quite effective – compensation for this limitation that, from a subjective viewpoint, virtually eliminates the visual impairment. The standardized communication between the 2/3-inch lens and camera includes a digital reporting on the changing focal length of the lens during zooming actions. The camera extracts that digital signal and uses it to actuate a digital gain control as shown in Figure 13. As soon as the focal length reaches that focal length where ramping begins the gain control will start to linearly elevate the signal level in accordance with the further progressions of the zoom control.

This excellent feature has been branded as ARIA – meaning **A**utomatic **R**estoration of **I**llumination **A**ttenuation.

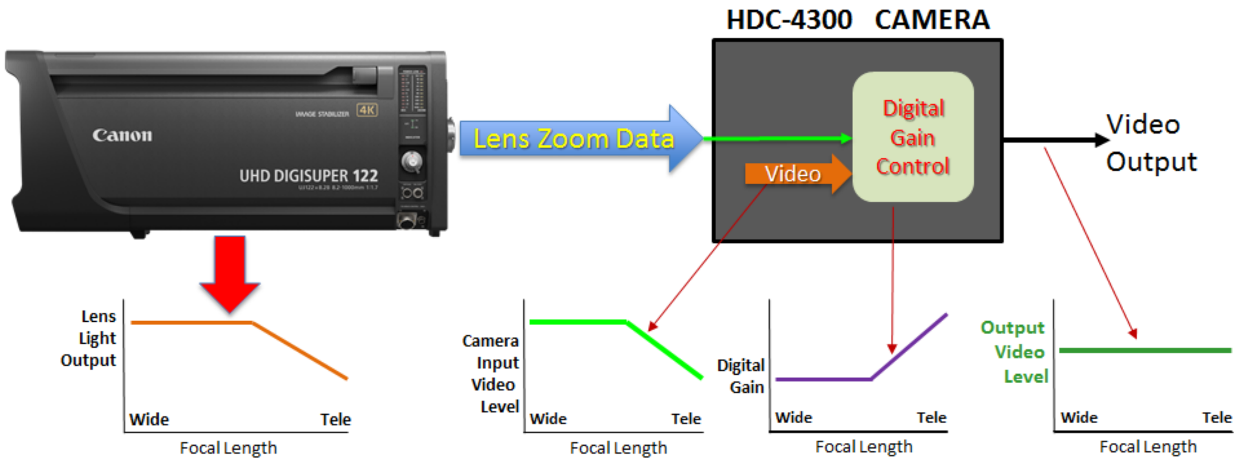


Figure 13 *Showing the principle of operation of the ARIA system*

3.3.3 Relative Light Distribution – Another illumination Attenuation

The specified lens F-number indicates the brightness of a lens at the *center of the optical axis.* The brightness at the *edge of the image* is invariably less and is expressed as a percentage of the center illumination. This peripheral illumination is sometimes termed Peripheral Illumination and is affected by (a) by the Cosine 4th Power Law, and (b) by optical vignetting. It is the second form of illumination attenuation.

The Cosine 4th Power Law states that the amount of this fall-off is proportional to the Cosine of the angle (at which the light rays are entering with respect to the optical axis of the lens) raised to the fourth power.

Vignetting (caused by the physical fact that the lens mechanical barrel eclipses part of the peripheral light, which causes a 360-degree darkening of the edges of the optical image and can be virtually eliminated if the diameter of the lens optics is sufficiently increased. Vignetting decreases as the lens is stopped down (which also improves the relative light distribution profile).

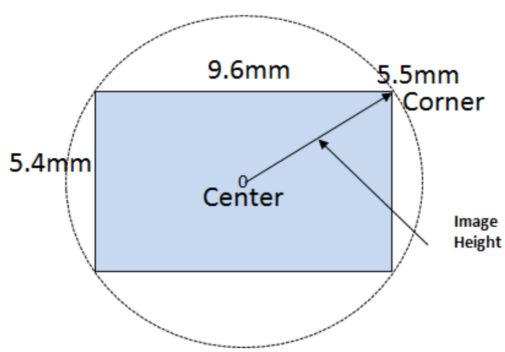


Figure 14 The Relative Light Distribution for the 2/3-inch image format is described as a percentage brightness change as a function of image height

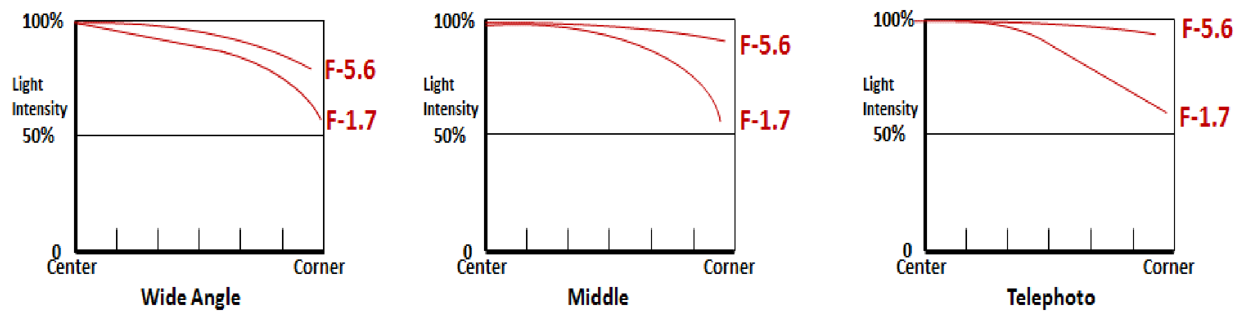


Figure 15 *Showing a typical peripheral illumination behavior of a lens at different focal lengths*

Traditionally, the process of "White Shading" is defined as the electronic compensation performed in the camera for the aberrations in video brightness or color associated with peripheral illumination. This is a manual process performed by the studio video operator. Waveforms in the form of horizontal and vertical sawteeth and parabolas are used to modulate a realtime gain control within the camera RGB processing to implement this compensation. Camera shading situations range from the highly controlled environment of the broadcast studio to the far less controlled scene illuminations encountered in outside broadcast productions. The challenges of the latter are overcome with the innovation of the ARIA system.

3.3.4 ARIA and Correction of Relative Light Illumination

Based upon the lens digital reporting on the individual settings of Zoom, Focus, and Iris, the HDC-4300 camera controls a digital gain control system that implements in real time the necessary nonlinear horizontal and vertical gain modulation that evens the video level fall-off across the image plane.

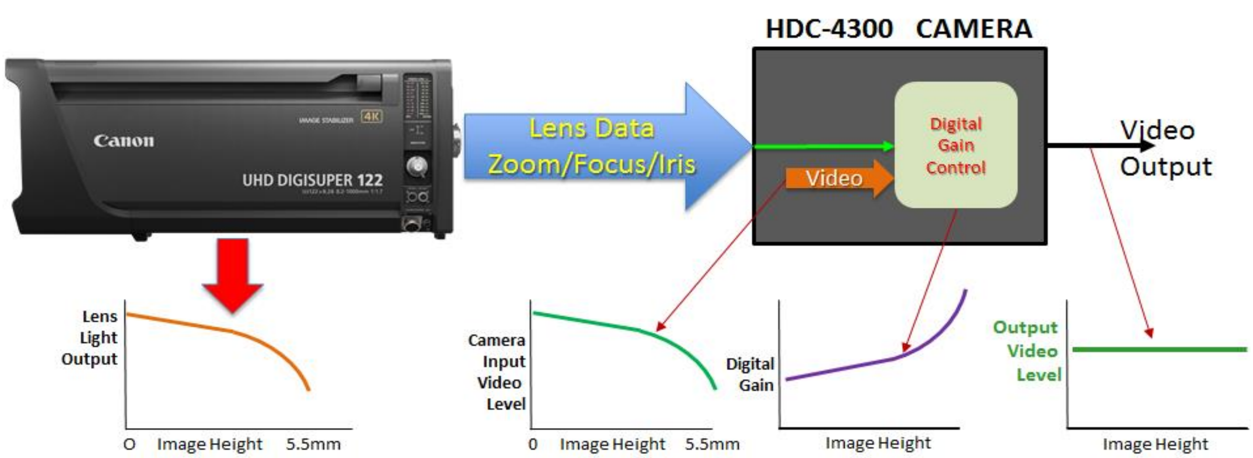


Figure 16 *Showing the camera gain modulation proportional to the lens peripheral illumination date*

4.0 DEVELOPMENTS IN 4K UHD OPTICAL PERFORMANCE

4.1 Extending the 4K Optical Performance Specifications

The two lenses are labeled 4K Premium and that does warrant an explanation as it is central to the extension of the performance specifications.

