Silver Halide and Silicon as Consumer Imagers

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An appreciation of the potential of silver halide as an image capture material for digital applications can benefit from an understanding of the characteristics and potential of silicon-based imagers. Here, we compare the imaging characteristics of contemporaneous silicon and AgX imagers on a common basis. Sensitometric and image structure comparisons of first generation Kodak Advantix 400 AgX color film and contemporary (1997–1998) Kodak Professional digital camera system (DCS) color imagers at 393 K, 1.6 M, and 6.3 M pixel sensor resolution are presented. The imagers compared have similar useful color imaging exposure thresholds. In speed-grain terms, the 6.3 M sensor DCS provides similar speed-grain in the lower scale and superior speed-grain in the upper scale when compared to the AgX film. The smaller sensors appear less capable in this regard. The sensors all provide shorter exposure latitude than the film. Further, within the context of pictorial imaging, it appears that the silicon array as employed in the DCS is close to its fundamental imaging efficiency limits.

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Introduction

The growing importance of silver halide(AgX) as an inexpensive and convenient capture media for digital images highlights the need for a better understanding of the strengths of both image capture systems.[1] Accordingly, the comparative performance of silver halide and silicon as imagers is of ongoing interest to the photographic community. One difficulty with such comparisons appears grounded in the distinct training and language of workers in these fields.[2] A natural approach towards bridging this gap follows from the speed metrics for digital cameras systems (DCSs). Building from the speed metric allows a direct sensitometric and signal/noise comparison between AgX films and DCSs. Here, we describe such a comparison for first generation Kodak Advantix 400 AgX color film and its contemporary (1997–1998) Kodak Professional digital still camera color imagers with 393 K, 1.6 M, and 6.3 M pixel sensors.

Film Speed

The speed of an AgX based pictorial material is inversely related to the minimum exposure level required to produce the first excellent image when using that material. The relationship between the ISO speed of a camera film and the mean exposure at a focal plane in an automatic camera, as defined in ISO-2721, is:

$$\text{ISO} = 10 \text{ lux-seconds}/\mathbf{H} \tag{1}$$

where ISO is the speed rating, a dimensionless number; and **H**, in lux-seconds, is the minimum mean focal plane exposure required to produce the first excellent image.[3,4] Films with well-defined latitude typically employ a scaling constant of about 10 with the required focal plane exposure placed at a sensitometric mid-scale as defined by the achievable latitude of the light sensitive material after a defined process. Distinct scaling constants and reference exposure points are employed for films with less well-defined latitudes. Consumer negative films for example, have a well-defined toe but an indistinct shoulder. Here, a reference exposure is determined based on toe densitometric properties, again after defined processing. Consideration of typical scene luminance ranges of about 1.8 log E and allowance for exposure errors leads to a minimum useful latitude of about 2.4 log E, centered about the camera normal exposure **H**.[5] The required latitude, in turn serves to define the offset between the camera normal exposure (near mid-scale) and the reference exposure (in the toe). The scaling constant (ca. 1.41 for a color negative film) incorporates this offset and appropriately sets the mean focal plane exposure **H** to again deliver an excellent image.

Digital Camera Systems and Speed

A typical consumer digital still camera has a two-dimensional array of discrete solid-state photo-responsive material organized for capturing scene information and circuitry for delivering that information in digital form. The array components are overlaid with a color filter array (CFA) to form a color sensor. On exposure, the individual pixels respond to light from portions of an image and convert that light into electrons, the electrons are then withdrawn from the imager as analog data, and the data digitized and stored to form a digital file having the pictorial information. The published ISO speed standards for DCSs, ISO 12232, are "...intended to harmonize with film ISO speed ratings."[6] Three speed reports are recommended by this standard.

First, a saturation, or 'best image' speed:

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$$\text{ISO} = 78 \text{ lux-seconds}/\mathbf{H}_{sat} \quad (2)$$

Second, a 'first acceptable image' speed:

$$\text{ISO} = 10 \text{ lux-seconds}/\mathbf{H}_{S/N=10} \quad (3)$$

Third, a 'first excellent image' speed:

$$\text{ISO} = 10 \text{ lux-seconds}/\mathbf{H}_{S/N=40} \quad (4)$$

The saturation speed has a reference exposure $\mathbf{H}_{sat}$ that is well above the intended average scene luminance at the sensor plane. The other two speeds, $\mathbf{H}_{S/N=10}$ and $\mathbf{H}_{S/N=40}$, define their reference exposures at the intended average scene luminance by consideration of a signal-to-noise ratio. Understanding these recommendations, couched as they are in signal-to-noise terms, provides a direct path for comparing a color DCS to a consumer color film.

