Image Sensor Characterization in a Photographic Context

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Abstract

The new Kodak KAI-11000CM image sensor, a 35-mm format, 11-Megapixel interline CCD, has been characterized in terms of its performance in photography applications. Traditional sensor performance parameters are summarized in addition to photographic image quality parameters. A photographic evaluation of the sensor, including measurements of signal-to-noise ratio and color fidelity, is described. Finally, a comparison of sharpness is drawn between the KAI-11000CM image sensor and the Kodak Professional DCS 760 digital camera in the context of a large 30" x 40" poster.

Introduction

CCD imagers are characterized as either interline transfer or full frame devices. Historically, the most demanding applications have required full frame imagers. Applications like astronomy and professional photography have used these types of imagers. The full frame imager is usually associated with higher sensitivity, because most of each pixel area is light sensitive. Full frame imagers have the limitation of requiring a mechanical shutter. The interline transfer device, however, offers greater flexibility to the camera designer, as it can operate in live preview mode by virtue of its electronic shutter feature. For this reason, interline transfer devices were selected to replace vidicon tubes in broadcast cameras and camcorders in the 1980s.

This paper examines the performance of a new interline imager created by Eastman Kodak Company, the Kodak KAI-11000CM image sensor. This imaging device has 11 million pixels and is designed to fill the 35 mm film gate (36.1 mm x 24 mm) of a traditional SLR. Such device characterization parameters as dark current, charge transfer efficiency, quantum efficiency, and read noise, together with photographic characterization parameters, such as noise-based ISO and color fidelity, will be developed. The KAI-11000CM image sensor was tested in a photographic context, using a digital camera-type configuration.

CCD Imager Theory

CCDs have four essential functions that relate to their operation: charge generation, charge collection, charge transfer, and charge measurement.

The efficiency with which a sensor generates charge is described by its quantum efficiency (QE). Photons strike the imager's pixel and generate charge in the silicon. Various pixel properties contribute to a sensor's QE. Photons striking the pixel encounter reflection, absorption, and transmission. Lenslets, color filters, and other materials must be penetrated by a photon to interact in the silicon. The device's quantum efficiency is equal to the ratio of generated photoelectrons to the number of incident photons.

Lenslets enhance the QE of the imager by focusing light into the photosensitive region, but they also induce an angle dependence in the QE. Large f/cones, such as those associated with low f/numbers, tend to include rays that strike the imager at large angles. These large angle rays, which strike the lenslets in the periphery of the imager, are refracted by the lenslet; but not enough to steer the ray into the photodiode portion of the pixel, thus reducing the QE. The QE for each pixel in the Bayer group is shown in Fig. 1. The response of green pixels next to red pixels, and that of green pixels next to blue pixels, is almost identical, as desired.

At the end of the commanded exposure time, photoelectrons collected in the photodiode are transferred to the vertical charge-coupled device (VCCD). The VCCD is adjusted to hold slightly more charge than the photodiode. This prevents blooming from occurring because all photodiode charge can fit into the VCCD. The charge capacity of the KAI-11000CM image sensor, as defined by the VCCD, is 52,000 electrons. This charge capacity sets the linear portion of the sensor's response, which is the portion of the response that is useful for photography. If a higher exposure is sensed by the imager, the photodiode will generate additional charge, but the charge will typically be swept into the vertical overflow drain (VOD) and be removed from the measurement.

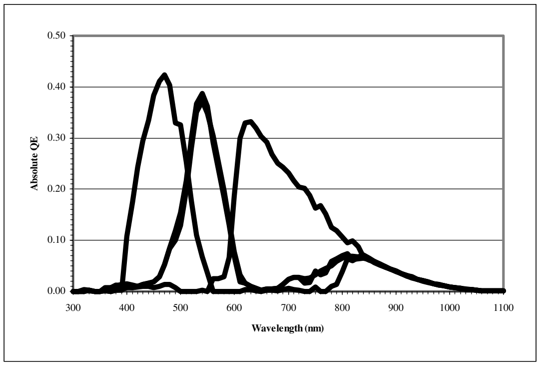

Figure 1. Absolute quantum efficiency Kodak KAI-11000CM image sensor.

Once the charge from a given pixel is collected, it must be transferred to the CCD output for measurement. Charge packets are transferred along the VCCD elements of each pixel until they get to the horizontal CCD (HCCD). The charge is shifted along the HCCD to the output where it is measured. Poor charge transfer can have deleterious effects on the image data. Residual charge can be left behind and be incorrectly assigned to another pixel. Color imagers with low charge transfer efficiency can mix colors or induce reduced MTF characteristics. The KAI-11000CM image sensor has very high CTE and does not produce these types of image artifacts.

