Photography with an 11-megapixel, 35-mm format CCD

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ABSTRACT

The new Kodak KAI-11000CM image sensor—a 35-mm format, 11-Megapixel interline CCD—has been characterized to evaluate its performance in photography applications. Traditional sensor performance parameters, including quantum efficiency, charge capacity, dark current, and read noise are summarized. The impact of these performance parameters on image quality is discussed. A photographic evaluation of the sensor, including measurements of signal-to-noise and color fidelity, is described.

Keywords: CCD, image sensor, interline transfer, digital photography, ISO

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1. INTRODUCTION

Two distinct architectures have evolved since the invention of the CCD: the full frame CCD and the interline transfer CCD. The full frame CCD was originally developed for demanding scientific applications like astronomy, but today it can be found in a variety of professional photography cameras, including digital backs for medium format cameras. The interline transfer CCD was developed primarily for video products like camcorders and broadcast cameras and replaced vidicon tubes in those products during the 1980s. More recently, interline transfer CCDs have found their way into performance-imaging applications like microscopy, fluoroscopy, and professional photography, where their video and shuttering capabilities offer advantages over the full frame CCD. The interline transfer CCD is the sensor type found in almost all consumer digital still cameras.

Eastman Kodak Company has developed a 35-mm format interline transfer CCD with 11 million pixels for use in professional digital still cameras. The device was first tested using traditional sensor characterization methods, focusing on standard device performance metrics, including quantum efficiency, charge transfer efficiency, read noise, and dark current. Next, the CCD was characterized specifically for photography using image quality metrics including noise-based ISO and color fidelity. In this paper, we will review the characterization results and discuss the relationship between standard image sensor metrics and photographic image quality.

2. PHYSICAL DESCRIPTION

Interline transfer CCDs use a pinned photodiode CCD pixel in which the processes of charge collection and charge transfer are delegated to different parts of the pixel. Photoelectrons are collected in a p+npn photodiode with anti-blooming capability. The p-region provides a barrier between the n-region, where charge is collected, and the n-substrate. The height of this barrier is set by the voltage applied to the substrate and determines how much charge the photodiode can hold. Excess charge flows over this barrier into the substrate. This style of antiblooming mechanism is called a vertical overflow drain (VOD) because the excess charge flows vertically rather than laterally, as is the case in most full frame CCD architectures. The barrier can be temporarily removed by applying a positive voltage to the substrate, emptying the charge in the photodiodes. The ability to clear all of the photodiodes of the sensor simultaneously provides an electronic shuttering capability that the full frame CCD pixel does not share. Because there is no electrode material covering the photodiode, the photodiode does not suffer from the same degree of absorption loss as the full frame CCD pixel. A microlens on the pixel surface is used to focus incoming light onto the photodiode to make up, in

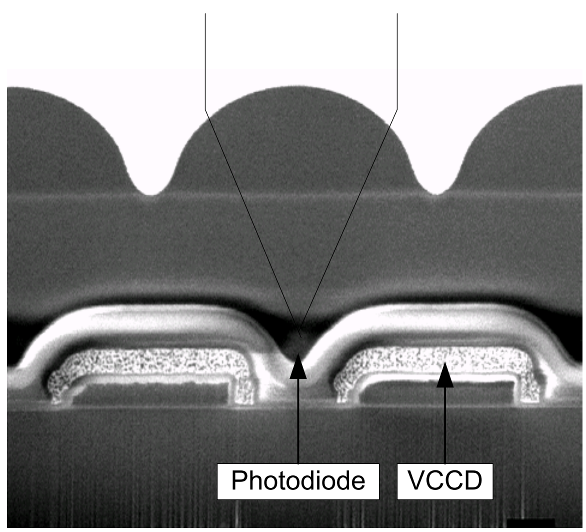

Figure 1: SEM cross-section of an interline transfer CCD pixel showing the photodiode, VCCD, and the focusing of incident light by the microlens.

part, for the fact that the entire pixel area is not light sensitive. An SEM cross section of this pixel type is shown in Fig. 1. Once image capture is complete, the collected charge is moved under a transfer gate and into one of the phases of the vertically oriented CCD structure that makes up the remainder of the pixel. Because the CCD portion of the pixel is not used for image capture, it is covered with a metal light shield. Once the image charge has been relocated to this region, the photodiodes can start collecting the next image, providing an uninterrupted video stream. The CCD register portion of the pixel is similar to a full frame CCD pixel—charge is transferred through a depleted n-buried channel. A p-stripe under the vertical CCD register isolates charge from the substrate, ensuring that the VCCD is not emptied when the electronic shutter pulse is applied.

