

Silver Halide and Silicon as Consumer Imagers

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Abstract

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 contemporary 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 393K, 1.6M, and 6.3M sensor resolution are presented. The imagers compared have similar useful color imaging exposure thresholds. In speed-grain terms, the 6.3M sensor DCS, which retails at more than $25,000, provides similar speed-grain in the lower scale and superior speed-grain in the upper scale when compared to the AgX film. However, it provides limited exposure latitude. Within the context of pictorial imaging, it appears that the silicon array as employed in the DCS is closer to its fundamental imaging efficiency limits than is AgX.

Introduction

The growing importance of silver halide 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. 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. 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 393K, 1.6M, and 6.3M 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. Generally, the relationship between the ISO speed of a camera film and the mean exposure at a focal plane in an automatic camera, ISO-2721, is:

$$ISO = 10\ lux\text{-}seconds/\mathbf{H} \quad (1)$$

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. The scaling constant for films with well-defined latitude is typically about 10. Distinct scaling constants and reference exposure points are employed for films with less well defined latitudes. Consideration of typical scene luminance ranges and allowance for exposure errors leads to a minimum useful latitude of about 2.5 log E, centered about the camera normal exposure **H**.

Digital Still Cameras

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." Three speed reports are recommended by this standard.

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

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

Second, a 'first acceptable image' speed:

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

Third, a 'first excellent image' speed:

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

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, not of sensor illuminance, but rather 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 sensitivity of an individual pixel to light is related to the absorptivity and quantum efficiency (QE) of silicon, to the pixel surface area exposed to light and to the proportion of light that can reach the active pixel area. Factors that decreases the amount of light reaching a pixel decreases its sensitivity. Specifically, the solid-state structure, or gates, needed to electronically access each pixel can absorb and reflect light while the CFA absorbs light.

Solid-state sensors fail as pictorial imagers when overexposed. The upper exposure limit of an individual pixel 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. There is a one-to-one correspondence between the number of absorbed actinic photons and the number of electrons generated and available for accumulation, i.e., the core QE approaches 100% in the visible region.

There are numerous noise sources inherent in solid-state sensing. With modern sensors, the dominant noise source at most exposure levels is photon-noise AKA 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 due to the statistical nature of the dark current. This noise equals the square root of the dark current. Readout noise arises as a result of extracting the image information from the pixel array. Components of readout noise include imager-reset noise, amplifier noise, and clocking noise.

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.

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.[1] 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.

Table I: Proportion 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%	2.29	- 0.598
Green	35%	~75%	~35%	9.08	0
Red	40%	~85%	~40%	13.53	+ 0.173

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

$$Y = 0.2125\,R + 0.7154\,G + 0.0721\,B \qquad (5)$$

where R, G, and B refer to the red, green and blue color channels respectively. Substituting, 0.2125 × 0.1353 + 0.7154 × 0.0908 + 0.0721 × 0.0229 = 0.0954, we see that 9.54% 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 34.89% of incident. In other words, in an optically perfect world, the sensitivity headroom for color capture is 0.56 log E.

Interestingly, workers at Fuji Photo Films have indicated that they believe the headroom in AgX, to be between 5 and 10X, (7.5X = 0.88 log E).[2]

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^-/micron² with these sensors, practically places $\mathbf{H}_{sat}$ at 556 absorbed photons/micron². Since 9.54% of the available light, in a color balanced sense, reaches the pixels, one can infer that 5,828 photons/micron² are incident at the speed point or 0.968 lux-s. Because the saturation speed is defined as: ISO = 78/$\mathbf{H}_{sat}$, this means that the ISO speed is predicted to be 78/0.968 = 80. The cameras using these sensors are reported to have a speed of ISO 80 to ISO 100.