Finally, the charge is transferred from the last phase of the HCCD onto the capacitive sense node. The capacitor presents a voltage that is proportional to the charge placed on it. Analog signal processing is applied to this signal to remove the noise associated with the resetting of the sense node. This imager has as charge-to-voltage conversion ratio of 14 µV/e. Thus, the total voltage for the imager's maximum response is approximately 700 mV. This is the voltage level associated with the maximum A/D codevalue.

The output amplifier that buffers the signal from the sense node contributes noise to the image data. The KAI-11000CM image sensor camera used in this analysis possesses low noise, with 34 rms electrons of noise at the 30 MHz pixel rate. This measure includes the contributions of the camera electronics, dark current shot noise, and amplifier read noise. The total dark noise was substantially minimized in the KAI-11000CM image sensor with accumulation-mode timing. Part of the dark current is generated in the photodiode, and part is generated in the VCCD portion of the pixel. Accumulation-mode timing reduces the dark current contribution from the VCCD by approximately 50X. The span between the imager's maximum response and its total noise floor is referred to as its dynamic range. The dynamic range of the KAI-11000CM image sensor is approximately 63 dB.

Photographic Evaluation

The KAI-11000CM image sensor's imaging performance is now approached from a different viewpoint. Instead of looking at the senor from a device-physics perspective, we now build a digital camera around it and characterize that system with photographic metrics. Understanding the KAI-11000CM image sensor's performance in this context will aid camera designers and will display what is achievable in terms of image quality with this imager.

Experimental Setup

The KAI-11000CM image sensor captures taken for the photographic evaluation were performed with a Horseman DigiFlex II camera body fitted with a KAI-11000CM image sensor board assembly. Raw CFA images were captured with a PC through a PCI-1424 framestore board from National Instruments. A simple series of test targets were taken for the purpose of analysis and calibration of the imaging system. In order to review images and make measurements, the 12-bit linear raw CFA image data was processed through to rendered sRGB.

Figure 2 shows the KAI-11000CM image sensor evaluation board attached to the *Horseman* camera. Figure 6 provides a rough sketch of the image processing chain. Proper exposure was determined such that an average reflector (18% assumption) would reside at 18/170ths of the imager's full well capacity and reflected the fact that 170% scene reflectance was captured and managed. This corresponds to 371 (for the green channel), 12-bit linear codes after dark-level subtraction. Scene reflectances range from 0% to 100% for perfectly diffuse reflectors, but objects with metallic surfaces demonstrate more specular reflectance, resulting in reflectances higher than 100%. Incorporating this high level of reflectance handling in the system calibration results in a higher base ISO measurement, but 170% reflectance handling is typical for Kodak professional digital still cameras. The green channel was utilized as the speed-defining channel, and red and blue were gained to achieve proper white balance. Three test targets and scenes were selected and developed for the purpose of challenging the imaging system from a noise and color perspective. The first was a Kodak proprietary test target that samples the gamut of colors and is used to develop color correction. Next was the standard ISO OECF target referenced in ISO-12232 and shown in Fig. 3. Finally, the realistic scene shown in Fig. 4, was used to test the imaging system.

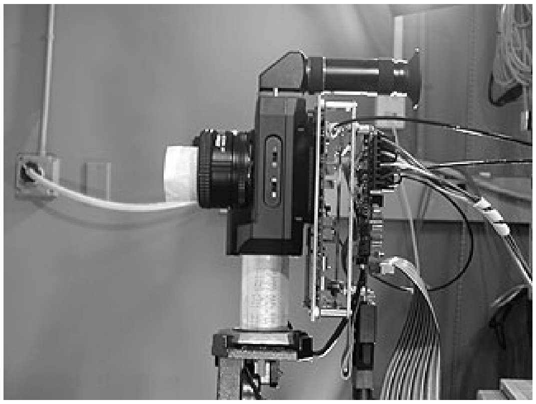

Figure 2. Horseman Digiflex Camera and The KODAK KAI-11000CM Image Sensor System.

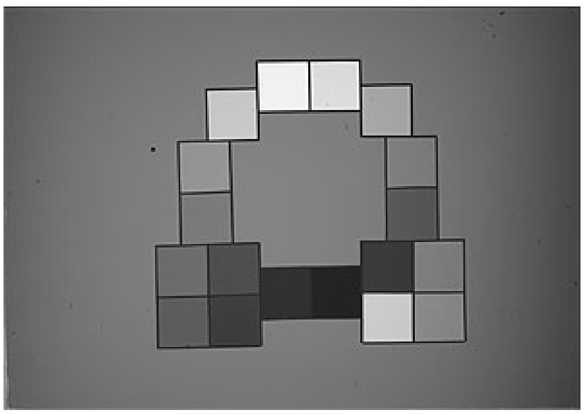

Figure 3. OECF Test Target.