4.1.1 4K Picture Sharpness

Figure 17 shows the relationship between the Nyquist frequency of the 4K image sensor and the associated optical Nyquist frequency. Also shown are the MTF characteristics of the latest generation HDTV lens and the new 4K Premium lens – *both specified at picture center.*

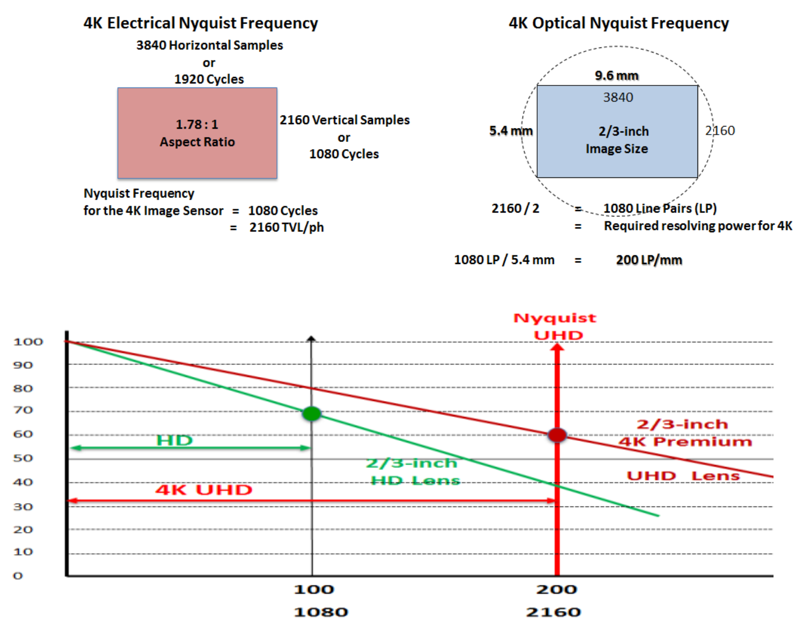


Figure 17 *MTF at picture center of the 4K UHD lens compared to that of a high-end HDTV lens*

It will be noted that the 4K Premium lens has a high depth of modulation at the 200 LP/mm Nyquist frequency. The significance of this is shown in Figure 18 where that lens MTF is convoluted with a hypothetical 4K camera MTF to produce the final lens-camera MTF shown in green.

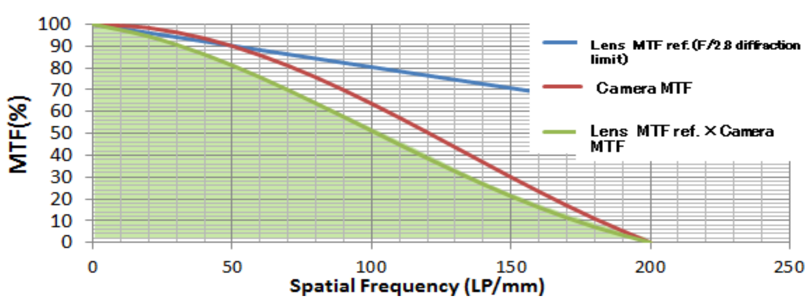


Figure 18 *The shaded green area is the lens-camera convoluted MTF*

The perceived subjective sharpness of the resultant lens-camera 4K image is related to the area of the MTF curve across the total bandwidth [2]. The greater that area the sharper is the perceived image. Figure 19 shows an approximation of the additional area that is added by the 4K Premium lens compared to that of a regular 4K lens.

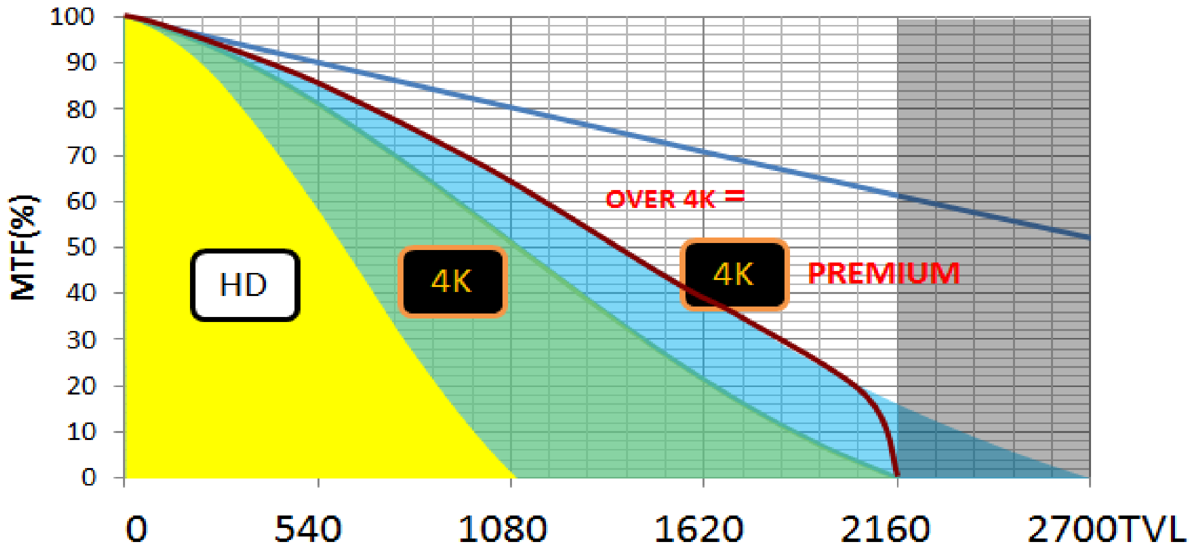


Figure 19 *The 4K UHD camera using the 4K Premium lens will deliver a higher MTF – as represented by the additional blue area*

The above discussion centered on the MTF at the picture center. Lens MTF falls off from that center toward the image extremities. It takes very sophisticated optical design strategies to manage the rate of that fall off and it is those strategies that distinguish the 4K Premium lens from a standard 4K lens. That difference is simplistically summarized in Figure 20.

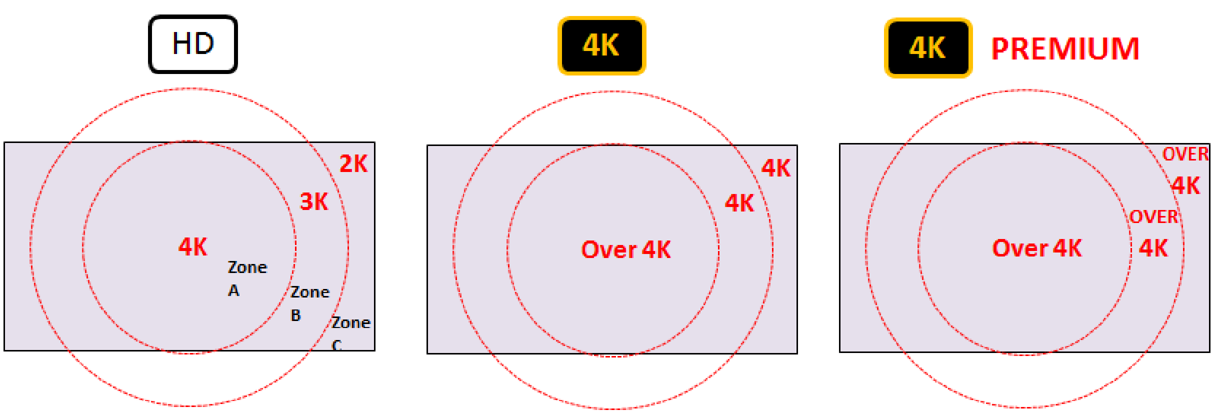


Figure 20 *Showing the difference in MTF profile across the image plane for an HDTV lens and the two levels of 4K UHD Lenses*

Critical to 4K image sharpness is extreme control over the accuracy of surface curvatures of each lens element. This becomes especially important to sustaining as high a sharpness as possible toward the image extremities. Recent advances in lens polishing technologies allow nanometer level control over surface tolerances. Figure 21 shows the final profile across the element surface using these new super-fine processes.