DCS sensitometry arises on a pixel-by-pixel basis. The core quantum efficiency (QE) of silicon approaches 100% in the visible region.[7] However, the sensitivity of an individual pixel to light is related to the absorptivity of silicon as employed in the sensor, to the pixel surface area exposed to light, and to the proportion of light that can reach the active pixel area. Factors that decrease the amount of light reaching a pixel decrease its practical sensitivity. Specifically, the solid-state structure, or gates, needed to electronically access each pixel can absorb or reflect light.[8] Similarly, the CFA that is required to provide color in a single sensor, fast shutter color camera absorbs light.[9,10] Solid-state silicon sensors provide roughly a one-to-one correspondence between the number of absorbed actinic photons and the number of electrons generated and available for accumulation, i.e., they act a multilevel detectors, and in this way each pixel provides full exposure latitude. Conversely, silver halide crystals can often act as on-off or single-level detectors, and latitude is provided by adjusting the practical sensitivity of the grains employed.[11]

The upper exposure limit of an individual pixel in a DCS is controlled by the number of electrons that can be accumulated by that pixel during an exposure event. This limit is called the charge-capacity or well-depth. Accordingly, solid-state sensors fail as pictorial imagers when overexposed because they are no longer capable of differentiating purposeful exposure differences.

There are numerous noise sources inherent in solid-state sensing. With modern sensors, the dominant noise source at most exposure levels is photon-noise, i.e., shot-noise. This noise arises from the inherent Poisson distribution of photons in light and is just the square root of the average photon flux. Next in importance is the fixed pattern noise (FPN) that arises from the random charge accumulation inherent in individual pixels. An otherwise perfectly matched pixel array will generate an inhomogeneous scene pattern because of the statistical nature of the dark current. This noise equals the square root of the dark current. Readout noise (RN) arises during extraction of the image information from the pixel array. Components of readout noise include imager-reset noise, amplifier noise, and clocking noise.[12,13]

An overlying CFA introduces color noise because, individual pixels collect only specified colors, and the sampled color pattern is interpolated to give full color information. This interpolation introduces color uncertainty into the final record. Color noise is not considered in the present analysis.[14]

TABLE I. Fraction of photons in each color range incident on and absorbed by a solid-state sensor, along with the relative speeds of each color record

Color	% of photons	CFA Trans.	in situ QE	Net %	Rel. log *E*
Blue	~23%	~65%	~15%	~2.3%	- 0.60
Green	~35%	~75%	~35%	~9.1%	0
Red	~40%	~85%	~40%	~14%	+ 0.17

Pixel Sensitometry

We are now in a position to consider the speed, latitude, sensitometry, and noise of a modern solid-state sensor. Let us first consider the first best image speed, i.e., the saturation speed based on $\mathbf{H}_{sat}$.

The CFA transmittance and native, *in situ*, QE for the pixels in the Kodak Digital Science™ KAF-6301 image sensor have been reported.[15] These are listed in Table I along with an estimate of the proportion of blue, green, and red photons in daylight. Sensors sharing this characteristic have been commercially employed in the Kodak Professional DCS-460 digital camera, Kodak Professional DCS-465 digital camera, and Canon EOS DCS-1 digital cameras. Like constants apply to the smaller Kodak Digital Science KAF-1600 and KAF-0400 series image sensors.

Following the ISO-12231 standard, the net color weighted luminance, **Y**, is given by:

$$\mathbf{Y} = 0.2125\,R + 0.7154\,G + 0.0721\,B \quad (5)$$

where R, G, and B refer to the red, green, and blue color channels respectively. Substituting, data from Table I in Eq. 5, we conclude that 9.5% of the incident photons contribute to the net luminance.

If the CFA transmittance in all color records were 100% and if the native, *in situ*, QE were 100%, then the net color weighted luminance for this perfect solid-state sensor would be 35% of incident. In other words, in an optically perfect world, the sensitivity headroom for color capture is 0.56 log *E* or just under 2 stops. Like limits follow from consideration of the CFA transmittance and the *in situ* practical QE of the individual green or red color records. While improvements in blue record sensitivity would enable a practical increase in color speed, this increase would not be significant according to ISO standards since the blue record carries little color weight in that standard. The practical impact would be on improved color reproduction in low light situations. Other promising CFA color selections are not considered in the present analysis.[16]

By way of reference, experts from several major manufacturers have indicated that they believe the improvement potential for AgX imaging to be between 5 and 10-fold (7.5X = 0.88 log *E*).[17]