The pixels of the KAI-11000CM are 9-µm square and incorporate a pinned photodiode and a 2-phase vertical CCD shift register. A microlens array focuses incoming light away from the VCCD and onto the photodiode. This pixel is large in comparison to the 3-µm pixels common in consumer digital still cameras and, therefore, provides considerably more sensitivity and dynamic range. The array consists of 4008 × 2672 pixels covering a total active area of 36.1 mm × 24.0 mm, or a 43.3-mm photographic diagonal. Buffer pixels separate the active pixels from light-shielded dark pixels as shown in Fig. 2. The sensor is available both with and without the color filter array (CFA). The sensor incorporates a fast dump drain, which allows the disposal of unwanted image rows prior to their transfer into the horizontal shift register. This feature can be used to flush the entire CCD in less than 50 ms before an image capture, to read out a small section of the imager at high frame rate for auto focusing or to decimate the image for live preview. The sensor has two outputs and uses a bi-directional, pseudo 2-phase HCCD, allowing the image to be read from either output or both. Each output consists of a 3-stage amplifier designed for a 30-MHz data rate. The 37.25 mm × 25.70 mm die is packaged in a 40-pin ceramic dual-in-line package (CerDIP).

The full 35-mm format offers significant advantages for digital photography. In most SLR digital cameras, the imager is installed into a modified film camera body that maintains the 36 mm × 24 mm film gate. The imager is usually smaller than the film gate dimension, and as a result, it subsections the focal plane. This has the effect of inducing focal length magnification. For example, if a 12-mm high imager (1/2 the height of the film gate for a 35-mm camera) is installed in the focal plane and a 50-mm focal length lens is used, the imager will make that lens behave like a 100-mm lens in terms of the field coverage. Even though the lens can deliver the additional coverage, the imager cannot collect it. The KAI-11000CM image sensor eliminates this problem because the imager dimension fills the frame. With a full 35-mm format imager, all lenses, and particularly wide-angle lenses, can be used to deliver their intended field coverage.

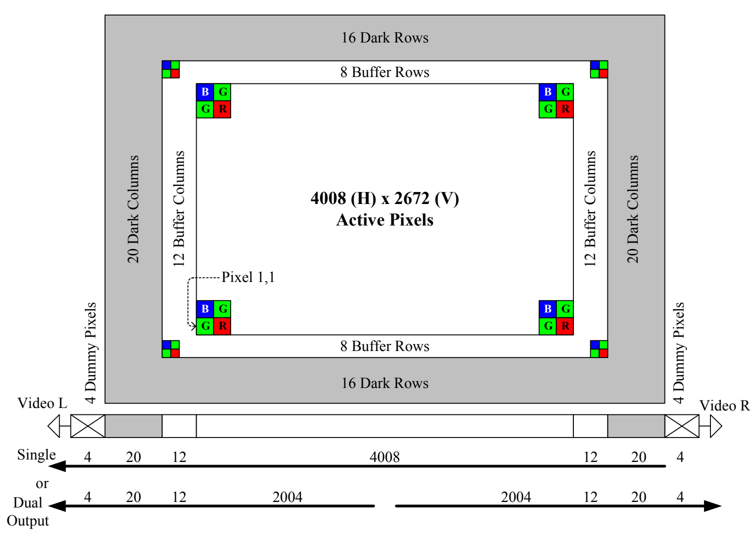

Figure 2: The Kodak KAI-11000CM image sensor format.

3. SENSOR CHARACTERIZATION

A CCD must perform four tasks to produce an image: charge generation, charge collection, charge transfer, and charge measurement. These processes and the techniques used to measure how well they are performed are detailed in other sources,[1] and will be reviewed only briefly here.

3.1 Charge generation

In order to capture an image, the CCD pixels must convert incident light into photoelectrons. This process is limited by reflection, absorption, and transmission. At each material interface above the device's active region, some light is reflected away from the sensor. In an interline transfer CCD, photons that strike the light-shielded portion of the pixel are lost to reflection as well. The materials over the photodiode also absorb some of the incoming light before it reaches the active region. Blue light, because of its high absorption coefficient, is especially susceptible to this loss mechanism. The absorption of blue light is minimized in an interline transfer CCD because there is very little absorbing material over the photodiode. Longer wavelength light is more susceptible to loss by transmission—it interacts with the silicon below the active region, producing electrons that recombine with holes or are swept away by the vertical overflow drain structure.

How efficiently an image sensor converts light into photoelectrons is its quantum efficiency. A quantum efficiency curve shows the percentage of incident photons in a given wavelength band that produce electrons in the device's active region. In a sensor with a color filter array, separate curves show the response of the green, red, and blue pixels over the entire wavelength range of the measurement. This measurement is made using a monochromator. Fluctuations in the intensity of light from the monochromator are removed by alternating CCD measurements with measurements using a calibrated photodiode. The resulting curve shows the collective effect of the CFA material's spectral transmission and the spectral response of the CCD. The quantum efficiency curve of a color KAI-11000CM image sensor is shown in Fig. 3.