Turning to the recommended DCS speed metrics, the first barely acceptable sensor image has a speed point $\mathbf{H}_{S/N=10}$. This is where the signal-to-noise ratio is 10:1 at the camera normal, i.e., this is the exposure required to place the shadow detail in a regime where the signal is just discernible from the noise (S/N ~ 1). The called for signal level can be calculated by solving the equation: $S/(S + FPN^2 + readout^2)^{1/2} = 10$, using the noise estimates for these sensors. Here $(S + FPN^2 + readout^2)^{1/2}$ 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 is appropriately solved on a per pixel basis since FPN and readout noise are stated on a per pixel basis. Solving for S, this occurs at 210 absorbed photons/pixel. In a noiseless system, where FPN and readout noise are effectively zero, i.e., one having only shot-noise, $\mathbf{H}_{S/N\ =\ 10}$ occurs at 100 absorbed photons/pixel. So, 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 $S/(S + FPN^2 + readout^2)^{1/2} = 40$. Solving for S, this occurs at 1806 absorbed photons/pixel. In a noiseless system, where FPN and readout noise are zero, i.e., one having only shot-noise, this occurs at 1600 absorbed photons/pixel. So, in the regime of excellent pictures, solving all noise problems adds 0.05 log E of speed and the system is nearly fully optimized for S/N.

Generally, the latitude of a pixel is the log of the ratio of the pixel charge capacity divided by the readout noise. With anti-blooming, the latitude of a 9 micron edged pixel = log (45,000 e^-/15 e^-) = 3.48 log E, which places the lowest meaningful exposure at ca. 15 absorbed photons/pixel, i.e., just at the per pixel noise level.

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), 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 color reversal films which are typically thought of as nonforgiving 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.

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. [3] The KAF-0400 sensor with about 394K 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 could be employed directly at a common image plane with heavy scene cropping.

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.[4] 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 since the color records are designed to have similar speeds and latitudes. The N/S ratio is arbitrarily placed in the figure.

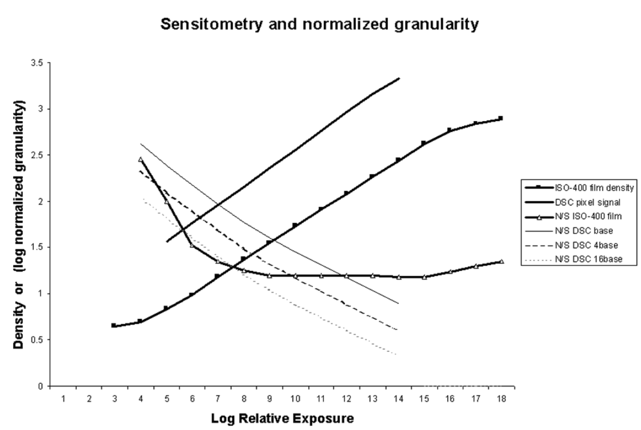

Figure 1. Useful color latitude and N/S ratio for an AgX color film and for 384K, 1.6M, and 6.4M DCS sensors.

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 (ca. $25,000 per camera). 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 required to provide excellent pictorial images for common consumer usage. 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.

Summary and Conclusions

Sensitometric and image structure comparisons of first generation Advantix 400 AgX film and contemporary (DCS) color imagers at 393K, 1.6M, and 6.3M sensor resolution have been presented. The imagers compared have similar useful color imaging exposure thresholds. In speed-grain terms, the 6.3M sensor DCS, which retails at more than $25,000, provides similar speed-grain in the lower scale and superior speed-grain in the upper scale when compared to the AgX film. However, it provides limited exposure latitude. Further, within the context of pictorial imaging, it appears that the silicon array as employed in DCSs is closer to its fundamental imaging efficiency limits than is AgX. It further appears that AgX, as an imager, currently provides favorable speed, image structure, and latitude for consumer imaging. This suggests that easy and convenient ways of providing digital representations of images captured on AgX films should be useful to the public. These new films will be digital AgX camera films designed for digitization and readily compatible with the nascent digital imaging infrastructure. Current AgX imagers are designed to capture, chemically image process, archivally store, and visually present pictorial information. 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 be best 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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Biography

Richard Szajewski received a B.S. degree in Chemistry from Fordham University 1971 and a Ph.D. in Organic Chemistry from Columbia University in 1975. After three years at M.I.T. where he worked in applied enzymology, he joined the Eastman Kodak Company in Rochester, NY. His work at Kodak has focused on advanced research and development activities related to color photography where he holds over 50 U. S. patents. He is a Registered Patent Agent.