With modern designs, noise is practically dominated by photon noise and naturally the signal-to-noise ratio improves with increasing exposure, i.e., the more exposure the better. However, overexposure leads to failure. These features drive the preferred exposure level for a DCS to the brightest light conditions consistent with not overexposing the sensor, and explain the placement of the camera normal for a best image at the highest possible exposure level consistent with minimal scene luminance range requirements. This exposure level follows from the sensor characteristics. The charge-capacity of ca. 556 $e^-/\mu m^2$ with these sensors,[15] practically places $\mathbf{H}_{sat}$ at 556 absorbed photons/μm^2. Because 9.5% of the available light, in a color balanced sense, reaches

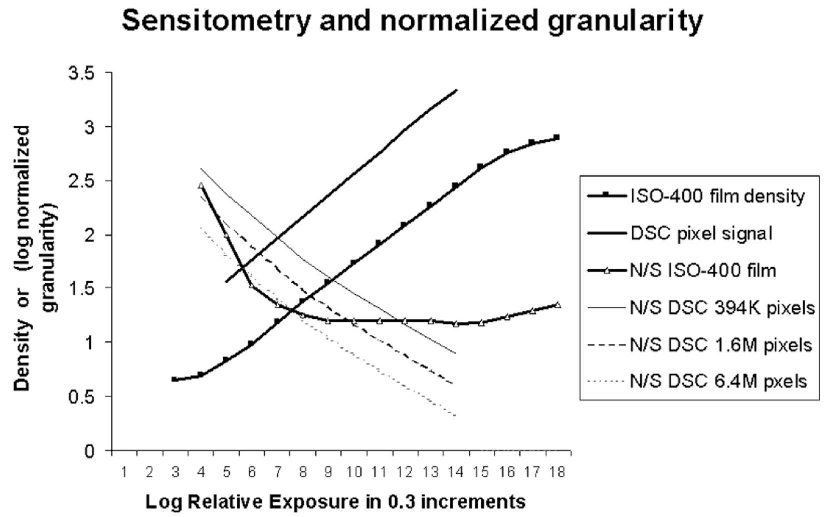

Figure 1. Useful color latitude and N/S (noise:signal) ratios for an AgX color film and for 384 K, 1.6 M, and 6.4 M DCS sensors.

the pixels, one can infer that 5,800 photons/µm+ or 0.97 lux–s, are incident at the speed point. Because the saturation speed is defined as: ISO = 78/$\mathbf{H}_{sat}$, this means that the ISO speed is predicted to be 78/0.97 = 80. The cameras using these sensors are reported to have a speed of ISO 80 to ISO 100.

Turning to the additional recommended DCS speed metrics, the first barely acceptable sensor image has a camera normal exposure at a light level where the S/N ratio is 10:1, i.e., at $\mathbf{H}_{S/N}$ = 10. This turns out to be the exposure required to place the shadow detail in a regime where the signal equals the noise (S/N ~ 1). The called for signal level can be calculated by solving the equation: $S/(S + FPN^2 + RN^2)^2 = 10$, using the noise estimates for these sensors. Here $(S + FPN^2 + RN^2)^2$ is just the weighted sum of the shot noise, the fixed pattern noise (~3 RMS e^-) and the readout noise (~15 RMS e^-) for the pixels in an array. This equation is appropriately solved on a per pixel basis because FPN and RN are stated on a per pixel basis. Solving for S, we obtain 210 absorbed photons/pixel. In a noiseless system, where FPN and RN are effectively zero, i.e., one having only shot-noise, $\mathbf{H}_{S/N = 10}$ occurs at 100 absorbed photons/pixel. Therefore, solving all noise problems adds 0.32 log *E* of lower scale speed. In the AgX domain, this is the equivalent of gaining a stop in speed by fixing a fog problem. The first excellent sensor image $\mathbf{H}_{S/N = 40}$ occurs when $S/(S + FPN^2 + RN^2)^2$ = 40. Solving for *S*, this occurs at 1806 absorbed photons/pixel. In a noiseless system, where FPN and RN are zero, i.e., one having only shot-noise, this occurs at 1600 absorbed photons/pixel. Therefore, in the regime of excellent pictures, solving all noise problems adds 0.05 log *E* of speed. One might conclude that the system is nearly fully optimized for S/N at this exposure level.[18]

Generally, the exposure latitude of a pixel is the log of the ratio of the pixel charge capacity divided by RN. The charge capacity of the 9 µm edged pixel with antiblooming is about 45,000 e^-. Therefore the latitude is log (45,000 e^-/15 e^-) or 3.48 log *E*. This places the lowest meaningful exposure at ca. 15 absorbed photons/pixel, i.e., just where the S/N is unity.