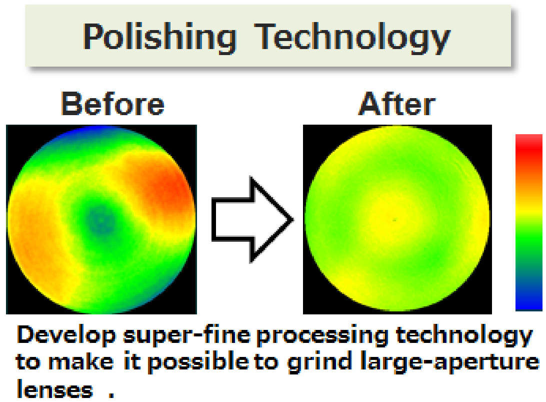


Figure 21 *Analysis of lens element surface tolerance following super-fine polishing process*

Powerful computer simulation capabilities have greatly reinforced the capabilities of design engineers to optimize both optical performance and optomechanical precision. One illustration is the ability to predict the tiny degree of deformation of a lens element by its mechanical retaining system – a deformation that can impair the critically important accuracy of ray transmission required for 4K resolution. Simulation allowed exploration of new optomechanical strategies to firmly support lens elements while minimizing their deformation. Figure 22 gives a sense of the power of these new design tools.

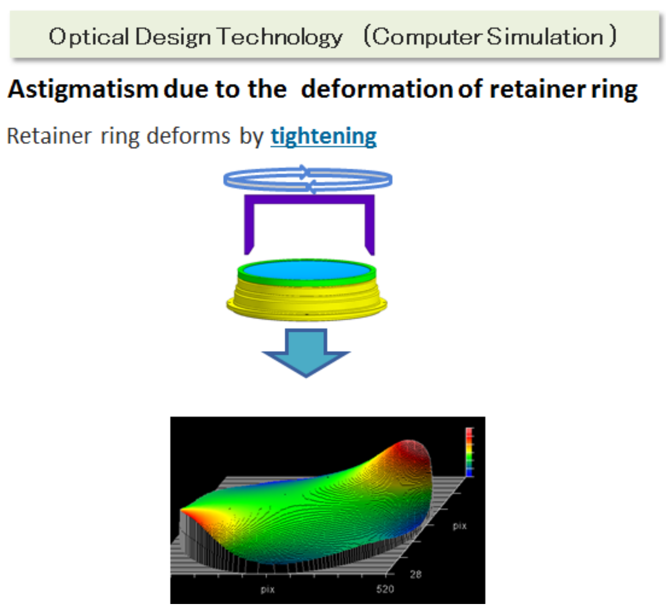


Figure 22 *The prowess of computer simulation aided the optimization of optical and optomechanical designs that minimize physical deformation of the lens element (shown in the lower image)*

4.1.2 *Minimization of Chromatic Aberrations*

Having four times more spatial resolution than HDTV the 4K UHD image sensors are capable of "seeing" much smaller chromatic aberrations than the HDTV sensor. Considering this doubling of both horizontal and vertical resolution, it is imperative that the lens mobilize design strategies to help minimize these aberrations.

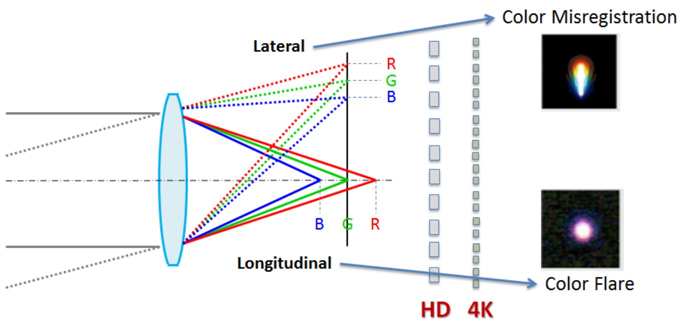


Figure 23 *The two chromatic aberrations and their increased visibility to a 4K image sensor*

In optical design a common strategy entails the use of more elements which offer additional degrees of freedom to optically compensate for the aberrations as the light rays traverse the system. However, lens size and weight constraints act as implacable opposition to over-utilizing the number of elements. Accordingly, other strategies were harnessed in this new lens design. Ultimately, this led to a radical new optical system design compared to that of the earlier HDTV long zoom lenses.

4.2 Special Challenge of HDR and WCG

Two important international standards recently emerged. The first was ITU Rec BT.2020 [3] that specified all of the formats entailed in UHD as well as a much wider color gamut (WCG) than that of HDTV. A second standard ITU Rec BT.2100 [4] specified all parameters relating to High Dynamic Range (HDR). These standards guided many aspects of the optical design of the new field lenses. These standards imposed additional challenges to the design of the new 4K UHD lenses.

Figure 24 *Showing the two key ITU standards for UHD Wide Color Gamut and HDR*

4.2.1 HDR

As illustrated in Figure 25 the disposition of the dynamic range of the camera image sensor defines a number of regions – having distinct optical attributes – within the overall light transmission through the lens.

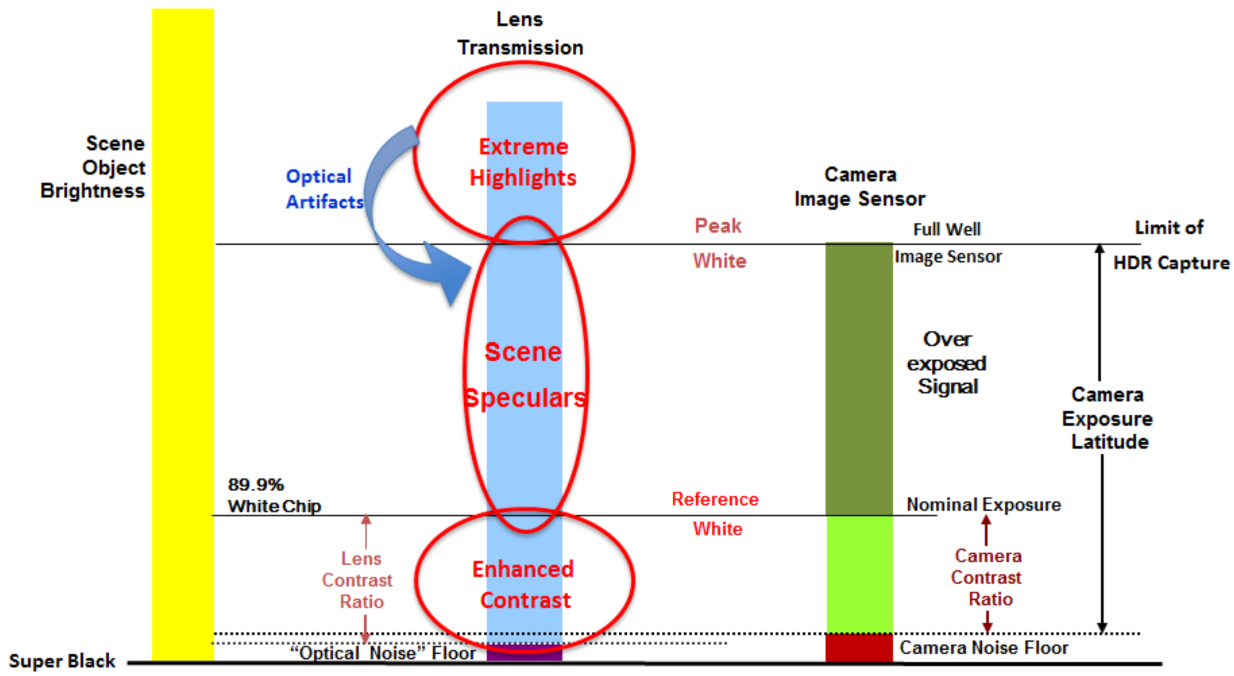


Figure 25 *Simplistic outline of the HDR significance to various levels of the lens optical transmission*

The optical performance of the lenses must accommodate the special demands of HDR in terms of the following:

1. **Deep Black Reproduction** – This defines the degree that the lens-camera system can reproduce detail in deeply shadowed areas of a scene.

