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A full-resolution 8K single-chip portable camera system

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Abstract

We have developed an 8K "full-resolution," 60-fps, portable camera system using a 133-megapixel complementary metal-oxide-semiconductor (CMOS) single-chip image sensor. The camera head weighs less than 7 kg, whereas the conventional 8K full-resolution three-chip camera weighs over 50 kg. The new camera can use both commercial 35-mm full-frame lenses and super 35-mm lenses by using lens adapters. It employs a compact 100-Gbps optical transceiver that can transmit the 8K full-resolution video signal to the camera control unit (CCU). The size of the CCU is 3U, which is comparable to CCUs used for broadcasting high definition television (HDTV) cameras. The camera supports the wide-color-gamut and high dynamic range (HDR) video formats, which were standardized in ITU-R BT. 2020 and BT. 2100, respectively. Moreover, a streaking noise correction circuit is implemented in the CCU. The 8K signal output interface from the CCU is compliant with the ITU-R BT. 2077 (U-SDI) standard. By performing an image shooting experiment, we confirmed that the limiting resolution of this camera was more than 4000 TV lines and the signal-to-noise (S/N) ratio was 57 dB at a sensitivity of F4.0/2000 lux.

Introduction

8K Super Hi-Vision is a next-generation ultrahigh-definition television system (UHDTV). It has a resolution of 7680 × 4320 pixels, which offers a heightened sense of reality and makes viewers feel as if they are actually there. Its video parameters were standardized as Recommendation ITU-R BT. 2020 [1] in 2012. The highest specifications for 8K UHDTV are 7680 × 4320 resolution with an RGB 4:4:4 sampling structure, a bit depth of 12 bits, wide color gamut, and 120 frames-per-second (fps) progressive scan. Moreover, the video parameter of high dynamic range (HDR) was standardized in ITU-R BT. 2100 [2] in 2016. We call an 8K video signal that meets all the highest specifications, including HDR, as "full-featured" 8K UHDTV. 8K test broadcasting started on August 1, 2016 in Japan, and regular service will start in 2018. NHK is now accelerating the development of 8K equipment.

NHK has already developed two types of 8K cameras using 33-megapixel image sensors. One uses three monochrome 33-megapixel sensors with a color separation prism [3]. These cameras are generally large and heavy because they require a large optical format prism for higher resolution and sensitivity. The other one uses a single color 33-megapixel sensor with a Bayer color filter array (CFA). The weight of an 8K single-chip color camera [4] can be reduced to 2 kg because the single-chip camera does not require a large color separation prism. However, the image quality of single-chip cameras is lower than that of a three-sensor camera, and a color interpolation signal processing (demosaicing) is required to reconstruct an 8K "full-resolution" (7680 × 4320 pixels for each RGB color) image from spatially incomplete color images [5][6].

To acquire an 8K full-resolution image by single-chip color imaging, we developed a 133-megapixel 60-fps CMOS image sensor [7] and performed basic imaging experiments [8]. Moreover, we developed a prototype 8K full-resolution 60-fps color image acquisition system [9], and performed an imaging experiment.

Based on past work, we developed a new full-resolution 8K portable camera system. This paper describes the design and imaging properties of the camera system. First, we show the configuration of the camera system. Next, we describe the details of the camera head and camera control unit (CCU) techniques. These details include noise reduction, optical design, HDR processing, wide-color-gamut processing, and streaking noise reduction. Finally, we discuss the imaging performance.

Configuration of Full-resolution 8K Single-Chip Portable Camera System

Figure 1 shows the configuration of the full-resolution 8K single-chip portable camera system. It consists of a camera head and a CCU, and is basically the same as our first prototype system [9]. The output signals from the 133-megapixel CMOS image sensor are converted into four 25-Gbps (for a total of 100-Gbps) signals and transmitted to the CCU over a fiber optic camera cable using CFP4 transceivers [10]. The CCU processes the sensor signal and generates an 8K full-resolution signal using the "U-SDI" interface standardized in ITU-R BT. 2077 [11].