The use of a microlens above the photodiode significantly increases the QE of the sensor, but it also produces some undesirable effects. The most troubling of these effects is angle roll off—the decrease in response with the angle of incidence of the incoming light. In the case of normally incident light, the microlens focuses incoming light into the photodiode aperture. However, light entering the microlens at higher angles can be directed away from the photodiode

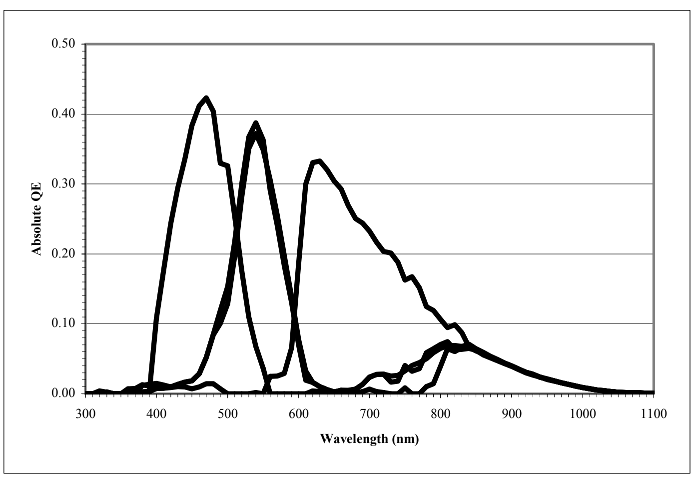

Figure 3: Absolute quantum efficiency of the Kodak KAI-11000CM image sensor.

and lost. Because the photodiode is narrower than it is tall, this effect is most pronounced in the horizontal direction. The relative response of a 9-um pixel with microlenses with respect to angle of incidence is shown in Fig. 4.
The higher the angles of incidence, the lower the response, causing the edges of the image to look darker than the center. This accentuates the similar and already present effect of the taking lens transmission. For a specific taking lens configuration, this can be corrected in image processing. However, no correction for this effect was applied to images taken during the testing of the KAI-11000CM.

3.2 Charge collection

In a color CCD, the quantum efficiency curves also indicate how well the sensor is collecting photoelectrons in the pixel in which they were generated. If a photoelectron is generated in a green pixel, but diffuses into a neighboring red pixel and is collected there, the result will be an exaggerated overlapping of the green and red curves known as cross talk. This cross talk is worst for small pixels and has little impact on the KAI-11000CM. Cross talk can also be caused by light hitting the CCD at a shallow angle and passing through, for example, a green filter but interacting in an adjacent blue or red photodiode. The quantum efficiency measured here was with normally incident light, therefore this effect is not included in the data. The peak wavelengths and overlapping of the QE curves determine the photographic color accuracy of the sensor.

The charge capacity of an interline transfer CCD is determined by the capacity of the VCCD. The photodiode capacity is adjusted to be smaller than the VCCD capacity so that charge transferred into the VCCD will not cause blooming. The charge capacity of the KAI-11000CM was measured using the photon transfer technique. The results are shown in Fig. 5. As the charge capacity is reached, the photon transfer curve flattens out and eventually drops off. It is the linear region of this curve that is useful in a photographic camera, and which determines the sensor's base ISO and maximum achievable signal-to-noise ratio. The linear charge capacity of the KAI-11000CM image sensor shown in Fig. 5 is approximately 52,000 electrons.

3.3 Charge transfer

After the exposure is complete, charge must be transferred, first, from the photodiode into the VCCD, next, along the VCCD, and, finally, along the HCCD to the output. If this first transfer is not performed effectively, the result is image lag. Lag in an interline transfer CCD is typically very low—on the order of a few electrons. The charge transfer along the VCCD happens slowly, therefore the efficiency is very high and not usually a cause of concern in photographic applications. The charge transfer along the HCCD happens more quickly, generally tens of millions of pixels per second. Because a very limited amount of time is allowed for each transfer, this transfer is the most likely to cause trouble. Figure 6 shows the charge transfer efficiency of the KAI-11000CM as a function of voltage swing applied to the HCCD and signal level. If the charge transfer in either direction is poor, the result is a decrease in the camera system