2. **Excellent Contrast** – to help ensure reproduction of subtle tonal gradations and textures over the nominally exposed signal levels (from black to 100% reference white) that are considered central to 4K imaging

3. **Clean Reproduction of Specular Highlight** – which capitalize on the extended dynamic range of the contemporary image sensors and constitute an important aspect of HDR imaging

4. **Management of intense highlights** – such as those caused by direct sun reflecting off cars and windows and car headlights at night can stimulate unwanted optical artifacts that can contaminate the desired HDR reproduction

Considerations of HDR and WCG necessitated the deployment of new multilayer coatings to help facilitate clean black reproduction (HDR) and an augmented spectral transmittance (WCG). In the context of HDR the Air Sphere Coating (ASC) technology is a critically important additional layer on top of the normal multilayer coatings that are used to help minimize internal reflections that conspire to lower light transmission efficiency and to contaminate deep black reproduction. ASC comprises sub-nanometer spheres that implement an ultra-low refractive index layer that is powerful in its ability to remove any residual reflection – as shown in the bottom right image in Figure 26.

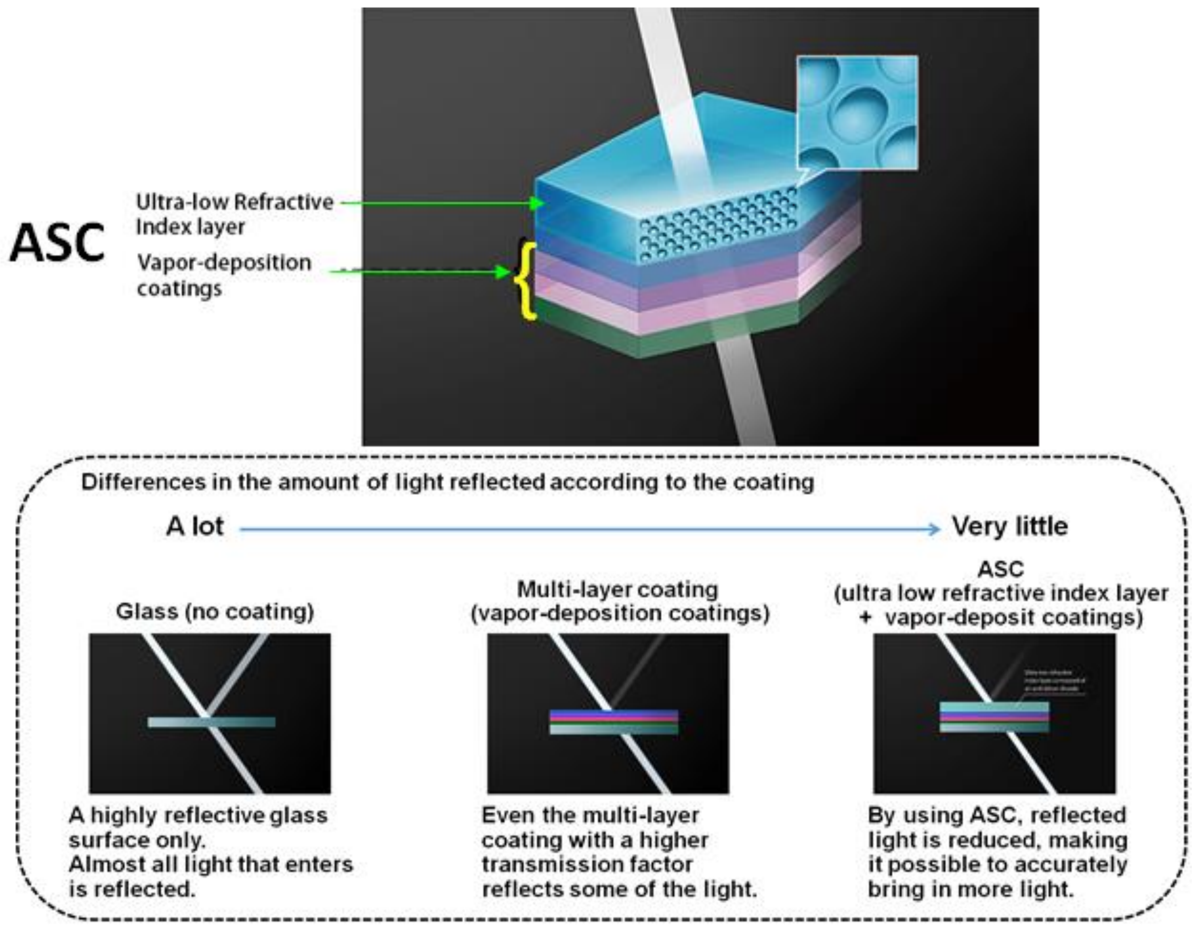


Figure 26 *Illustrating the reinforcement of ghost canceling offered by the addition of the ASC layer*

4.2.2 Wide Color Gamut

The color gamut of a camera is determined when the three spectral sensitivities of the image sensor(s) are processed to convert them to a three dimensional color space. That processing traditionally entails a 3 x 3 linear matrix – prior to application of the camera OETF transform. The spectral responses of the trichromatic RGB camera overlap to various degrees (design choice of the camera manufacturers).

The spectral response of the lens obviously modifies those of the camera.   The spectral response of the new lenses was refined to accommodate the wider color gamut specified in the ITU-R BT.2020-2 standard. An important linkage that exists between HDR and WCG is the reproduction of color [5].

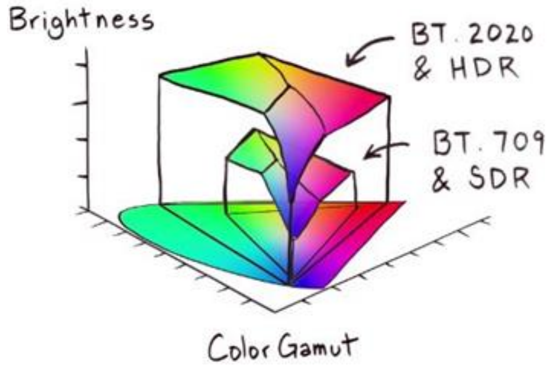


Figure 27 *HDR elevates the level of Luma and this, in turn elevates the color volume*

Both color and intensity bear directly upon the appearance of color [6]. However, not all colors are available at high intensities (blue being the principle example). Despite this, the higher intensities of HDR accordingly can help enhance the subjective richness of many colors – this is described as an increase in their color volume.

4.2.3 Effect of HDR / WCG on Visibility of Chromatic Aberrations

While HDR and WCG quite visibly enhance imagery there is an insidious side to them both – or rather, to their unanticipated effect on the visibility of chromatic aberrations. As stated earlier, the increased resolution of the 4K image sensor can render even a small degree of these aberrations more visible. The combined effect of HDR / WCG further elevates the visibility of a chromatic aberration that might be subjectively invisible in an SDR rendition.

