Advances in CMOS Image Sensors and Associated Processing (Part 2)

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ABSTRACT

Part I of this series focused on Canon technology that exploited the large size of the 35mm Full Frame CMOS image sensor with the modest spatial sampling of 1920 (H) x 1080 (V) to realize a uniquely large photosite of 19um x 19um.

Part II of this series focuses on a new Super 35mm CMOS image sensor specifically developed to support origination of High Dynamic Range (HDR) motion imagery. The deployment of two separate photodiodes within each photosite is central to achieving the 15-stop dynamic range. The dual photodiode also supports a unique in-sensor phase detection strategy that is followed by powerful data processing that closes a focus control loop around the cine lens. Alternatively, for those who prefer manual focus operation, a separate data process provides a Focus Guide in the form of signaling to the viewfinder that unambiguously indicates achievement of sharpest focus on the chosen subject.

ALTERNATIVE TO ALGORITHMIC DEBAYERING – DIRECT COMPONENT READOUT

The traditional single wire output from a Bayer image sensor – as outlined in Figure 1 – entails formulating the serial data stream into whatever file format the individual camera designers favor. This must subsequently be decoded to create the individual RGB frames. Of necessity this decoding entails sophisticated algorithms – and even with the best of these there are inevitable residual reconstruction errors.

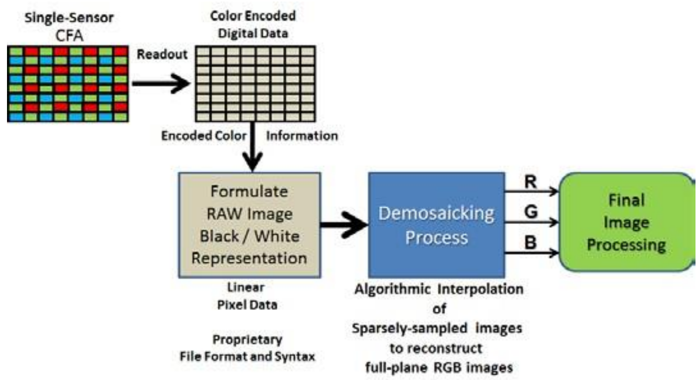

FIGURE 1: *SHOWING THE TRADITIONAL SINGLE WIRE READOUT OF THE BAYER ENCODED SIGNAL*

In the original EOS C300 camera the dexterity of the multichannel readout architecture of the specially developed Canon 4K CMOS image sensor implements a direct parallel read out of the four constituent 2K components that constitute the 4K Bayer sampling structure – as simplistically outlined in Figure 2.

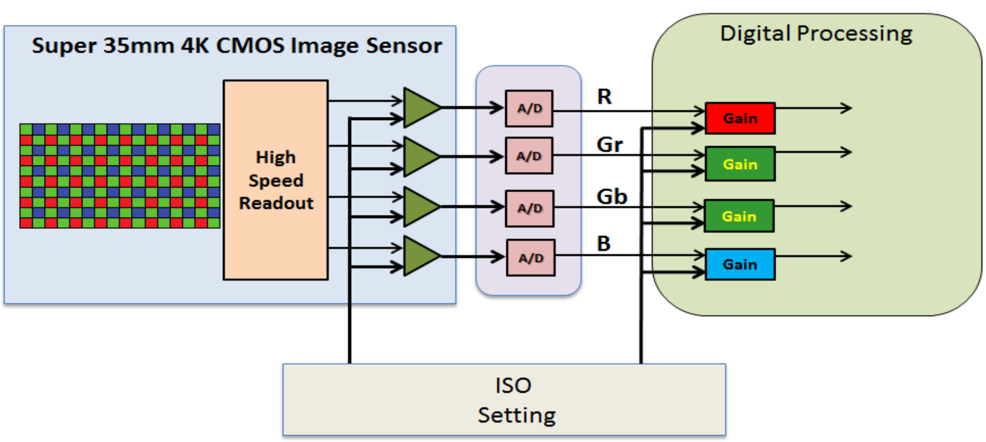

FIGURE 2: *OUTLINING THE PRINCIPLE OF THE PARALLEL READOUT WITHIN THE IMAGE SENSOR OF THE FOUR 2K COMPONENTS THAT CONSTITUTES A DIRECT DECODING OF THE 4K BAYER COLOR SAMPLING*

A totally new Super 35mm 4K image sensor developed for the second generation C300 Mark II utilizes the same readout strategy as the earlier image sensor in the C300 camera. The dexterity of the readout capability of the CMOS image sensor allows access to the pixel level and this, in turn, allow precision dismemberment of the 4K Bayer encoding into the four 2K constituent components of R, Gr, Gb, and B. Thus, a debayering process has been implemented that requires no downstream algorithmic decoding – which totally eliminates the traditional associated reconstruction errors [1].