Figure 4. Test Scene.

Base ISO

The KAI-11000CM image sensor possesses a base ISO of 160. The ISO was measured as described in the ISO-12232 standard. The Base ISO is the lowest exposure index at which an imager should be exposed. It is also the exposure index associated with the highest SNR and with the lowest highlight handling. Base ISO is also referred to as the saturation-based ISO, and is defined to be:

$$ISO_{sat} = \frac{10}{H} \qquad (1)$$

where H is the focal plane exposure in lux-seconds associated with an average reflector. Frequently, the focal plane is inaccessible to the experimenter when a measurement is required. This was the case with the KAI-11000CM image sensor test camera; therefore the taking lens aperture and the scene luminance were used to compute the ISO as shown below:

$$ISO_{sat} = 15.4 \cdot \frac{A^2}{L \cdot t} \qquad (2)$$

where L is the luminance of an average reflector or the average luminance of the scene in candelas/m2, t is the time the imager is collecting light in seconds, and A is the effective f/#:

$$A = (1 + 1/R) \cdot f/\# \qquad (3)$$

where R is the ratio of the height of the object to the height of the image.

The ISO calibration of a microlensed imager is complicated by aperture-microlens interaction. A slight ISO reduction becomes evident as the aperture is opened. This is due to the fact that a portion of the light focused by the microlens onto the pixel is imaged onto nonlight-sensitive regions. Each microlens images the camera lens stop onto the pixel. At low f/#, the stop grows relatively large, as does the image of the stop on the pixel. As the image of the stop exceeds the width of the photodiode, light is lost, and the sensitivity of the device appears to become reduced. For the KAI-11000CM image sensor pixel, this effect was measurable below f/2.8; therefore, images for this evaluation were taken at higher f/#s. If through the lens (TTL) metering can be used, this effect is only a small problem. Otherwise, if photographers elect to shoot wide open, they will have to compensate for the ISO shift or receive underexposed images.

Base ISO is an important imaging system specification, as it gives the camera user a basis upon which to set exposure. A camera system can functionally be exposed at *any* exposure index, but the noise level will dictate whether or not the resulting image is acceptable. The camera system’s maximum ISO is the maximum exposure index at which the camera system can still produce “acceptable” images. Thus, a camera system has a range of exposure indices over which it can operate, bounded at the low end by imager saturation and at the high end by camera noise.

Although base ISO is useful in setting proper exposure, it is not the best measure of an imager’s sensitivity. Higher QE translates into higher base ISO, but so does lower the charge capacity. Therefore, of two imagers with equal quantum efficiency, the sensor with the smallest dynamic range may be awarded the highest base ISO. A better measure of an imager’s sensitivity is its noise-based ISO—a measure of the exposure required to achieve a targeted SNR.

Noise-Based ISO

It is difficult to put a hard number on the noise-based ISO of an imager because noise degrades gradually as the exposure index is increased. What may be acceptable noise for one application may not be for another. If photographers "need the shot," they may elect to take a higher noise penalty in order to get it. This is like push processing in film where apparent film speed is increased by increasing the time that exposed film is in the developer, only done here in real time during the image capture.

KAI-11000CM image sensor images were taken at a range of exposure indices in the Kodak Digital Capture Studio. Both the test target and the test scene were captured at ISO-160 through ISO-5120 in one-stop increments. Figure 5 shows the SNR vs exposure index for the KAI-11000CM image sensor test camera, along side the same measurements performed on a Kodak Professional DCS 760 digital camera, which incorporates a 6-megapixel, full-frame CCD with 9-µm pixels. The SNR quoted is the 18% intrapatch luminance SNR, where the luminance signal is the Y signal—a linear combination of the sRGB signal's R, G, and B code values in the processed image. The luminance signal is derived from an image of the 18% OECF patch.

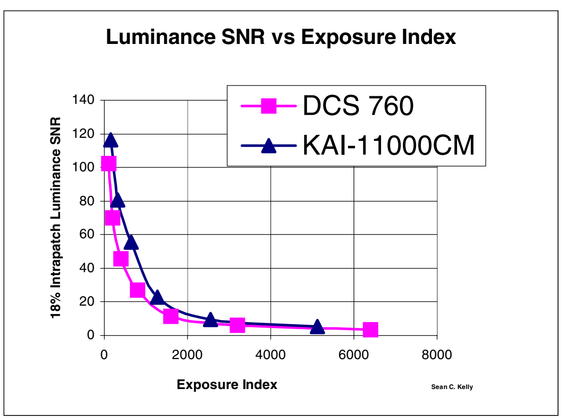

Figure 5. SNR v. Exposure Index.