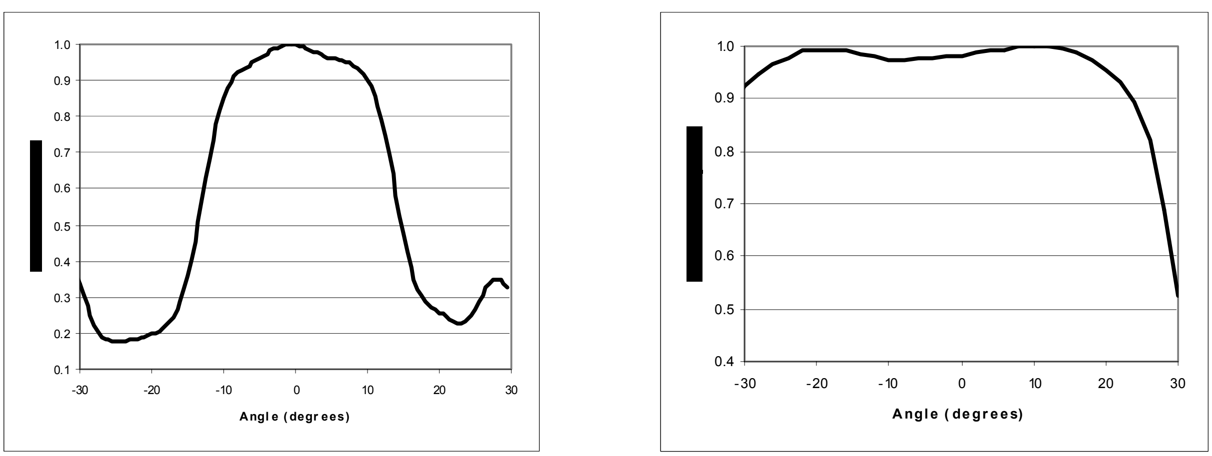

Figure 4: Horizontal and vertical angle response for a test imager with the KAI-11000CM pixel design.

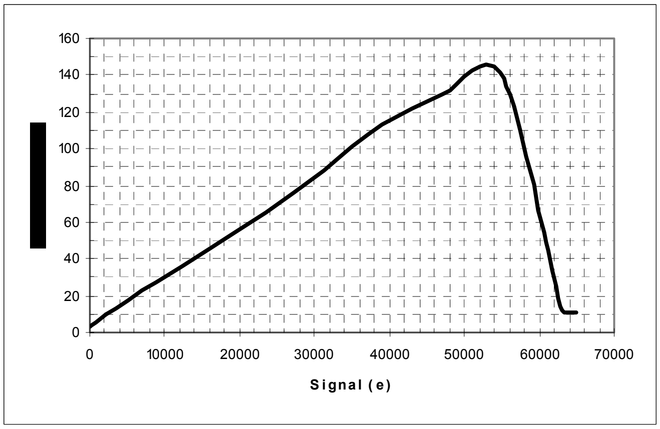

Figure 5: Photon transfer curve for KAI-11000CM image sensor.

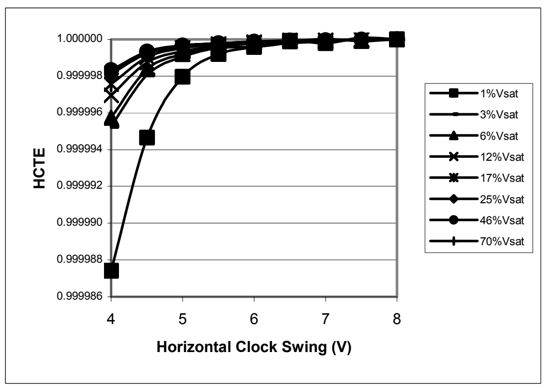

Figure 6: HCTE as a function of clock swing and signal level for the KAI-11000CM.

MTF or a loss of image sharpness. In the case of a color sensor, poor CTE can also cause color problems. Charge that is not effectively transferred combines with charge in the pixel behind it. Because these pixels contain information about different color planes, this one-sided color cross talk can result in a hue shift in color images. During the characterization of the KAI-11000CM, the HCCD was operated with a 6-V swing.

3.4 Charge measurement

The final task for the CCD is that of charge measurement. Charge packets are transferred from the last phase of the HCCD onto a capacitive sense node. The voltage change on the capacitor is buffered by an output amplifier. Analog signal processing in the camera removes the noise associated with the resetting of the sense node after each charge packet is measured, but the noise contributed by the amplifier stage remains. The KAI-11000CM output provides a charge to voltage conversion ratio of 14 μV/e. When the sensor is operated near its 50,000-electron capacity, the signal swing on the output is 700 mV. A 3-stage amplifier provides sufficient bandwidth at this signal level to operate the sensor at the desired 30-MHz pixel rate. Using both outputs, this pixel rate provides 5 fps at full 11-megapixel resolution.

3.5 Noise sources

The maximum signal-to-noise ratio (SNR) achievable by a particular imager depends on its well capacity and its noise floor, i.e., its dynamic range. The noise floor of the KAI-11000CM test camera was measured to be 34 electrons rms at the full 30-MHz pixel rate. This total noise floor is the quadrature sum of a 25-electron rms sensor noise and a 23-

electron rms contribution from the camera electronics. The sensor noise includes the amplifier read noise, the shot noise associated with dark current, and clocking noise. All measurements were taken at room temperature.

Dark current was minimized using accumulation mode clocking.[2] In this clocking scheme, the time that the VCCD gates spend in accumulation is maximized in order to suppress surface dark current. The clocking scheme used is shown in Fig. 7 and the dark current performance of the sensor in this clocking mode is shown in Fig. 8. The VCCD clocking scheme does not influence the dark current of the photodiode.