DUAL PIXEL STRATEGY – ELEVATION OF DYNAMIC RANGE

Among numerous design strategies in the Super 35mm CMOS image sensor developed for the EOS C300 camera was an innovative new photosite design that employed two separate photodiodes – each being 6.4 x 3.2 micrometers. For simplicity, this novel design is referred to as the Dual Pixel CMOS image sensor.

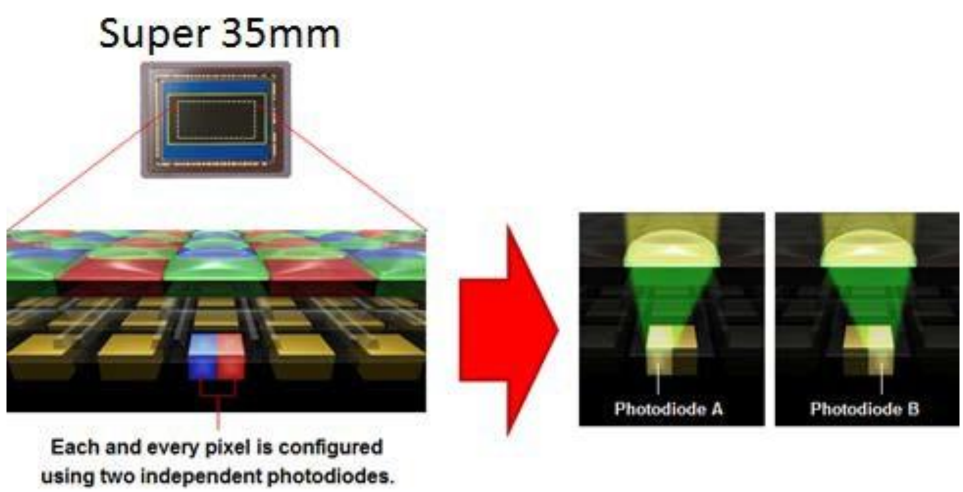

FIGURE 3: *A REPRESENTATION OF THE DUAL PIXEL CMOS IMAGE SENSOR WITH A SPECIALLY DESIGNED MICROLENS THAT OPTIMIZES THE FOCUSING OF THE INCIDENT LIGHT ONTO BOTH PHOTODIODES*

The smaller lateral dimension of the individual photodiode supports a higher charge transfer efficiency (see more detailed explanation of this in Part I of this series detailing the ME20F-SH image sensor) which in turn facilitates a greater speed in totally emptying the accumulated charge from each during the imager reset period. The two charges are later summed following readout and A/D conversion. The photodiode was also designed as a higher density N-type which elevates the number of saturation electrons. The combination of these strategies produces an elevation of the overall dynamic range of each photosite.

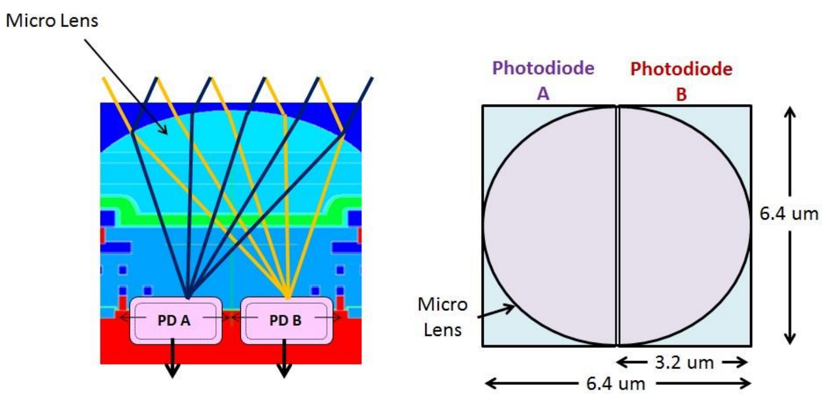

FIGURE 4: *SHOWING THE DUAL PHOTODIODE STRUCTURE OF A SINGLE PHOTOSITE IN THE 4K CMOS IMAGE SENSOR USED IN THE CINEMA EOS CAMERAS*