Image subsections were extracted from processed images to show the effect of the signal-to-noise degradation at higher ISO. Squares measuring 125 x 125 pixels were taken from the 18% reflectance patch of the OECF target images and from a section of the test scene. No noise filtering was applied to any of the images. It is common for professional digital camera to provide exposure index settings up to 1600, and the KAI-11000CM image sensor performs well in this range, providing a signal-to-noise ratio of 20 as shown in the plot in Fig. 5.

Color Fidelity

The Kodak KAI-11000CM image sensor color error was assessed by capturing and analyzing a specialized target, which samples 64 XYZs of the color gamut. This test target was illuminated with HMI Arri Daylight Simulators. The spectral quantum efficiency of the device, lens transmission, and IR filter transmission are all factors in the native spectral sensitivity of the imager in a camera system. To the extent that the camera's spectral sensitivities are color-matching functions, they are matrix-correctable to sRGB. As a means of defining and communicating the color fidelity of this capture system, average ΔE* is measured. The average ΔE* is the average of all the vectors between the aim and the reproduction. The KAI-11000CM imaging system, with a 50 mm f/1.4 Nikon lens and B&W IR cut filter, yields an average ΔE* = 4.5. This color position is similar to other professional digital cameras, including the DCS 760 digital camera. Without the application of the matrix, the native imager response produces an average ΔE* of 12.2.

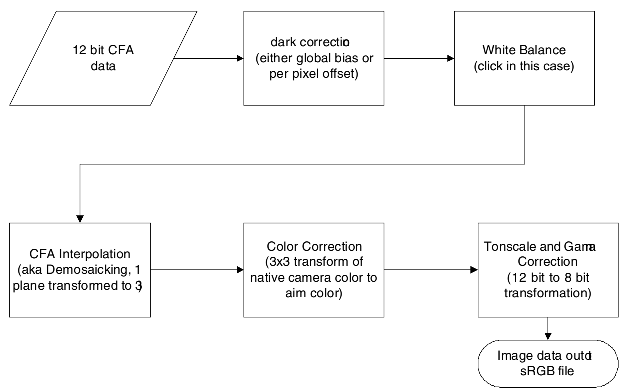

Figure 6. Image Processing Datapath.

Image Quality Analysis

Image quality is dramatically improved by using this 11-megapixel imager, compared to the 6 megapixel imager in the DCS 760 digital camera. Much higher acutance or visually relevant sharpness is achieved with the KAI-11000CM image sensor. The sharpness increases the overall multivariate image quality of captured imagery by 6.8 JNDs over the 6-megapixel imager, or one whole subjective quality category[1]. Assumptions in this analysis include: Nikon 35 mm f.l. @ f/8, birefringent anti-aliasing filter, 5 x 5 sharpening kernel (individually optimized for each system), 40" x 30" poster printed at 333 dpi, 24" viewing distance and printed on AgX paper. It is further noted that such an imager provides the opportunity to capture sharp, high-quality images, even at the low f/#, while holding imager and auto-focus positioning tolerances at the same level as the lower-resolution, smaller-format camera system.

Conclusions

The Kodak KAI-11000CM image sensor is well suited for a professional 35-mm format digital still camera. Its 35-mm format provides full coverage of the film gate, eliminating the magnification error common to digital cameras, based on 35-mm format camera bodies. The interline transfer CCD architecture with fast dump feature provides live image preview and 50-ms flushing of the sensor. This architecture is inherently robust against crosstalk between pixels, yielding professional quality color fidelity. The sensor's low dark current and read noise contributed to the test camera out performing the Kodak Professional DSC 760 digital camera in SNR at exposure indices from 160 to 5120. Further, image quality analysis shows a substantial difference between Kodak Professional DCS 760 digital camera and Kodak KAI-11000CM image sensor images, when analyzed as printed to 30" x 40" posters. Poster prints will look one whole quality category better when the capture comes from the high-resolution KAI-11000CM image sensor.

References

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2. G. Putnam, "Photography with an 11-megapixel, 35-mm format CCD," *IS&T/SPIE Electronic Imaging*, January 2003.
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Biographies

Sean Kelly received his BS degree in Applied Physics from the State University of New York at Geneseo in 1989 and an MS in Electro Optics from University of Dayton in 1992. Since 1992, he has worked in the area of Digital Image Processing in his commercialization and R&D assignments at the Eastman Kodak Company. He is currently the group leader of the Digital Capture Group. This group supports both commercialization and R&D initiatives at Kodak with imaging science expertise.

Gloria Putnam received her BS degree in Physics and a BS degree in Mathematics from California State Polytechnic University, Pomona. She is currently an applications engineer in the Image Sensor Solutions Division at Eastman Kodak Company, where she assists camera designers with the implementation of Kodak imagers in applications ranging from digital photography to remote sensing.