For large imagers, dark current generation during read out can lead to a dark current ramp or other pattern in the image. In the images shown below, the dark offset level was subtracted using a frame rate clamp, rather than a line rate clamp, nevertheless, no ramp is visible. When a ramp is visible, dark frame subtraction can be used to eliminate it. This has been done in digital still cameras using CMOS imagers with much higher dark current than that of the KAI-11000CM. However, the process of subtracting frames adds to the noise floor, because the noise of the image frame and the dark frame add in quadrature. This noise increase can be minimized by using an average of several dark frames for frame subtraction, but because no ramp or pattern was visible in the images used for the evaluation, no dark frame subtraction was used. Also, no point or column defect correction was used.

4. PHOTOGRAPHIC EVALUATION

The characterization described above gives a fairly complete description of the imager performance and can be analyzed with the requirements of any application in mind. Photographic image quality is determined primarily by signal-to-noise ratio and color accuracy, both of which can be estimated analytically from the standard sensor characterization parameters already discussed. The purpose of the photographic evaluation described below is to measure these image quality parameters directly and collect images that demonstrate the results.

4.1 Experimental setup

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

order to review images and make measurements. Figure 9 shows the KAI-11000CM evaluation board attached to the *Horseman* camera. Figure 10 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 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.

Limited test targets and scenes were selected and developed for the purpose of challenging the imaging system from a noise and color perspective. These experiments used three test targets/scenes. The first was a Kodak proprietary test target that samples the gamut of colors and is used to develop color correction. The next was the standard ISO OECF target defined in ISO-12232[3] and shown in Fig. 11. Finally, a realistic scene was used to test the imaging system and is also shown in Fig. 11.

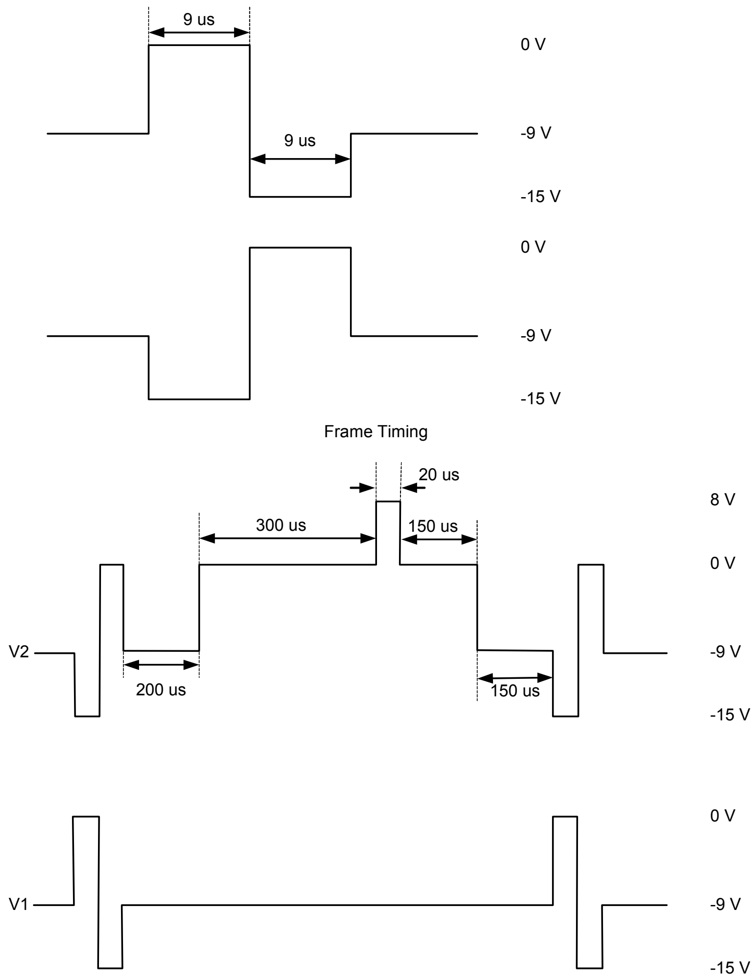

Figure 7: Vertical line and frame timing used in the characterization of the KAI-11000CM image sensor.

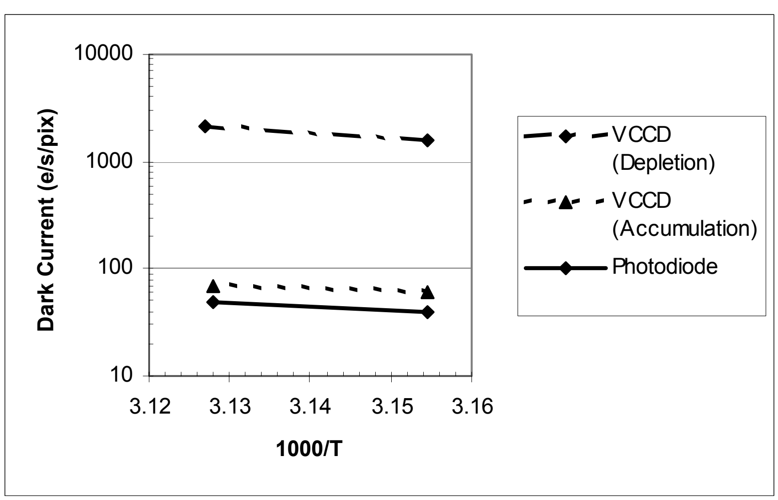

Figure 8: Photodiode dark current and VCCD dark current for both accumulation mode and depletion mode clocking.