SECOND GENERATION DUAL PIXEL CMOS IMAGE SENSOR – 15-STOP DR

The C300 Mark II employs a new generation Super 35mm CMOS sensor which is based on the same dual photodiode per photosite. Additional innovations within the photodiode design in combination with new on-chip noise cancellation technology have simultaneously lowered the noise floor and further elevated the saturation level of the charge well. In addition, a new microlens design heightens the efficiency of light direction onto the two individual photodiodes while also improving the separation between the two photodiode outputs.

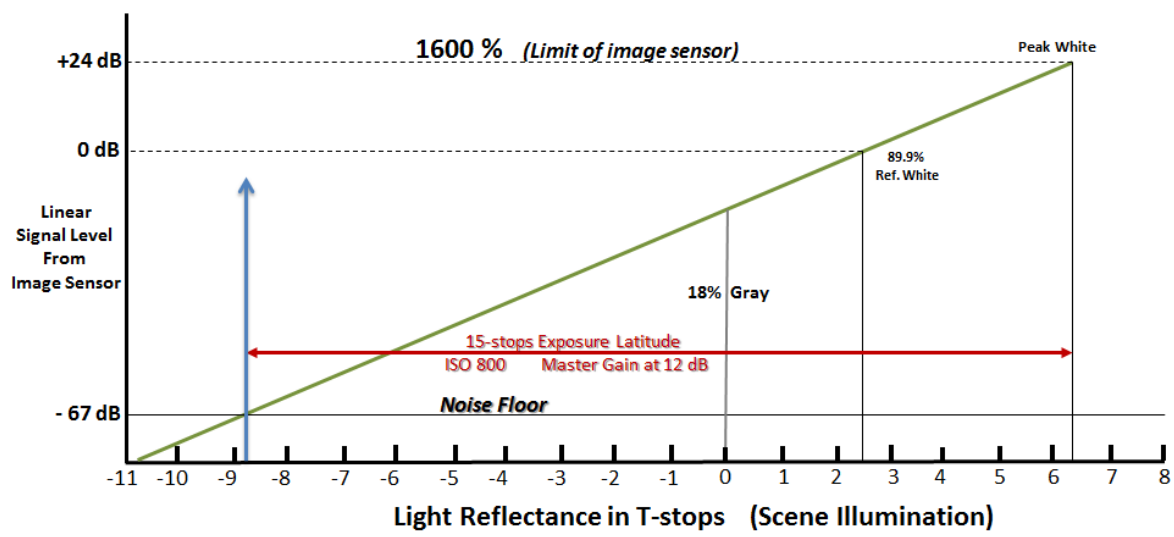

FIGURE 5: *SHOWING THE LINEAR ANALOG SIGNAL LEVEL CAPABILITY OF THE NEW CMOS IMAGE SENSOR*

The combination of these new design strategies contribute to a more than two-fold increase in effective photosite dynamic range. This provides a definitive ***15-Stop*** dynamic range capability in this new cinematography camera – providing one-stop capability above that of the C300 in the upper region and two stops below that of the C300 in the lower region. The reduced noise floor allows the ISO range to be extended up to ***ISO 102,400.***