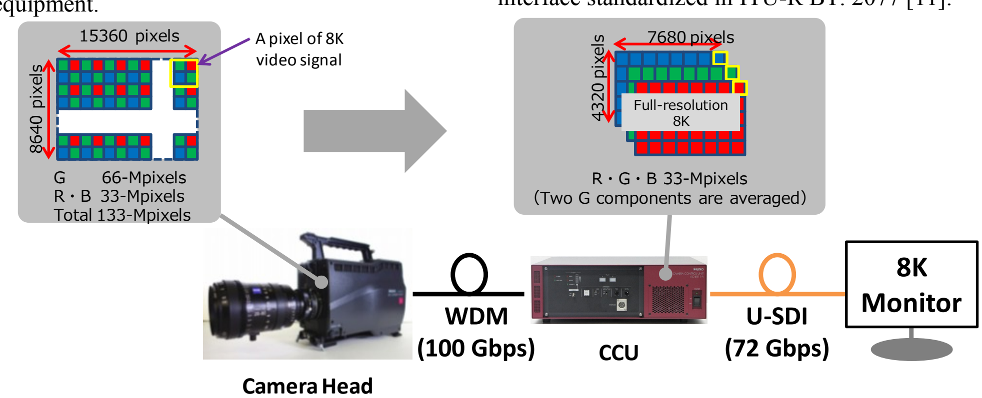


Figure 1. Configuration of a full-resolution 8K single-chip portable camera system

Camera Head

Overview of Camera Head

Figure 2 shows the appearance of the portable camera head that was developed. The weight of the head without a lens is 6.3 kg, which is one-seventh that of the conventional three-sensor full-resolution camera [3] and two-thirds that of the first prototype system [9]. The specifications of the camera head are listed in Table 1. This camera head adopts the single-chip color imaging system employing the 133-megapixel CMOS image sensor.

Figure 2. Appearance of 8K portable camera head

Table 1: Specifications of the camera head

Weight	6.3 kg
Sensor	133-megapixel CMOS Image Sensor
Optical format	35-mm full-frame
Lens mount	PL / EF / F mount (using lens mount adaptor)
Filters	ND: Cap, 1 (through), 1/4, 1/16 CC: 3200K, 4400K, 5300K, 6200K
Signals	Output: 25 Gbps × 4 ch Return signal: 3G-SDI × 4 ch
Size	300 (W) × 210 (D) × 290 (H)
Power Consumption	140 W

Image Sensor

Figure 3 shows the 133-megapixel CMOS image sensor. The specifications of which are shown in Table 2. The total number of active pixels is 133-megapixels (15360 × 8640 pixels), quadruple those in the conventional 33-megapixel CMOS image sensor. The pixel size of the image sensor is 2.45 µm. The active area is 37.632 mm × 21.168 mm (diag. 43.2 mm), corresponding to the 35-mm full-frame image format. The image sensor uses the Bayer color filter array (G1, G2, B, R), and the number of active pixels is more than 33-megapixels for each color. The 2 × 2 pixels of the image sensor configure a pixel of an 8K full-resolution signal in order to obtain it without interpolation. The image sensor can read all 133-megapixels at 60-fps, 12 bits. The output data consists of 112 channels of 1.15-Gbps current mode logic (CML) signals, for which the total data rate is approximately 128-Gbps.

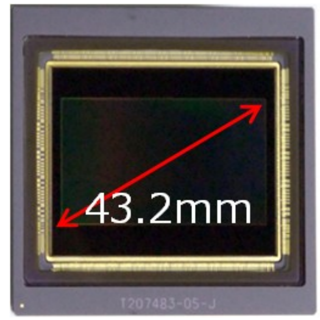


Figure 3. Visual appearance of the 133-megapixel sensor

Table 2: Specifications of a camera head

Optical Format	35-mm full-frame	
Pixel Count	Total	15488 (H) ×8766 (V)
	Active	15360 (H) ×8640 (V)
Pixel Size	2.45 µm ×2.45 µm	
Active Area	37.632 mm × 21.168 mm (diag. 43.2 mm)	
Color Filter	Bayer CFA (G1, G2, B, R)	
Frame Rate	60 fps, Progressive	
Bit Depth	12 bits	
Output	112 ch. CML 1.15 Gbps / ch @ 60 fps	
Package	1125-pin PGA	

Optical Design of Camera Head

The optical format is 35-mm full-frame. Various lens mounts such as PL, EF, and F can be used with lens mount adapters. Moreover, if using an adaptor lens that converts optical format from Super 35-mm to 35-mm full-frame, Super 35-mm lenses for cinematic shooting can be used.