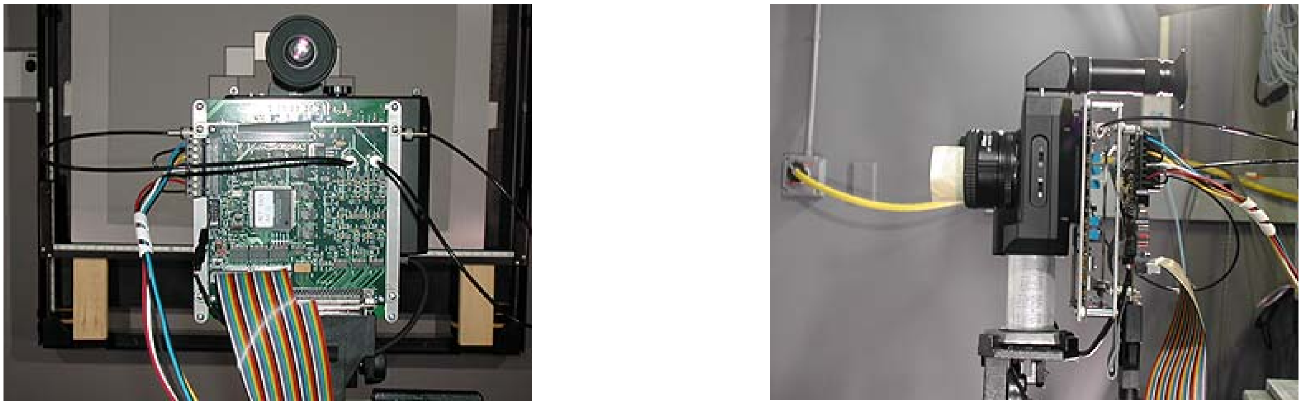

Figure 9: Digiflex Camera with KAI-11000CM imager board

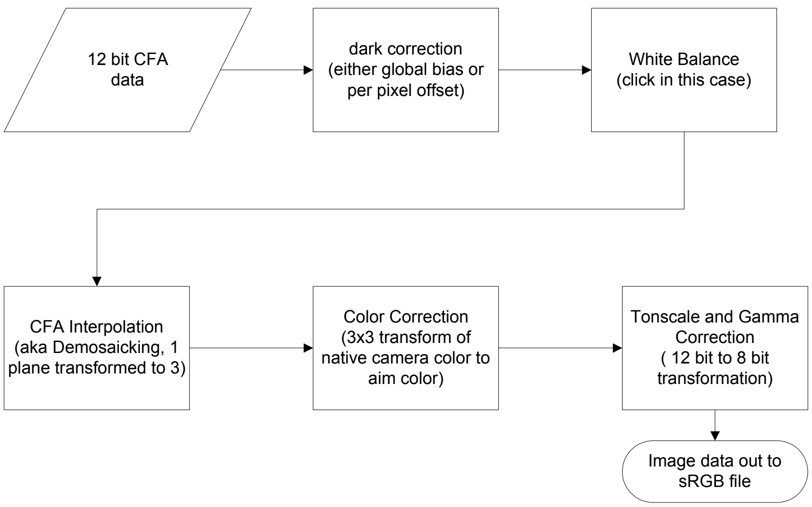

Figure 10: Image processing chain.

Figure 11: OECF target and test scene

4.2 Base ISO

The KAI-11000CM possesses a base ISO of 160. The imager's 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

$$ISO_{sat} = \frac{10}{H}$$

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 test camera; therefore the taking lens aperture and the scene luminance were used to compute the ISO[4]

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

where L is the luminance of an average reflector or the average luminance of the scene in candelas/m^2, t is the time the imager is collecting light in seconds, and A is the effective f/#

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

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 device's sensitivity appears to become reduced. For the KAI-11000CM 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 a nonissue. 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. Exposure is controlled by the imager's integration time, camera shutter, and the lens aperture. These exposure control parameters are set based on scene luminance to achieve optimum 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 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.

4.3 Noise-based ISO

It is difficult to put a hard number on the noise-based ISO of an imager, because noise degradation is gradual 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 images were taken at a range of exposure indices in a Kodak digital studio. Both the test target and the test scene were captured at ISO-160 through ISO-5120 in one-stop increments. Fig. 13 shows the SNR vs exposure index for the KAI-11000CM 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. Table 1 shows the exposure indices exercised, the related aperture settings, and exposure times. 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.

Image subsections were extracted from processed images to show the effect of the signal-to-noise degradation at higher ISO. 125x125-pixel squares 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 typical for a 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.