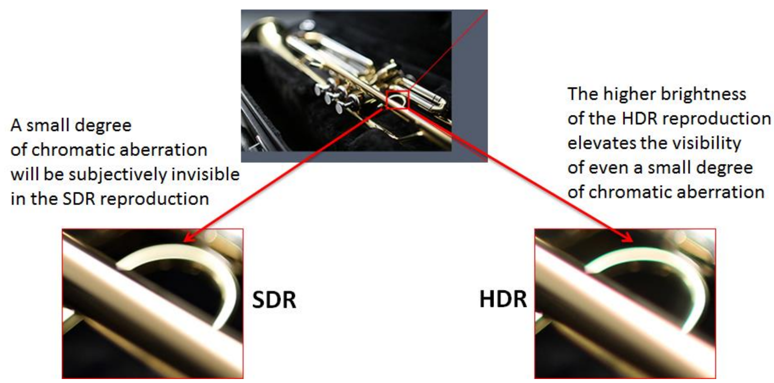


Figure 28 *Showing the effect that HDR / WCG can have on the visibility of chromatic aberrations*

4.2.4 Digital Corrections for Chromatic Aberration

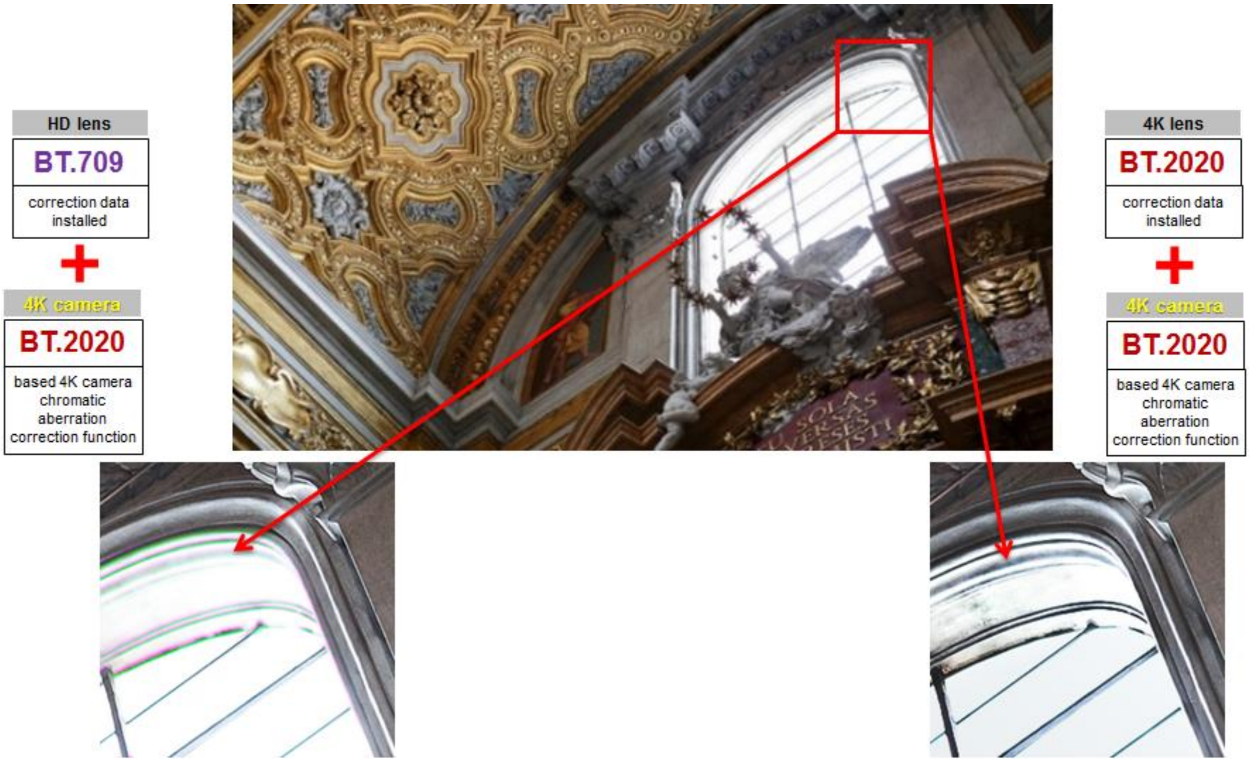


Figure 29 *It is important that the stored error files in a given lens are compatible with an associated camera*

4.3 New Creative "Bokeh Effect"

Long zoom field lenses are used to cover major concerts and other events, and here creative aspirations seek effects that can possibly add to the visual story-telling. In anticipation of this continuing trend, Canon is introducing a totally new operational control in these two new field lenses – that is termed "Bokeh Effect". The term "Bokeh" is known as a descriptor for the aesthetic quality of the blur produced in the out-of-focus parts of an image produced by a lens.

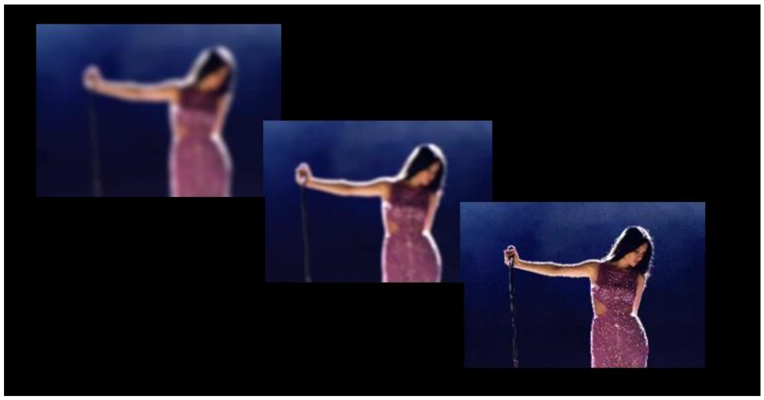


Figure 30 *Showing the progressive defocusing that can be introduced by the camera operator*

This new operational control moves part of the rear optical group G5 in the lens to implement the precision degree of defocus (see Figure 9).

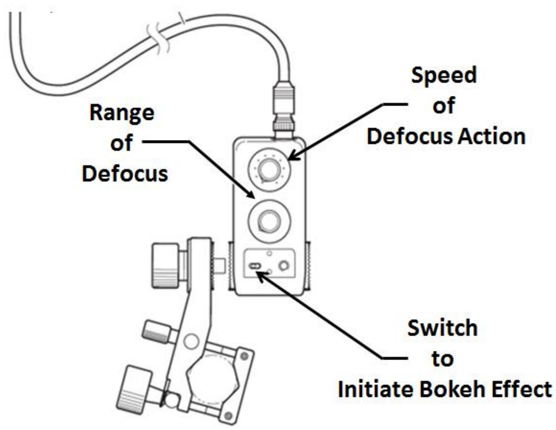


Figure 31 *Showing the macro controller available to the camera operator to implement the new "Bokeh Effect"*

When close to the wide end focal length of the lens – where the focus control has little effect on actual scene focus – this new macro control allows the camera operator to introduce a variety of controlled blurring effects into the image. Both the degree of blur and the speed of its implementation are adjustable by the camera operator. There is zero angle of view alteration. The effect can be switched off at will and precise focus is restored. Of special note is that the introduced blur is equally effective at the extreme telephoto focal range.

5.0 DEVELOPMENTS IN PHYSICAL ATTRIBUTES OF THE LENS

5.1 Challenge to Maintain Image Stability in Long Zoom Field Lenses

Long zoom lenses are very vulnerable to image instabilities caused by inadvertent perturbations or vibrations. There are several lens-camera motions that degrade images – defined as angular shake and lateral shake. Angular shake is blurring caused by an angular change (yawing and pitching) at the end of the lens with the camera or the lens base acting as the fulcrum. Such movements are typically in the 2 – 10 Hz range when the lens-camera systems are swaying on high platforms. That frequency range can extend up to 20Hz in situations where high winds are encountered.

For a broadcast 2/3-inch field lens with a 122:1 zoom ratio, a level of physical vibration having a deflection of a mere 0.05 degrees would produce an optical image disturbance that is more than half of the picture height when the lens was set to maximum focal length and the 2x extender switched in. This would create totally unacceptable imagery.