Figure 4 shows the configuration of the optical system of the camera head. The flange back (FB) distance of the camera head is 22 mm. The length L of the lens mount adaptor is designed such that sum of L and 22 mm matches the FB distance for each lens mount.

The lens adaptors have a mechanism to adjust the FB distance because the 35-mm full-frame lenses and the Super 35-mm lenses cannot adjust the FB distance. The lens adaptors can adjust the FB distance within a width of ±1 mm.

Our first prototype system had only one filter turret for neutral density (ND) filters and color-temperature conversion (CC) filters because the FB distance was very short compared to that of conventional broadcast cameras. To increase the number of turrets in the very limited FB space, the thickness of the CC filter has been greatly reduced. As a result, the new camera head has two filter turrets, each of which is independently used for ND and CC filters.

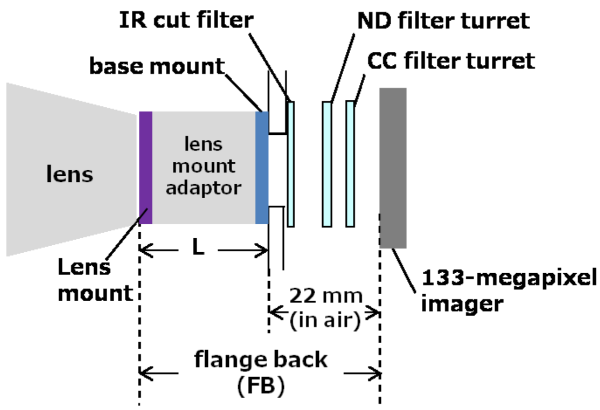


Figure 4. Flange back of the camera head

Optical Transmission

The output data rate of all pixels of the 133-megapixel CMOS image sensor at 60-fps, 12 bits is over 100-Gbps, corresponding to 67 times that of a high definition television (HDTV) video signal (HD-SDI: 1.5-Gbps). In order to transmit the output data from the camera head to the camera control unit (CCU) on a common optical camera cable, we used a CFP4 transceiver. This converts four 25.78-Gbps electronic signals into four optical signals and multiplexing them on an optical fiber. This leads to downsizing of the camera head. Furthermore, power consumption is less than that of WDM interfaces used in the conventional 8K camera [3].

Figure 5 shows the block diagram of the camera head. To meet the CFP4 input format, the data formatter converts output signals from the 133-megapixel CMOS image sensor into four 25.78-Gbps data streams. The CFP4 transceiver generates four 25.78-Gbps optical signals (1295 nm, 1300 nm, 1304 nm, and 1309 nm), and multiplexes them into one optical fiber of a standard camera cable. In the CCU, the CFP4 receiver restores four 25.78-Gbps optical signals into an 8K full-resolution signal.

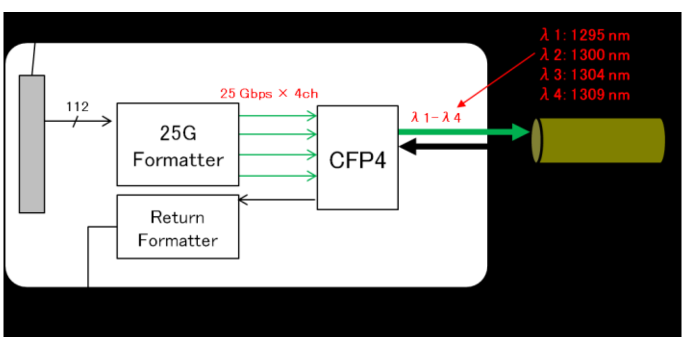


Figure 5. Block diagram of the developed camera head

Image Sensor Noise Reduction

Our first prototype system had two noise-related problems in the image sensor. One was column-wise fixed-pattern noise (FPN), and the other was horizontal-patterned noise with temporal variation. The circuit board of the image sensor was revised to reduce this noise.

The column FPN derives from the property variations of each analog-to-digital converter (ADC) in the image sensor. To reduce the column FPN, we distributed decoupling capacitors for ADC reference voltages near each input pin to minimize routing resistance.

The horizontal-patterned noise originated from the power supply circuit. Since the first prototype system used switching regulators in order to generate power supply of the image sensor, switching noises of the regulator got into that. As a result of redesigning power supply circuit, the new camera system has suppressed mixture of switching noises into power supply.