The practical color latitude of such a sensor is lower than might be expected because each color record has about the same latitude, but these useful latitudes are shifted in exposure space. From Table I, we see that the upper exposure latitude limit is practically controlled by the most light efficient collecting color record (red), while the lower exposure latitude limit (here assuming we need S/N ~ 1 as the lowest acceptable exposure for a color record) is practically controlled by the least efficient light collecting color record (blue). So, the expected 3.48 log *E* of latitude is practically reduced in these cameras by about 0.77 log *E* to about 2.7 log *E* (i.e., about 9 bits), which is enough to capture a pictorial image. As a point of calibration, this range is quite similar to that encountered with some color reversal films, which are typically thought of as non-forgiving of missed exposure placement. Overexposure of these sensors causes color specific clipping of scene highlights while underexposure causes loss of meaningful color information in shadows.

The speed-grain (or S/N) comparison of a DCS-captured to a film-captured image awaits the transformation from pixel-based sensitometry and noise to array-based sensitometry and noise for the DCS and the correction for image magnification based on DCS pixel array size. These corrections are accomplished by considering both the number of individual pixels subsumed by a typical film noise-scanning aperture and by adjusting that result to a common image size.[19]

We consider three Kodak Digital Science sensors, the KAF-0400, the KAF-1600, and the KAF-6301, each of which has served as the imager for at least one popular commercial DCS.[20] The KAF-0400 sensor with about 394 K pixels produces VGA (base resolution) images. The KAF-1600 sensor produces ca. 1.6 MB or 4-base resolution images now popular for consumer DCSs. The KAF-6301 sensor produces 16-base resolution, 6.4 MB images. The sensor arrays have all been normalized against a full-frame 240-formatted film. This normalization was chosen because the total imager area for the KAF-6301 sensor is practically indistinguishable from that of full-frame Advanced Photo System (APS). Here, a common light delivery system, as in a camera and lens, assures a common relationship of the imager, AgX, or silicon, to scene luminance. The smaller KAF-0400 and KAF-1600 imagers are analyzed assuming a common image plane with digital zoom, i.e., with scene cropping of non-central scene information.

AgX and Pixel Sensitometry Together

Figure 1 shows the sensitometry and gamma-normalized granularity of Kodak Advantix 400 color film in visual density terms. Gamma-normalized granularity is a N/S metric, which is intuitively useful to the classically trained photographic scientist because it increases or decreases directly with granularity, or noise.[21] This data is presented as visual densities to bring it to a single sensitometric scale for easier comparison with pixel sensitometry in luminance or **Y** space. The suppression of color specific information is less critical here because the color records are designed to have quite similar speeds and latitudes. The N/S ratio is arbitrarily placed in the figure. This same figure shows the color weighted luminance space sensitometry and the magnification corrected N/S curves for the three sensors.

It is readily apparent that each technology has its strengths. Firstly, both technologies exhibit similar useful threshold color sensitivities. At lower light levels, the AgX imager exhibits a superior S/N behavior when compared to the two smaller pixilated arrays and similar S/N to the largest pixilated array as employed in the Kodak DCS-465. At higher light levels the silicon imagers all exhibit superior S/N behavior. This is largely because the AgX imager is engineered to provide similar S/N characteristics over most of its optically printable latitude, a design tool beyond the scope of what is now possible with silicon imagers. Further, the S/N of the AgX imager is just that which provides excellent pictorial images for common consumer usage based on practical knowledge of consumer needs. As explained earlier, the silicon imager exhibits a useful color imaging latitude of about 2.7 log E. This AgX imager exhibits a color imaging latitude more than 4.2 log E.

Based on optical modulation transfer function (MTF) measurements, Kodak Advantix 400 color film is estimated to record about 31 million total pixel equivalents in its 18 by 30 mm frame. The film thus outperforms all of the DCS sensors in this regard. It is gratifying to note that the relative pictorial performance of the AgX and silicon imager-based systems predicted on the basis of objective criteria outlined here compares favorably with previously reported psychophysical results.[22]

It must be recognized that the comparison of the optically printable Advantix 400 color film to the sensor output of a DCS system is flawed. The film has already suffered all of the image degradation associated with chemical color processing, while the DCS sensor output has not. Accordingly, the comparisons presented above should be viewed as a worst-case silver halide sensor outcome relative to a best-case silicon sensor outcome. Several authors have discussed the potential benefits of optimizing silver halide films for image capture and subsequent scanning.[23]