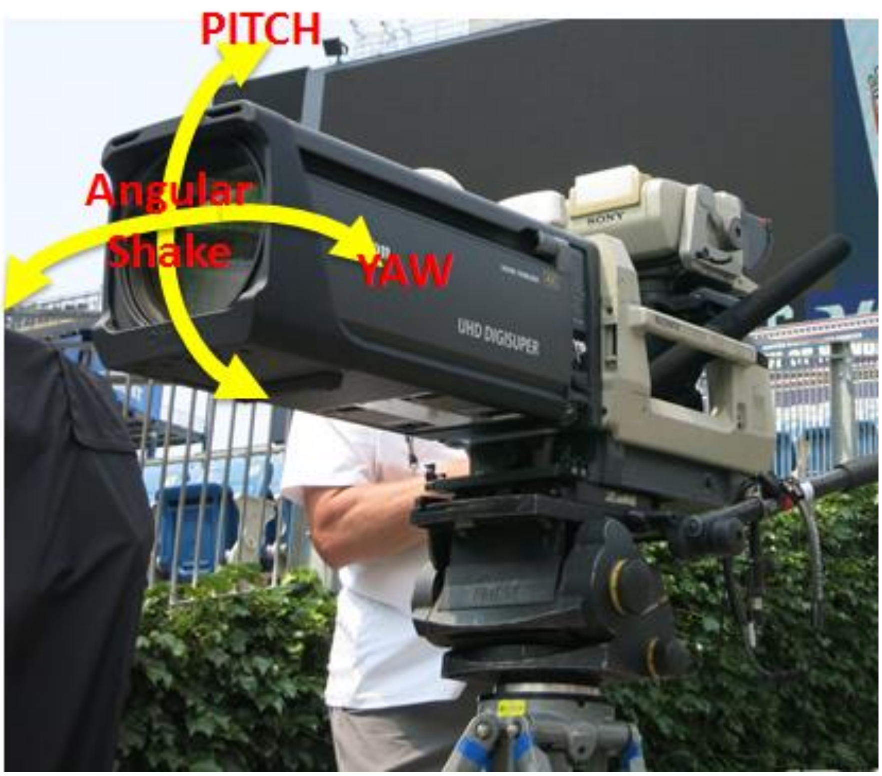


Figure 32 *Illustrating the types of lens perturbations regularly encountered on a shoot*

5.2 Principle of Shift-IS Correction

The new field lenses incorporate a built-in image stabilization system based on Shift-IS technology. The principle of the Shift-IS correction is illustrated in Figure 33 – which postulates a sudden vertical perturbation of the lens (center image) that would move the image projected on to the camera image sensor. But that inadvertent lens movement is sensed by motion detectors within the lens which reports this to the CPU which calculates a correction amount and direction that generates a control signal to move a special lens group to counteract that optical image shift and maintain a fixed image position on the image sensor.

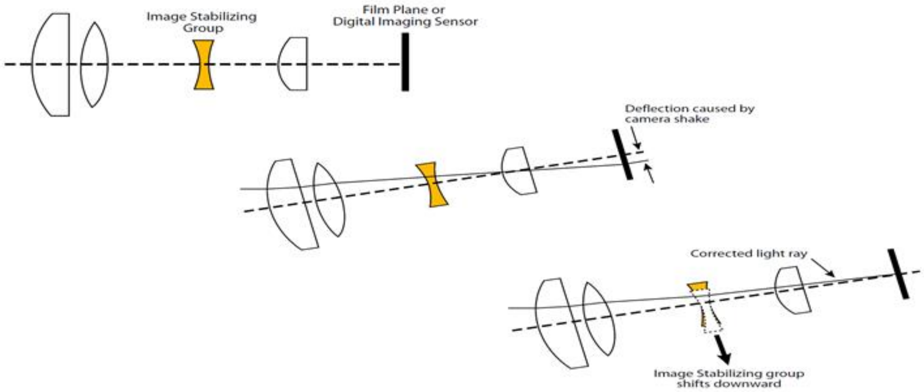


Figure 33 *Shift-IS stabilization relies on the controlled movement of a lens group to counteract the image shift caused by lens movements*

In terms of implementation, a lens group is placed near the rear of the lens system and the correcting action entails a horizontal or vertical (or both) physical shifting of that lens group (under microcomputer control) to implement the requisite change in the path of the light rays. The Shift-IS technology lends itself very well to correcting modest amplitude disturbances and vibrations in long focal range lenses.

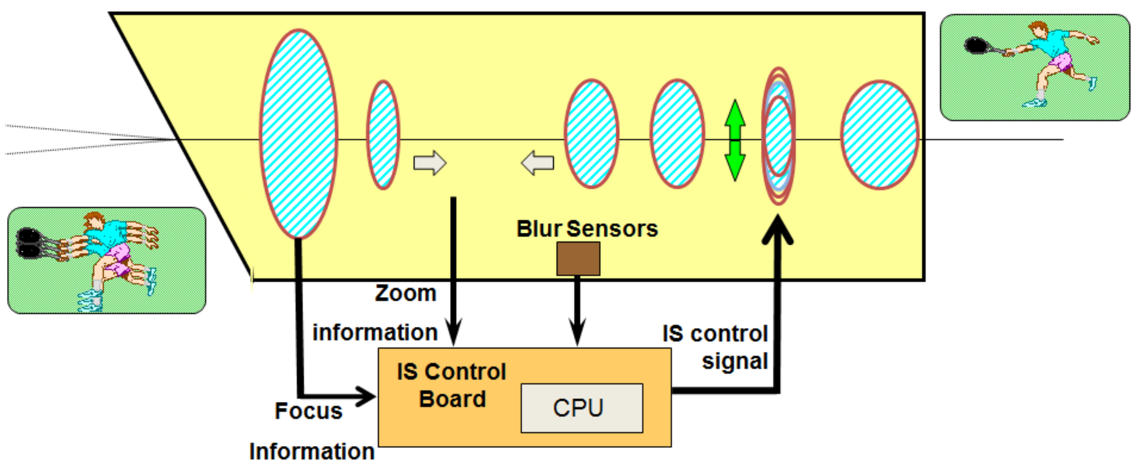


Figure 34 *The principle of Shift-IS technology is a control loop that positionally moves a lens group to counteract a horizontal or vertical (or combination of both) image shift caused by vibration*

5.3 Overall Control Loop for Shift-IS Correction

Figure 35 shows a simplistic overview of the control loop entailed in Shift-IS correction. The detection system requires simultaneous measurement of pitch and yaw. Motion detectors, one for horizontal movement, and a second for vertical movements, are positioned at optimal points within the large long-zoom lens body. Their electronic outputs are fed to the system microcomputer – where appropriate lens motion analysis is made. The microcomputer computes a correcting control signal which feeds driver circuits that, in turn, manipulate two actuator systems that physically alter the position of the shift lens assembly in either horizontal or vertical, or both, directions in a manner that restores the lens light rays to their correct intended position on the camera image sensor. Two position sensors that monitors the shift lens horizontal and vertical movements report back to the microcomputer thus closing a feedback loop having high speed and a high degree of precision.