Camera Control Unit

Overview of the CCU

Figure 6 shows the appearance of the camera control unit (CCU). The height of the CCU is only 3U in a 19-in rack size, and the weight is 12 kg. The size of the CCU was reduced from 5U to 3U compared with the first prototype.

The specifications of the CCU are listed in Table 3, and the block diagram of the CCU is shown in Figure 7. It receives 100-Gbps optical signals multiplexed at the camera head, and a CFP4 transceiver in the CCU converts them into 25-Gbps ×4 electronic signals. The CCU performs signal processing, including fixed pattern noises (FPN) cancellation, gain control, black level adjustment, shading correction, linear matrix correction, and detail enhancement circuit. The CCU outputs 8K full-resolution 60-fps signals using the U-SDI optical interface compliant with ITU-R BT. 2077 [11]. This interface can connect 8K production equipments with a multi-mode optical fiber cable consisting of 24 channels.

The CCU generates 8K, 4K and HD video signals simultaneously. The 4K video signal can be switched from a down-converted video to a cropped video from an 8K video signal. A camera return signal from the CCU to the camera head can be dealt with 4K or HDTV resolution, and camera operators can confirm the return signal in 4K or HDTV resolution.

Figure 6. Appearance of camera control unit

Table 3: Specifications of camera control unit (CCU)

Size	3U (19-in size)
Weight	12 kg
Functions	Fixed pattern noise (FPN) cancellation Gain control Black level adjustment Shading correction Linear matrix correction Detail enhancement 12 axis color correction Chromatic aberration correction
Output signals	8K: U-SDI × 1 4K: 3G-SDI × 1 HD: HD-SDI ×1
Return signals	4K: 3G-SDI × 1 HD: HD-SDI × 4
Dynamic range	ITU-R BT. 2100 (Hybrid Log-Gamma) ITU-R BT. 2020 (SDR)
Colorimetry	BT. 2020 / BT. 709
Power Consumption	210 W

High Dynamic Range Signal Processing

High dynamic range (HDR) was defined in ITU-R BT. 2100 [2]. Two HDR systems was standardized. One system is the so-called perceptual quantization (PQ) and the other is the Hybrid Log-Gamma (HLG). The PQ specification defines a very wide of display brightness levels, using an electro-optical transfer function (EOTF) finely tuned to match the human vision system. In contrast, the HLG specification defines an opto-electronic transfer function (OETF), a conversion function from scene luminance to the video signal level. The standard dynamic range (SDR) specification also defines OETFs based on scene luminance. Therefore, HLG system is suitable for HDR/SDR simultaneous broadcasting and live productions.

In order to render common the signal processing of HDR and SDR, gamma correction tables that can support HLG processing are installed in the gamma-correction circuit of our camera system. Figure 8 shows the OETFs of HLG processed in the gamma correction circuit of the CCU. The horizontal axis is equivalent to the sensor output signal level normalized by the maximum sensor output code, and the vertical axis is the camera output code after HLG processing. Although the reference dynamic range is 1200% in the ARIB standard [12], the CCU has variable dynamic range settings of 400%, 600%, 800%, 1200%, 1600%, and 2000% to meet the requirements of the scene begin shot.

Color correction

A color system can be also selected from the BT. 709 [13] color gamut and BT. 2020 wide color gamut. The color gamut of BT. 2020 is wider than that of HDTV, which was standardized in BT. 709. Figure 9 shows the ideal camera spectral sensitivities of the ideal camera for BT. 2020. The curves are not physically realizable because they have negative lobes. The camera system applies a 3 × 3 linear matrix (LM) to approximate the effect of the negative lobes.

The CCU also offers a color adjustment function based on 12-axis colors. This function allows separate adjustment of hue and saturation in each of 12 sectors that constitute the three primary colors (red, green, and blue), complementary colors (cyan, magenta, yellow), and six colors between them. Even if multiple cameras that are different with color reproduction are mixed in shooting, the CCU can control the color balance in detail.