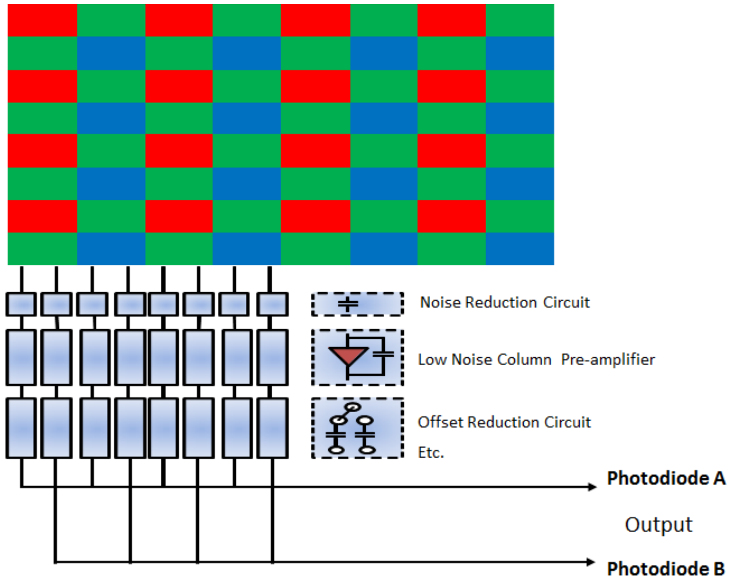

FIGURE 6: *SHOWING THE PRINCIPLE OF THE DUAL OUTPUT FROM EACH INDIVIDUAL PHOTOSITE AND THE ASSOCIATED ANALOG PROCESSING THAT TAKES PLACE WITHIN THE IMAGE SENSOR ITSELF*

In 2014, Canon introduced the second generation C100 Mark II which employed the same Super 35mm 4K CMOS image sensor as the C300 and C100. But this camera further exploited the two separate photodiodes within each photosite to empower a phase detection system that identifies the degree of defocus in an image – allowing incorporation of an innovative new Auto Focusing system having high precision. This initial implementation proved very effective under normal shooting conditions. We will first describe the basics of what is termed the Dual Pixel CMOS Auto Focus system based upon that first embodiment in the C100 Mark II camera.

Dual Pixel CMOS Auto Focus System

C100 Mark II embodies a powerful auto focus system where the sensing of sharp focus takes place within the image sensor photosite itself. It mobilizes the dual photodiodes within each photosite to create two separate images that facilitates a phase detection system that indicates the degree of defocusing.

FIGURE 7: *PRINCIPLE OF THE AUTO FOCUS CONTROL SYSTEM WHERE DATA FROM THE DUAL PHOTODIODES WITHIN EACH PHOTOSITE CONSTITUTES A PHASE COMPARISON WHICH IS PROCESSED TO CREATE A CONTROL SIGNAL FOR THE LENS FOCUS*

Figure 8 illustrates the manner in which the sets of dual pixel outputs from the CMOS image sensor are sent to the DIGIC DV5 processing microcircuit that was developed by Canon. Within this processor, these streams are fed to the primary RGB video processing system (where the two photodiode signals are summed) and separately to a data processing system that makes all of the decision-making and data processing associated with the Auto Focus system.

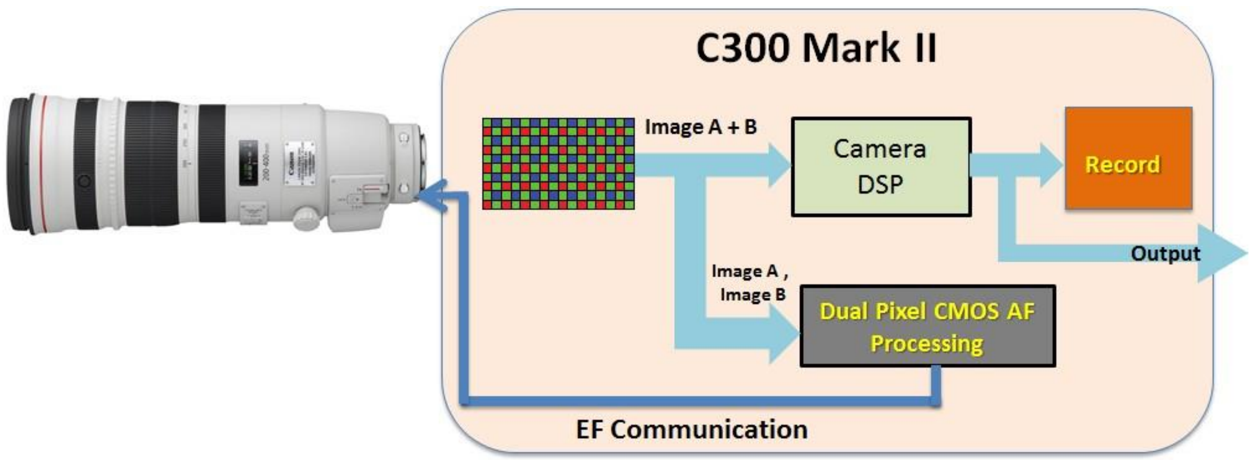

FIGURE 8: *SHOWING THE SEPARATE PROCESSING OF THE DUAL PIXEL DATA FROM THE IMAGE SENSOR – FOR VIDEO AND FOR AUTO FOCUS – AT THE ENTRY STAGE OF THE DIGIC DV5 PROCESSOR*

While all of the eight million photosites are delivering the "dual pixel" data, the operational aspects of Auto Focus dictate that only a select number of these are activated at any given time. This is because the camera operator will make the decision on which particular subject within the overall picture frame is chosen for sharpest focus. Consequently, a cursor type system must be implemented to facilitate this choice.