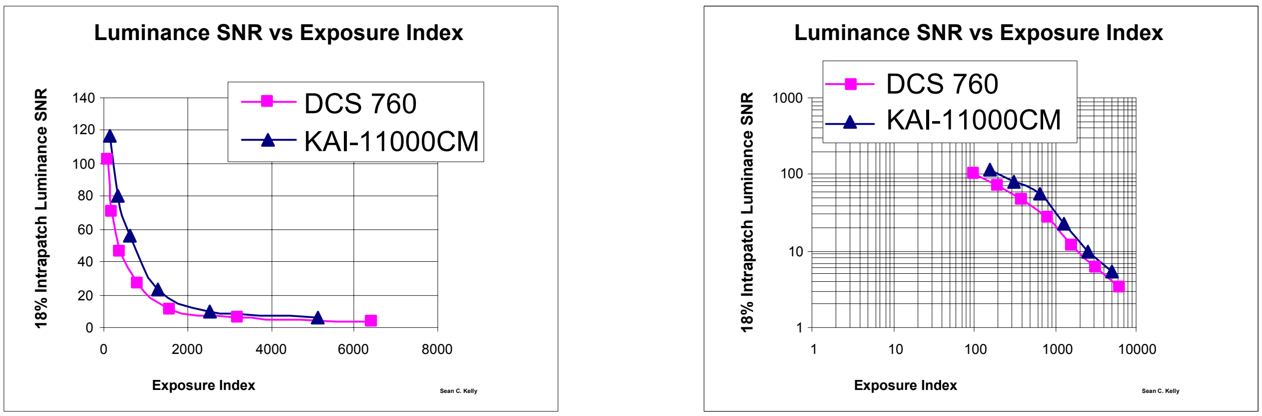

Figure 12: Linear and log plots of the luminance SNR vs exposure index for the KAI-11000CM test camera system.

Exposure Index	Shutter Time (seconds)	Aperture (f/#)
160	1/15	10.9
320	1/30	10.9
640	1/60	10.9
1280	1/125	10.9
2560	1/250	10.9
5120	1/500	10.9

Figure 13: Settings used to obtain exposure indices from Fig. 12.

Each picture subsection shows the increased noise position associated with each exposure index. ISO-5120 images are associated with approximately 3% of the exposure of the base ISO-160 images and thus utilize approximately 32X gain to achieve proper appearance in terms of mean signal. The high 11-megapixel resolution of the KAI-11000CM offers advantages in terms of noise position because the spatial frequency of the noise is much higher than typical content structure. Thus, unless intensive zoom is used, the pictures will be more acceptable than a 4 or 6 megapixel image with equal measured noise. The more obvious advantages of 11-megapixel resolutions are demonstrated in Fig. 26.

4.4 Color fidelity

KAI-11000CM color error was assessed by capturing and analyzing a specialized target which samples 64XYZs of the color gamut. This test was illuminated with HMI Arri Daylight Simulators. The spectral quantum efficiency of the device, lens transmission, and IR filter 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, as shown in Fig. 27. The KAI-11000CM imaging system with a 50 mm f/1.4 Nikon lens and B&W IR cut filter yields an average $\Delta E^* = 4.5$. This color position is similar to other professional digital cameras, including the DCS 760 digital camera. Figure 27 also shows the affect of not applying the color correction matrix. The error vectors are obviously longer and the average $\Delta E^* = 12.2$.

Figure 14: ISO-160.

Figure 15: ISO-320.

Figure 16: ISO-640.

Figure 17: ISO-1280.

Figure 18: ISO-2560.

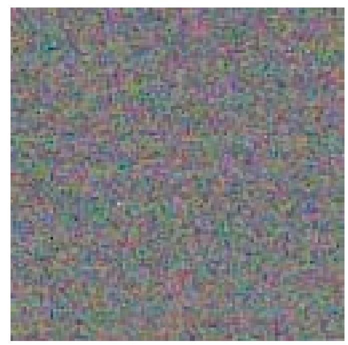

Figure 19: ISO-5120.

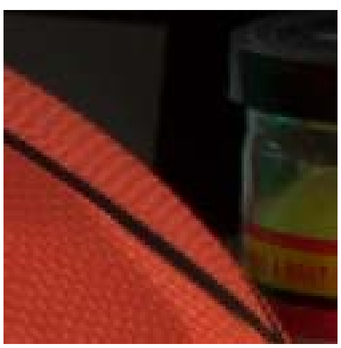

Figure 20: ISO-160.

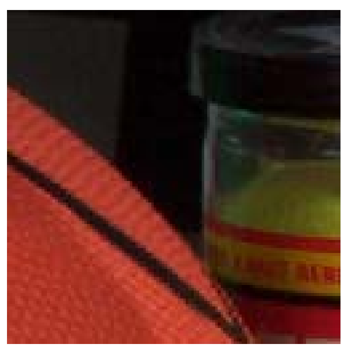

Figure 21: ISO-320.

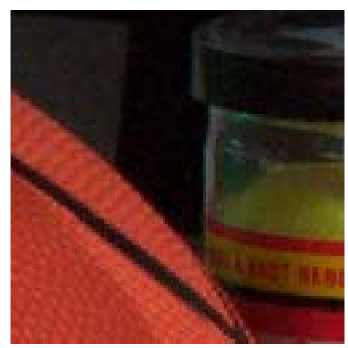

Figure 22: ISO-640.