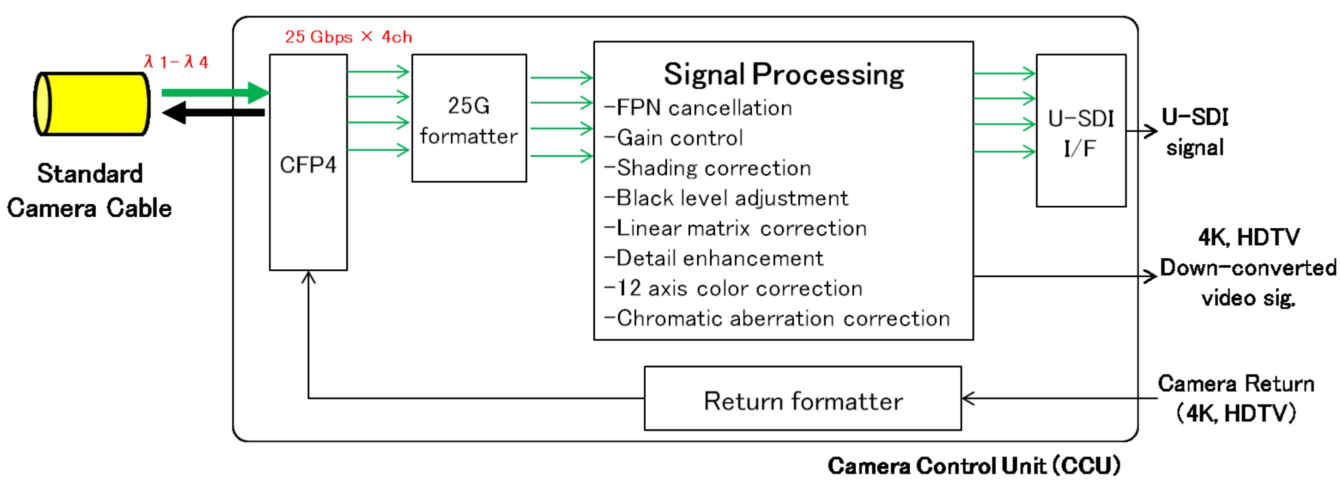


Figure 7. Block diagram of the developed camera control unit (CCU)

Chromatic aberration correction

The CCU provides compensating color shift due to the difference in the refractive indices of each color. Figure 10 shows the block diagram of this circuit. The method of correction is based on pixel position shift of the red and blue signals horizontally and vertically [3]. First, this circuit calculates amount of pixel shift from correction table stored in memory of the CCU. This table consists of correction data for typical values of the lens, for each of 16 × 9 areas obtained by dividing the active area. Next, this circuit suppress color shift with respect to green by performing a geometric conversion on the red and blue signals. The magnitude of correction is at most ±4 pixels and the precision of correction is 1/4 pixel. This function can cancel chromatic aberration at the corner of an 8K full-resolution image, and improve the blurring color at the corner.

Image Acquisition Experiments

Imaging Characteristics

We performed imaging experiments using the developed camera system to evaluate the characteristics of the 8K full-resolution video signal. The experimental results are listed in Table 4, and the measurement results of the modulation transfer function (MTF) using the ISO 12233 [14] slanted-edge method are shown in Figure 11. The MTF of the camera system using a 35-mm full-frame cinema lens (f = 50 mm, T5.6, horizontal direction) exceed 35% at 3200 TV lines, and 20% at the Nyquist frequency (4320 TV lines), which is equivalent to those of a conventional three-chip 8K camera. The ideal value was calculated as an image sensor with a 4.9 µm pixel pitch, and 100% aperture ratio under wavelength of 550 nm, F5.6, and aberration free lens. We confirmed over 4000 TV lines by examining a magnified view of the center portion in the resolution chart.

We measured the signal-to-noise ratio (SNR) of the image acquisition system. The SNR was 57 dB at a sensitivity of F4.0 for a 2000-lux illuminance and dynamic range of 200%. The SNR value was 14 dB higher than that of the first prototype system for the same sensitivity condition because of the image sensor noise reduction in the camera head. Further, residual FPN components due to the FPN suppression circuit were also reduced from 2.3 LSB to 1.4 LSB compared with the first prototype system. Figure 12 shows sample images under low illuminance conditions. The stripe FPN was suppressed well compared with the first prototype system.