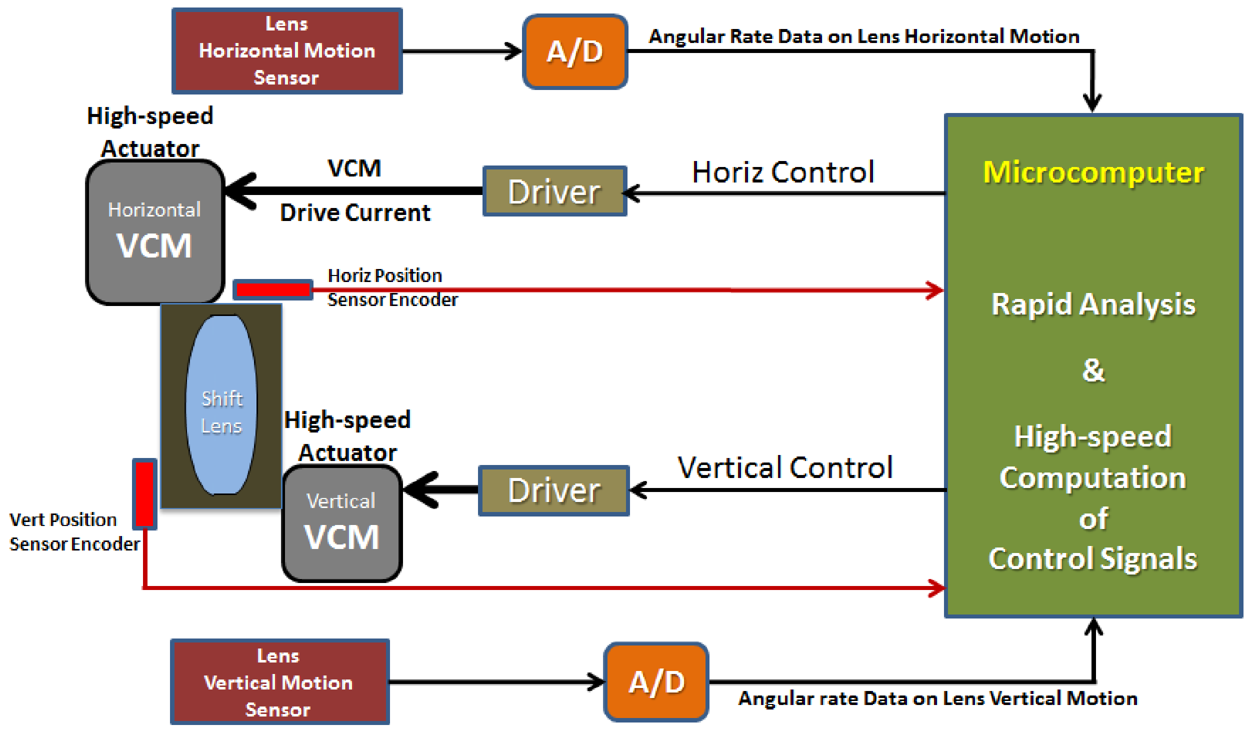


Figure 35 *Outlining the overall control system for Shift-IS correction*

For a correcting control system that can actuate the Shift-IS lens group with the requisite rapidity and precision required for virtual real-time removal of image shake, a closed loop feedback control system must be realized where all elements of that servo system function with high precision at very high speed. In particular, the transient response of the feedback control loop must be critically damped with particular attention paid to elimination of any overshoots or backlash in the actuators controlling the movements of the correcting lens group.

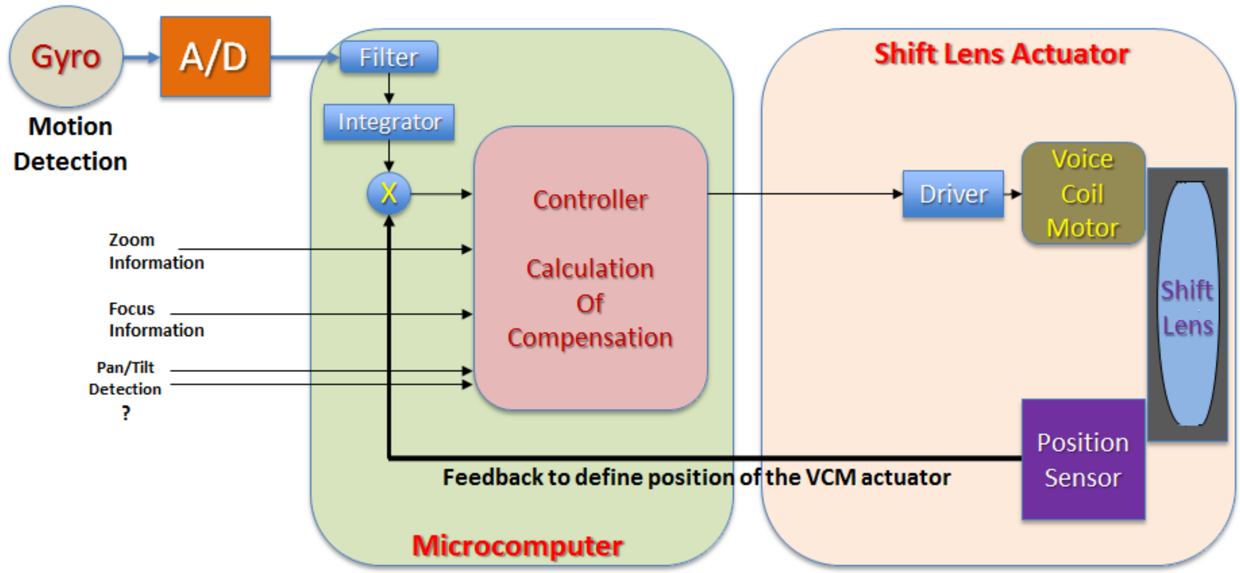


Figure 36 *Showing a high-level block diagram of the control feedback loop for one movement axis*

The motion detectors are dual-axis vibration gyroscope (piezoelectric angular velocity sensors) that detect the speed and angle of any lens movement. The microcomputer processes the angular displacement and the shift-lens position data, establishing the new set-point. The degree of success of the correction is critically dependent upon the achievement of essentially real-time control of the compensation lens group. That, in turn, is dependent upon:

1. Speed of detection of lens movement
2. Speed and precision of calculation of the degree and direction of the movement
3. Speed of actuation of the compensating shift-lens group
4. Accuracy of the shift–lens positioning detection

In the new IS system, high-speed arithmetic processing was enhanced by hardware evolution, making it possible to use sensors that can detect with high accuracy up to high frequencies. Furthermore, noise output from the sensors was reduced and this has been enhanced by development of advanced noise reduction technology that allows detection only of the required vibration components. Allied with improvements to the algorithm of the vibration suppression control, it has now become possible to provide a system that maintains high vibration suppression performance from low frequency to high frequency.

5.4 Detection of Vibrations and their Correction

Two gyroscopes sense pitch and yaw with high sensitivity. They output an angular rate data and this is first filtered to reduce offset drift contribution. The filtered angular rate data is then integrated to obtain the relative angular displacement caused by the lens vibration. It must then be scaled in order to convert the measured angular lens-camera movement into a directed linear movement of the shift-lens that will cancel the effect of the vibration effect on the image.

Actuation of the shift lens entails two key technologies. The first is Voice Coil Motor (VCM) technology that offers excellent control characteristics when strong and precise mechanical actuation over short physical distances under electronic control is required. The second is a closely integrated movement sensor producing a voltage proportional to the movement of the shift lens assembly that is used as the feedback signal.

The VCM's electromechanical energy conversion process is based on the Lorentz Force principle – see Figure 37.

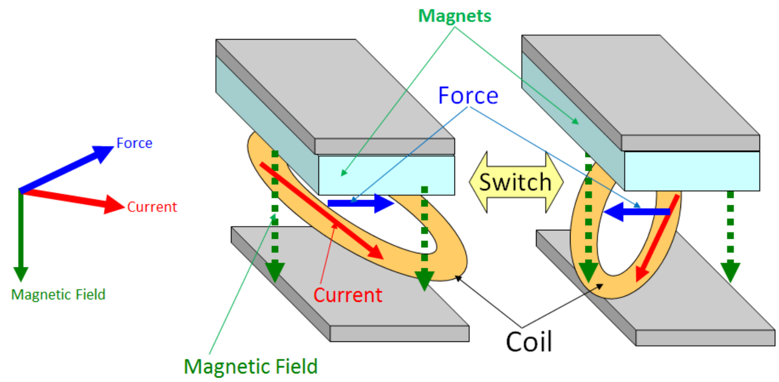


Figure 37 *Showing the principle of the Voice Coil Motor*

The coil is mounted on a non-magnetic arm and is free to move within the housing. When a current is applied to the coil the interaction between its electrically-generated magnetic field and the fixed magnetic fields generates a force that enables the shift-lens housing to move by a distance directly proportional to the power created by this current. Using a coil of low inductance, this makes possible cycle times that are typically an order of magnitude faster than solenoid devices. When the direction of the current is switched, the direction of the coil's movement will also change. One VCM applies YAW rotation and the second applies PITCH rotation.

5.6 Virtual Elimination of Image "Lag" Following Operational Pan/Tilt Movements

The image stabilization system must be capable of distinguishing between unwanted physical perturbations to the lens-camera system and operational control of panning and tilting of the same. It has long been the nemesis of the camera operator that a small degree of image overshoot (generally termed as "Lag" by sports camera operators) has followed the cessation of the operational pan and tilt movements – a consequence of a lingering confusion within the IS control loop. To this day this is the leading cause of camera operator refusal to engage the image stabilization systems on long zoom lenses.

In the UJ122x8.2B field lens new correction strategies have been implemented. Vibration isolation control using both angular velocity information and angle information became possible from vibration control that uses only conventional angle information. As a result, the vibration component of the sensor detection signal and the panning operation component can be separated rapidly and with high accuracy. The result is the virtual elimination of the lag associated with sudden cessation of operational movements of the lens-camera system.