In this first implementation of Dual Pixel CMOS Auto Focus (for simplicity Auto Focus is referred to as AF) system the "cursor" was fixed in the center of the image frame and had dimensions chosen based upon extensive testing.

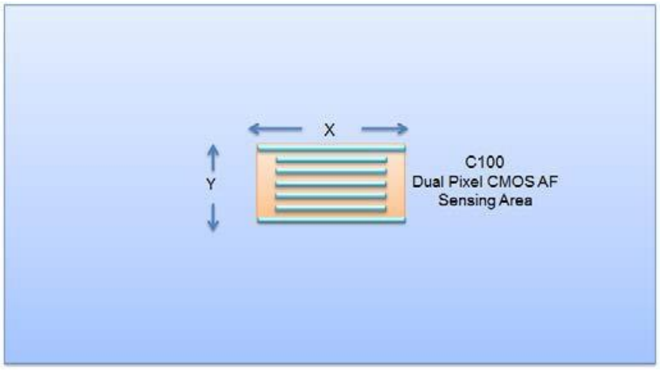

FIGURE 9: *SHOWING THE FIXED CENTRAL ACTIVATION OF DUAL PIXELS IN THE C100 MARK II FOR AUTO FOCUS – REQUIRING THAT THE CAMERA FRAME THE SELECTED SUBJECT WITHIN THIS RANGE*

The phase detection sampling lattice is made up of a number N of selected adjacent vertical samples of photosites – with each constituting an AF Sampling LINE – and then M of these Sampling LINES making up the total vertical sample.

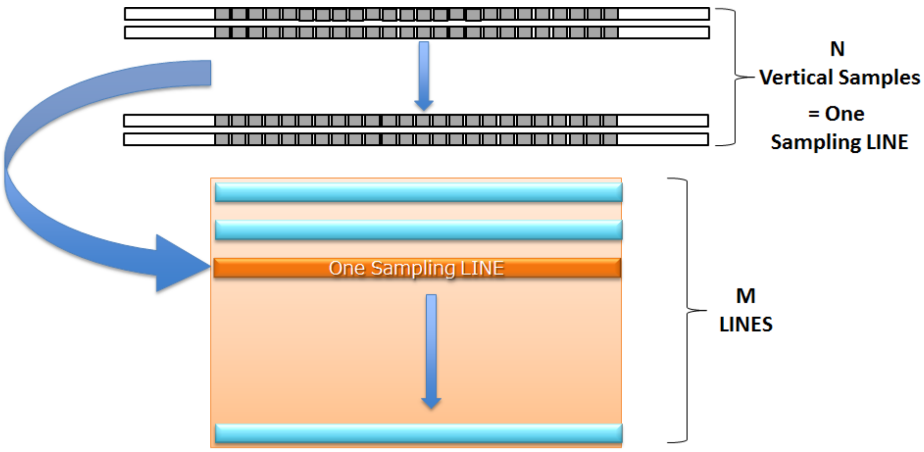

FIGURE 10: *SHOWING THE SPATIAL STRUCTURE OF THE AUTO FOCUS SAMPLING LATTICE WITHIN THE CMOS IMAGE SENSOR*

This system worked remarkably well in the C100 Mark II. However, a broadening experience revealed an extensive range of shooting situations that are encountered in the real world of program origination that challenged the reliable performance of the Dual Pixel CMOS AF system. Analysis of these yielded a range of recommendations:

1. Broad request to provide spatial movement of the sampling area – so that different subjects within a given scene can be selected for sharpest focus
2. Ranging performance improvement is needed in low scene illumination situations
3. Improvement in accuracy of the system as ISO setting increased
4. Auto Focus should ideally be a real-time action (or as close as possible to real-time) so speed of calculations should be increased

5. Improvement in the calculating algorithm to elevate reliability

As part of the development of the new generation Super 35mm 4K image sensor for the second generation C300 Mark II, a totally new Dual Pixel CMOS AF system was developed in concert. A denser sampling lattice was developed to increase sensing sensitivity and accuracy over a wider range of scene illumination and camera ISO settings. The new sampling lattice is actually a matrix of nine adjoining photosite arrangements as shown in Figure 11.