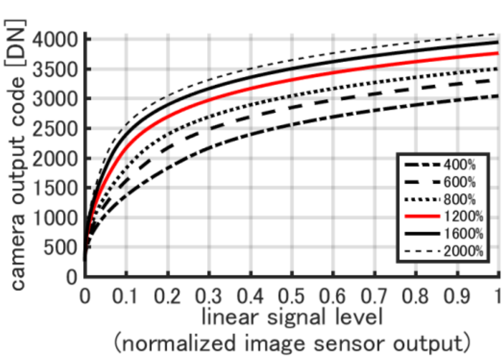


Figure 8. OETF of HLG signal processing

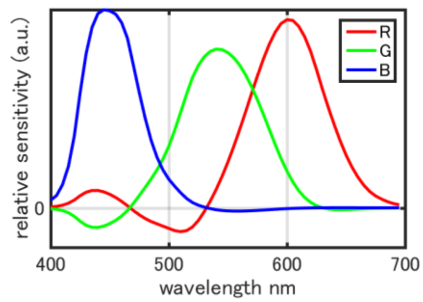


Figure 9. Ideal camera spectral sensitivities for BT. 2020.

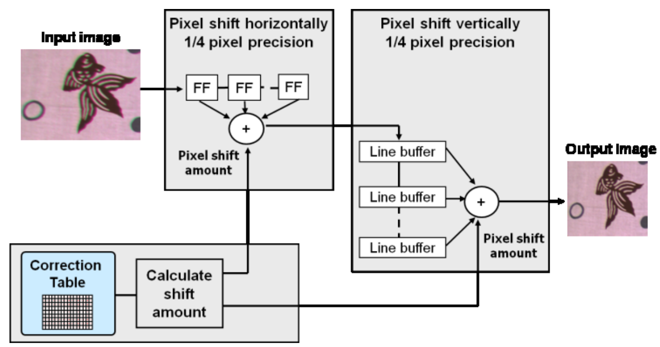


Figure 10. the block diagram of the chromatic aberration circuit.

Table 4: Imaging characteristics of full-resolution 8K portable camera

Sensitivity	F4.0, 2000 lx
S/N, Dynamic range	57 dB, 200%
MTF	35% at 3200 TV Lines 20% at 4320 TV Lines (Nyquist)
Limiting resolution	Over 4000 TV Lines

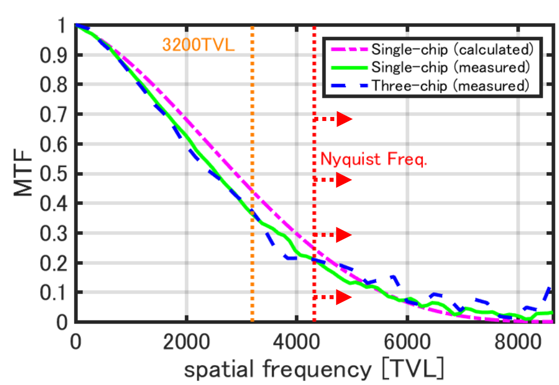


Figure 11. MTF characteristics of the portable camera system

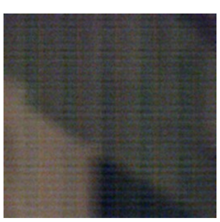
Streaking Noise Reduction Experiment

"Streaking" is a noise that spreads horizontally to the left and right from a highlighted object, as shown in Figure 13. When strong incident light enters the image sensor, a large amount of signals are generated from photodiodes where a highlighted object formed. Since each photodiode connects the gate of the amplifier CMOS transistor for each pixel, there are high voltage inputs to amplifier transistors, and a large amount of current flows from the source of the amplifier transistors to the ground wires. This introduces ground voltage fluctuation because the ground wires of the amplifier transistors connect horizontally and the ground wires themselves have high resistance. The ground turbulence changes the operation point of the amplifier transistors except for the highlight entering the pixels. As a result, the streaking noise that spreads horizontally from a highlighted object can be seen.

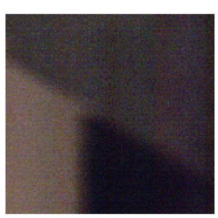
The CCU has a streaking noise reduction circuit that uses the signal of the optical black (OB) pixels placed to the left and right of an active pixel area. The streaking noise reduction circuit subtracts smoothed signal values of OB pixels from the active pixel signal values with streaking noise. The smoothed signal values are calculated by the following three steps:

1. Horizontally-average all OB pixel values in a single line
2. Eliminate FPN component of averaged OB pixel values
3. Process a mean filter vertically (in this experiment, we set the number of filter taps to 5)