6.0 Virtual System Support

The UJ122/111 lenses both feature a 16-bit absolute value encoder to support precision position information that is brought out on the standard 20-pin connector (same pin layout, and protocol as used in Canon's HDTV lenses). That information can be delivered as a serial communication or a direct count from the encoder's digital pulse.

Figure 38 *Showing the standard 20-pin connector used for the virtual interface*

7.0 Extending the Physical Specifications

The two lenses are physically identical. Every effort was made to maintain a size and weight familiar to the many operators of contemporary HDTV field lenses. Figure 39 compares the new UJ122x lens to that of the latest generation HDTV field lens – the XJ95x8.6B.

Figure 39 *Comparing the size and weight of the new UJ122x8.2B zoom lens with that of a high-end HDTV lens*

It should be noted that the dimensions are very close indeed – a mere 27 mm (approx. one inch) lengthening of the UJ122 and UJ111 compared to this HDTV long zoom lens. The weight did increase as shown – a consequence of larger optics and new lens element mounting strategies. The physical styling of the lens was enhanced over that of previous long zoom field lenses – as shown in Figure 40.

Figure 40 *Showing the new styling of the UJ122 and UJ 111 lenses*

Note the carrying handle has been extended almost the entire length of the lens body and that a curvature was added to the housing that aesthetically softens the overall appearance.

8.0 OPERATIONAL SPECIFICATIONS

The table below summarizes the primary optical operational specifications of the two new long zoom field lenses. It should be noted that both have a maximum relative aperture specification of F-1.7 that is maintained over the focal range of their respective wide settings to 340mm – following which they encounter the F-drop (ramping) down to F-5.0 in the case of the UJ122x and to F-4.65 for the uJ111x.

	UJ122x8.2B		UJ111x8.3B	
Mount	B4		B4	
Application	2/3" 4K camera / 2/3" HD camera		2/3" 4K camera / 2/3" HD camera	
Built-in Extender	1.0x	2.0x	1.0x	2.0x
Focal Length	8.2 - 1000 mm	16.4 - 2000 mm	8.3 - 925 mm	16.6 - 1850 mm
Zoom Ratio	122x		111x	
Maximum Relative Aperture (F number)	**1:1.7** [at 8.2-340mm] 1:5.0 [at 1000mm]	**1:3.4** [at 16.4-680mm] 1:10.0 [at 2000mm]	**1:1.7** [at 8.3-340mm] 1:4.65 [at 925mm]	**1:3.4** [at 16.6-680mm] 1:9.3 [at 1850mm]
Angular Field of View	60.7°x 36.5° [at 8.2 mm] 0.55°x 0.31° [at 1000 mm]	32.6°x 18.7° [at 16.4mm] 0.28°x 0.15° [at 2000mm]	60.1°x 36.0° [at 8.3mm] 0.59°x 0.33° [at 925mm]	32.3°x 18.5° [at 16.6mm] 0.30°x 0.17° [at 1850mm]
M.O.D.	3.0m		3.0m	
Shooting Range at M.O.D.	314.8 x 177.1cm [at 8.2mm] 2.7 x 1.5cm [at 1000mm]	157.4 x 88.6cm [at 16.4mm] 1.4 x 0.8cm [at 2000mm]	311.6 x 175.3cm [at 8.3mm] 2.9 x 1.6cm [at 925mm]	155.8 x 87.7cm [at 16.6mm] 1.5 x 0.8cm [at 1850mm]
Approx. Size (w x h x l)	approx. 9.9 x 10.1 x 25.1 inch **approx.** 250.6 x 255.5 x 637.4 mm		approx. 9.9 x 10.1 x 25.1 inch **approx.** 250.6 x 255.5 x 637.4 mm	
Approx. Weight	approx. 58.6 lbs. / 26.6 kg		approx. 58.6 lbs. / 26.6 kg	

9.0 SUMMARY

This White Paper reports on the multiple design criteria underlying the development of two second generation 2/3-inch 4K UHD long zoom lenses. Based upon the high expectations of all those considering coverage of major outside broadcasts in 4K UHD, and leveraging the multiple inputs from those who used the first generation 4k UHD lenses – some unusually high goals were set for the design of these new lenses. Their operational specifications were extended, specific attention was directed to improving the 4K UHD sharpness at the picture edges while also lowering the visibility of chromatic aberrations, and the all-important built-in image stabilization system was redesigned to overcome longstanding limitations to such systems.

On the Operational side – the high promise of vivid 4K imagery on ever-larger displays spurred directors in the sporting world and in the outdoor concert world to press for extensions in focal range beyond those established in the HDTV production world – a quest to capitalize on what higher resolution might bring to more dramatic framing options. Notwithstanding the industry recognition of the longstanding optical challenge in simultaneously extending focal range at both the telephoto and the wide angle extremes – the plea to try and do so was also widespread. Canon accepted the challenge to seek a breakthrough here.

1000 mm was established as the goal for the telephoto extreme on the basis of fully framing athletes on the small 2/3-inch image format size from the considerable distance of a quarter of a mile. A consensus on a 60-degree horizontal viewing angle – to allow more effective framing of stadia and stages – augured for a wide angle focal length approaching 8mm. The design was finalized to cover a focal range of 8.2mm to 1000mm – a zoom range of 122:1. This is the UJ122x8.2B field lens. The dramatic advances in the prowess of computer simulation in recent years was to play a major role in facilitating the collective improvements within the optical system design that allowed this dual focal range extension. Recognizing that not all outside broadcasts require such extended focal ranges, Canon simultaneously developed the UJ111x8.6B having a focal range from 8.6mm to 925mm.

It has been a decades-old frustration for the world's camera operators to deal with the vexing F-Drop (termed Ramping by many) phenomenon associated with long zoom lenses – where the light transmission through the lens starts to fall after a certain long focal range is reached. The optical solution would entail a dramatic increase in the size and weight of a zoom lens and this was never considered practical in the real world of outside broadcasts. A collaborative development between Sony and Canon produced an elegant and remarkably simple solution in the electronic domain within the camera. The same principal was extended to also electronically compensate for the dynamics of peripheral lens illumination (essentially a realtime shading correction that tracks changes to this as the lens operational controls are exercised). The paper describes the new ARIA system that has generated high enthusiasm among those who have seen this compensation.

On the 4K UHD Performance front – the marketplace urging of improvements to the sharpness of the image extremes combined with the additional resolution challenge posed by the simultaneous broadening of focal range at both extremes to pose a major challenge to the optical design. All of the subsystems within the overall optical system were fully re-examined and the latest advances in optical computer simulation were applied to grapple with the multiple variables that impact image sharpness. The input floating focus group was completely redesigned – using new glass materials and some large diameter aspheric surfaces to achieve the requisite edge sharpness and severe curtailment of chromatic aberrations on wide-angle settings. The zooming optical system was redesigned – deploying a multi-group approach to the moving lens groups that implement the focal range changes. The highest attention was paid to ensuring the nanometer level of surface tolerances on all of the glass elements of the lens.

The addition of HDR and WCG performance specifications entailed re-examination of the technologies and techniques for ensuring deep black reproduction and careful shaping of the spectral transmission characteristics of the overall lens system. The addition of Air Sphere Coating technology – for the first time in a broadcast lens – significantly improved the HDR performance.

A novel new optical creative effect has been incorporated in the lenses. Termed the "Bokeh Effect" this offers a control to the camera operator that allows a controlled degree of image defocus to be rolled in.

On the Image Stabilization front – the early users of 4K UHD outside broadcasts quickly learned that this degree of image resolution was imperiled by even the smallest physical disturbances that are regularly encountered in outside broadcast shooting. Image stabilization systems have been incorporated in long zoom field lenses for decades, but paradoxically, they are regularly disabled by camera operators. This, because a perennial challenge to the design of built-in image stabilization is the minimization of side effects associated with the cessation of operational panning and tilting movements – typically manifested as a minor image overshoot that is termed lag by camera operators. Given the imperative of eliminating image blur in high resolution 4K UHD imagery Canon undertook a major redesign of the image stabilization system to subjectively eliminate this discouraging artifact. Multiple tests to date testify to the success of this new IS system – both in terms of blur elimination on long focal lengths and the virtual elimination of lag.

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