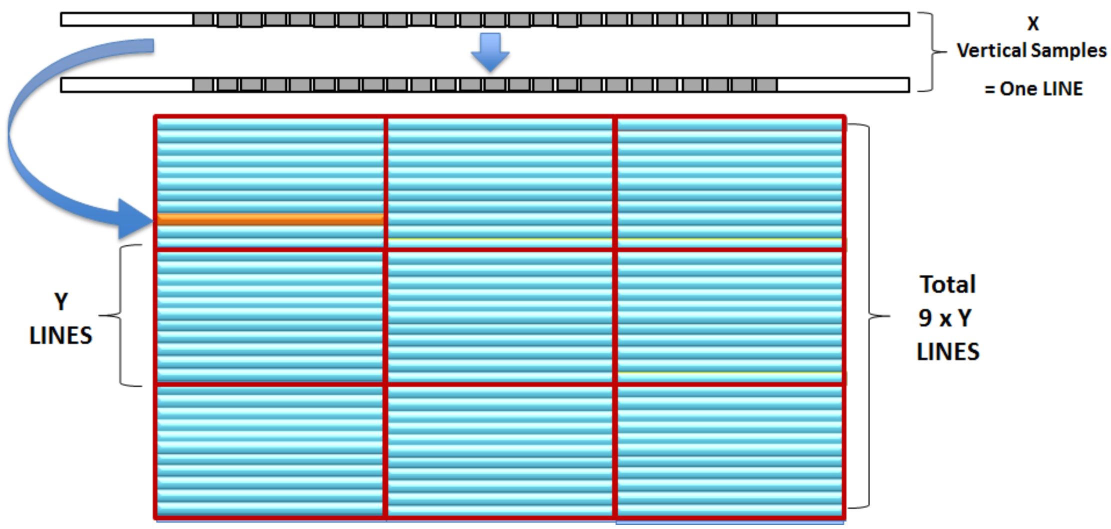

FIGURE 11: *SHOWING THE SUBSTANTIALLY LARGER SAMPLING LATTICE THAT MAKES UP THE AF DETECTION IN THE C300 MARK II IMAGE SENSOR*

Each sub arrangement has been increased to Y Lines (compared to N lines for the earlier system). With nine such arrangements that becomes a total of 9xY selected lines of photosites. Operational flexibility was significantly broadened by allowing that sampling lattice to be repositioned (via a controlling joystick) across 80% of the total photosite structure of the image sensor – as shown in Figure 12.

FIGURE 12: *SHOWING THAT THE DUAL PIXEL CMOS AF SELECTION AREA CAN BE MOVED AROUND SOME 80% OF THE ACTIVE IMAGE FRAME TO ALLOW SELECTION OF DIFFERENT SUBJECTS WITHIN THE SCENE FOR SHARP FOCUS*

Data Processing for Dual Pixel CMOS Auto Focus

The data processing that is required is quite sophisticated. A parallel feed of the two images created from the individual photodiodes within each photosite is concurrently sent to the Dual Pixel CMOS Auto Focus processing system and the RGB video processing system. A variety of corrections and adjustments are applied to these sampled images A and B as this can aid the precision of the detection depending upon lens settings. Correlation processing then takes place that identifies the spatial separation of those processed images (the phase shift principle underlying this detection). The results are sent to a microcomputer that makes the calculations for the requisite correction signal. Experiences gained with the first Dual Pixel CMOS AF system contributed to an improved algorithm design that tests the reliability of the detection data and makes appropriate adjustments. The microcomputer also accepts the control signal from the joystick that moves the sampling Dual Pixel CMOS AF area and implements the associated variable spatial selection of the photosites.

Operational Control over Action of Dual Pixel CMOS Auto Focus

Early experiences with Dual Pixel CMOS AF in the C100 Mark II camera exposed the reality that there was a wide range of creative desires associated with acceptable actuation speed of the lens control loop. This speed depends upon the type of production and the personal aspirations of the shooter. It was explained that different projects sought different lens drive speeds. Many felt that this first generation auto focusing lens drive action was simply too fast. In addition, especially in television drama production and moviemaking – where traditionally the Director and DoP (Director of Photography) often like to exercise a “feathering” control over the initial portion of a rack focus – the takeoff speed of the auto focus drive also requires some choices.