We measured the streaking noise in the developed camera system. Figure 14 shows the horizontal pixel values that were vertically-averaged values of 100 lines to suppress random noises. The pixel values of Figure 14 are shown in 12-bit scale, and the black dotted line shows 256 DN, black level of the camera system. This result showed that streaking noises varied non-linearly in the horizontal direction. The noises were different between G1 and G2 components. Figure 15 shows the measured horizontal pixel values after smoothed OB pixels were subtracted. We evaluated the streaking noises in the 1920th horizontal pixel that was the middle position of the screen center and the screen edge. The streaking noise at the 1920th pixel reduced from 83 DN to 56 DN for the red channel. Furthermore, Figure 15 shows the reproduced images capturing a highlighted object before and after correction. Comparing Figure 16 (a) and (b), streaking noise was suppressed by through streaking noise reduction, but the nearer the pixel that strong at which incident light entered. The streaking noise component cannot be suppressed by only subtracting offset components.



(a) First prototype image acquisition system



(b) Newly developed camera system

Figure 12. Sample image under low luminance conditions

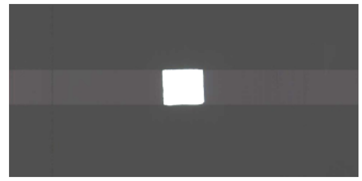


Figure 13. Sample image of the streaking noise

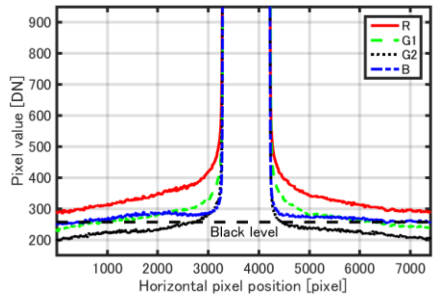


Figure 14. Measured horizontal pixel values before streaking noise reduction

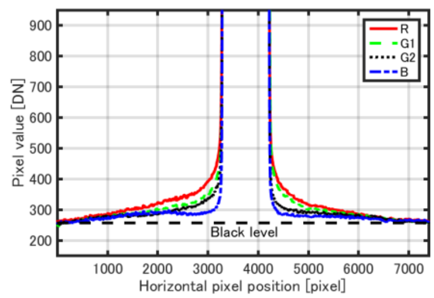
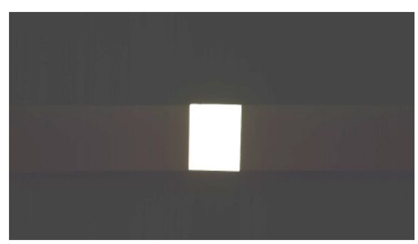
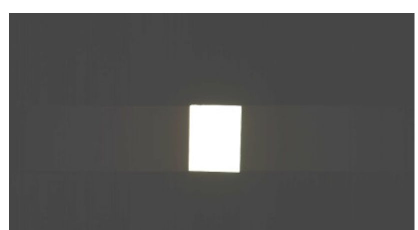


Figure 15. Measured horizontal pixel values after streaking noise reduction



(a) Before correction



(b) After correction

Figure 16. The result of a correction experiment in shooting a highlight object

Conclusion

We developed a portable camera system that can obtain full-resolution 8K 60-fps video using a 133-megapixel CMOS image sensor. The size of the camera head was drastically reduced compared with a conventional three-chip full-resolution 8K camera. We also developed a 3U-sized CCU with HDR processing, and wide color gamut processing. Results of imaging experiments showed that the resolution characteristics are equivalent to or surpass those of a conventional three-chip 8K camera. By improving the image sensor circuit board design, the SNR under the same sensitivity condition was 14 dB better than that of the first prototype image acquisition system. We measured the streaking noise of developed camera system. The results showed that the streaking noise cannot be suppressed by subtracting offset components.

The portability of this camera system was considerably better than that of a conventional full-resolution 8K camera system, such that we can easily shoot 8K full-resolution video. We will produce full-resolution 8K contents to utilize the high mobility of this camera system. In future work, we will attempt 120-fps driving with the 133-megapixel 60-fps CMOS image sensor using a line skipping operation and line interpolation signal processing.

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Author Biography

Tomohiro Nakamura received his BS and MS in electrical engineering from Waseda University (in 2006 and 2008, respectively). He joined Japan Broadcasting Corporation (NHK) since 2008. Since 2012, he has been engaged in the research of 8K camera systems at NHK Science and Research Technology Laboratories. He is a member of the Institute of Image Information and Television Engineers of Japan (ITE).