Summary and Conclusions

Sensitometric and image structure comparisons of first generation Advantix 400 AgX film and contemporaneous (DCS) color imagers at 393 K, 1.6 M, and 6.3 M pixel sensor resolution have been presented. The imagers compared have similar useful color imaging exposure thresholds. In speed-grain terms, the 6.3 M sensor DCS provides similar speed-grain in the lower scale and superior speed-grain in the upper scale when compared to the AgX film. The smaller sensors are less capable in this regard. All the silicon sensors provide shorter exposure latitude than the AgX film. Within the context of pictorial imaging, it appears that the silicon array as employed in DCSs is close to its fundamental imaging efficiency limit. It further appears that AgX as a color imager can provide favorable speed, image structure, and latitude for consumer imaging. This suggests that easy and convenient ways of providing digital representations of color images captured on AgX films should be useful to consumers. Current AgX imagers are designed to capture, chemically image process, archivally store, and visually present pictorial information. The new films will be digital AgX camera films designed for digitization and readily compatible with the nascent digital imaging infrastructure. As image manipulation and presentation are shifted to the digital area, AgX film re-engineering opportunities will arise. The future here is one of employing the strengths of both digital and analog technology to provide excellent systems that meet the needs of our customers and consumers. In this context, that can mean employing AgX as a capture material and transferring the image manipulation, transmission, and presentation to the digital arena where it can best be handled. It is crucial to remember that advances in digital image manipulation and enhancement can apply to all digital files whatever their source. This area is still in its infancy and the best days are yet to come.

References

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2. In the details that follow, the imaging characteristics and potential of silicon imagers for consumer photographic purposes are dissected from the ground up because the appropriate comparisons do not appear to be otherwise available. Readers interested in exploring AgX imaging are directed to T. H. James, Ed., *The Theory of the Photographic Process*, 4th ed., Macmillan, New York, 1977. While the following analysis is couched in terms of a CCD imager, similar constraints apply to the now popular CMOS imager. The CCD structure was analysed both because of the more ready availability of data and because it was believed to represent a more advanced imager design for quality applications.
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9. Shutter times of 1/100th s or faster are required for consumer cameras because of the need to provide consumers with stop action photography in a hand-held device. This need, in turn, dictates the use of single full-frame arrays for consumer DCSs.
10. See B. Bayer, U. S. Patent 3,971,065 (1976) for a detailed description of Red–Green–Blue CFAs as employed in the DCSs described in this work. Additional details can be found in Ref. 13, below.
11. For the most part, small silver halide grains are either developable or not and can be thought of as single-level, i.e., one bit or on–off detectors. Some, typically larger surface area, grains can generate multiple and independently developable sites. These grains can differ in the extent of development based on their extent of exposure and as such are multibit or multilevel detectors. For additional details see (a) R. P. Szajewski, J. T. Kofron and J. Osborne, *The International East–West Symposium II*, SPSE–IS&T, Springfield, VA, 1988, pp E17ff; and (b) L. Eshelman, *ICPS'98*, KVCV, Antwerp, Belgium, 1998, pp 413ff .
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16. Some newer DCSs employ cyan–magenta–yellow arrays that enable increased light throughput. The noise implications of these arrays have not apparently been described.
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18. R. L. Baer and J. Holm, *IS&T's 1999 PICS Conference*, IS&T, Springfield, VA, 1999 pp 35ff, have provided an analysis for a distinct DCS.
19. The color film granularity was measured using a 48 μm circular aperture. This corresponds to an 11.5X magnification between film and print. For the smaller sensors, a larger magnification is appropriate. The implications of sensor size on practical imager speed in a camera and the required differential magnification of the resultant images to provide a constant image size to a consumer follow directly from the application of geometric optics to a photographic system. I have chosen to normalize the DCS noise to that measured for the AgX system because the DCS noise power spectrum is substantially flatter than that of the AgX film. For more detailed descriptions, see: (a) S. Ray, *Camera Systems*, Focal Press, London, 1983; (b) A. Cox, *Photographic Optics*, Amphoto, New York, 1974; (c) A. Horder, Ed., *The ILFORD Manual of Photography*, Ilford, Essex, 1958; and (d) L. P. Clerc, *Photographic Theory and Practice*, Focal Press, London, 1972. Some practical pictorial examples from DCSs can be found in (e) *A Guide to Digital Photography, Theory and Basics*, Agfa-Gevaert N. V., Mortsel, Belgium, 1996.
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