The new Dual Pixel CMOS AF system in the C300 Mark II embodies a menu that allows two degrees of freedom in “tuning” the response time. The focusing speed itself has a choice of ten speeds selected under SPEED in the menu – consisting of a Standard speed and then a choice of two faster speeds and a choice of seven slower speeds. This capability is only possible with those EF lenses that have slow-speed drive capabilities. Separately, what is termed the RESPONSE setting is a separate setting of the system that offers a choice in how quickly a focusing action is initiated – thus adding a creative dimension to a rack focus between two subjects within the scene.

Focus Guide System

For the cinematographer who prefers traditional creative manual focus operation, the dual pixel system can alternatively be switched from the Auto Focus control loop to an open loop system that utilizes the Dual Pixel CMOS AF data processing to instead transfer precision signaling to the camera viewfinder.

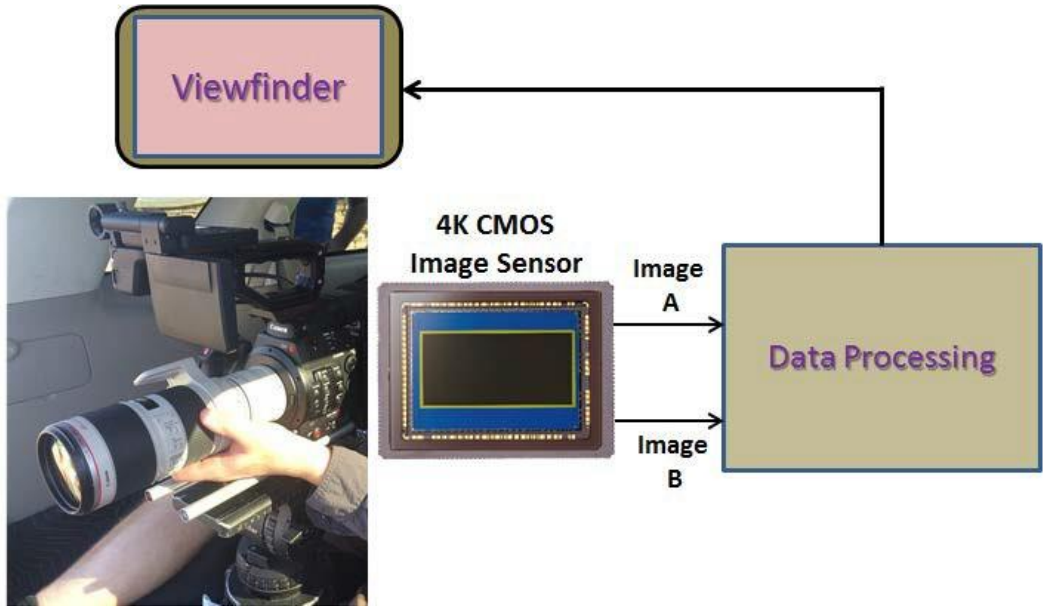

FIGURE 13: OUTLINES THE PRINCIPLE OF THE FOCUS GUIDE SYSTEM: THE IMAGE SENSOR DETECTS MANUAL ACTUATION OF THE LENS FOCUS CONTROL AND THE DATA PROCESSING SIGNAL IS SENT TO THE VIEWFINDER

The following outlines the nature of the signaling in the camera viewfinder. In this mode, three gray colored arrows appear around a box cursor that is centered on the subject chosen for precision focus. The arrow's direction signals the direction to turn the focus ring to achieve the sharpest look. When precision focus is achieved, the viewfinder cursor and the indicating arrows snap to a green color.