Figure 23: ISO-1280.

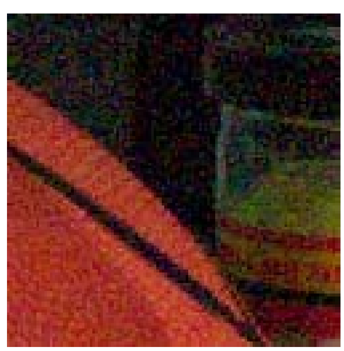

Figure 24: ISO-1260.

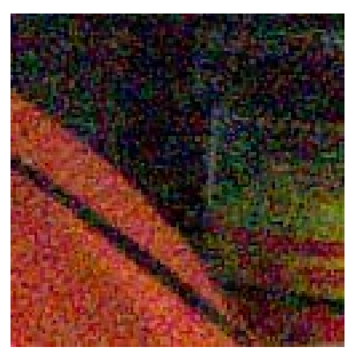

Figure 25: ISO-5120.

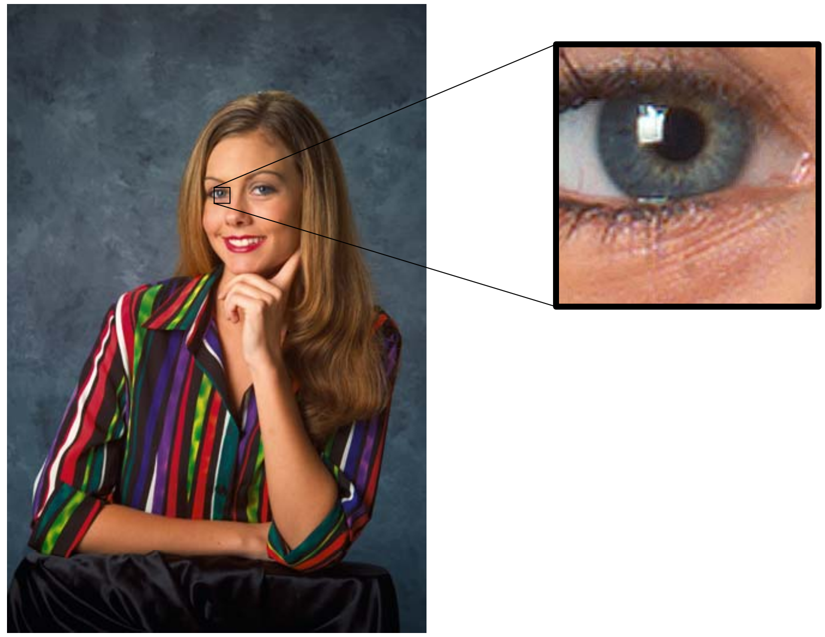

Figure 26: An 11-megapixel image taken with the KAI-11000CM test camera, and a blow-up of image detail.

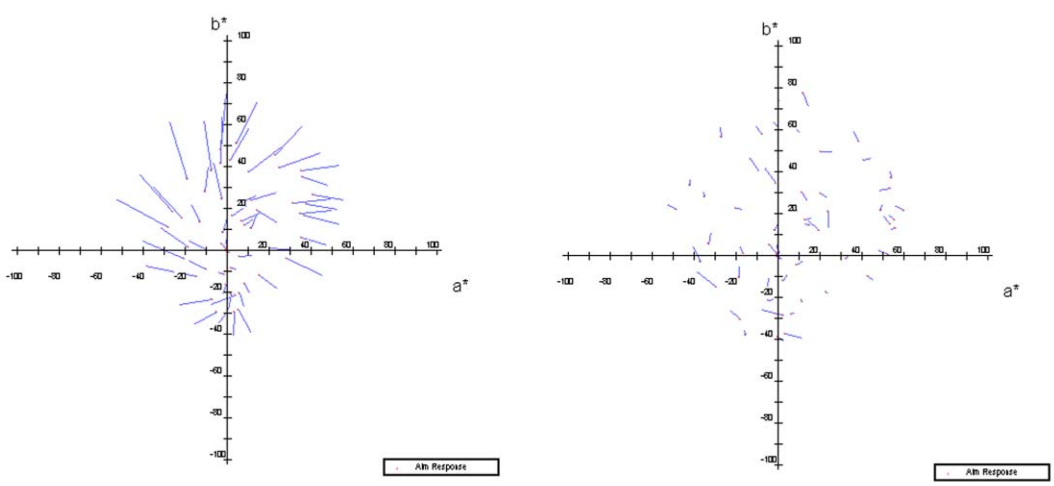

Figure 27: a*b* plot before and after color correction is applied.

5. CONCLUSION

The Kodak KAI-11000CM image sensor is ideally 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 cross talk 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.

6. ACKNOWLEDGMENTS

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