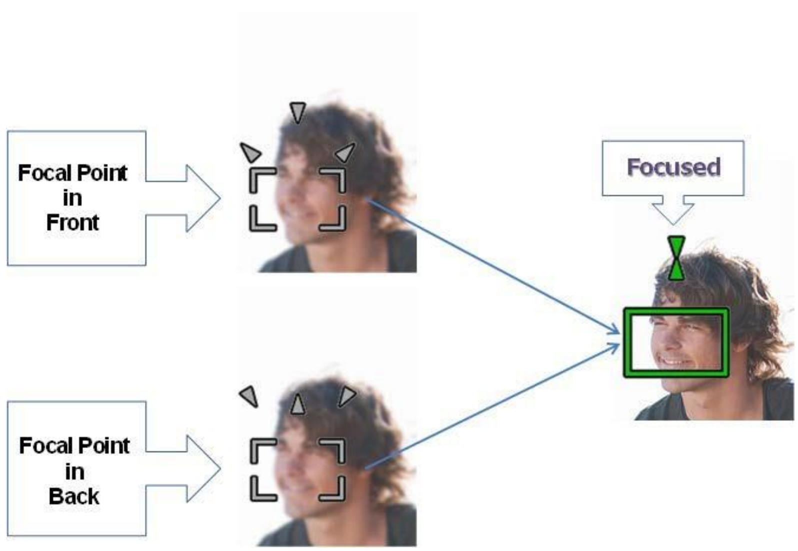

FIGURE 14: *THE GUIDE CURSOR DETAIL USES THREE ARROWS TO INDICATE TO THE CAMERA OPERATOR THE DIRECTION TO ROTATE THE FOCUS CONTROL. AT THE POINT OF PRECISE FOCUS ON THE CHOSEN SUBJECT THE CURSOR SNAPS TO A GREEN COLOR.*

The implementation of the Focus Guide system is outlined in Figure 15.

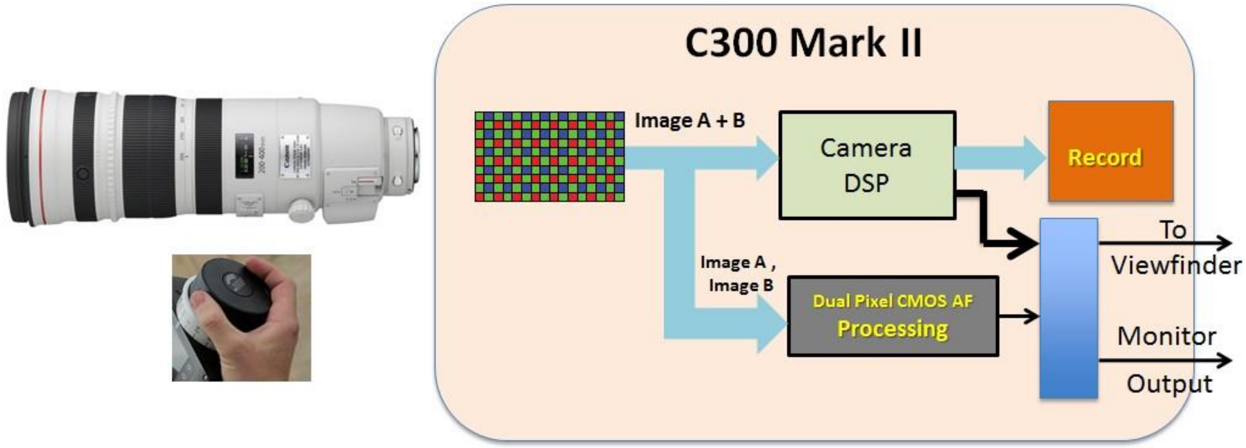

FIGURE 15: *FOCUS GUIDE SYSTEM MODE OF OPERATION – OPENS THE CONTROL LOOP TO THE LENS AND THE DATA PROCESSING SYSTEM INSTEAD SENDS SIGNALS TO THE VIEWFINDER AND MONITOR OUTPUT THAT GUIDE THE MANUAL FOCUS ACTION*

SUMMARY

Part II of this series focused on a 4K Super 35mm sensor that can switch between 4K (4096 x 2160 with a 17:9 aspect ratio) and UHD (3840 x 2160 with a 16:9 aspect ratio) spatial sampling. Each of those approximately eight million photosites utilizes two separate photodiodes. By expediting efficiency in charge well readout, this duality ensures an effective elevation of dynamic range. This image sensor delivers 15-stops of dynamic range supporting HDR functionality in the C300 Mark II camera. At the same time, this photodiode duality also offers an in-sensor phase detection that is subsequently processed to close a control loop around the camera lens thus providing a very precise auto focus system.

REFERENCES

R.B. Wheeler and N. Rodriguez “The Effect of Single-Sensor CFA Captures on Images Intended for Motion Picture and TV Applications” SMPTE J., 2007