Taking a Closer Look at Camera Specifications

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Camera specifications can leave customers scratching their heads. Standardization of specifications and procedures will make the selection task easier by providing trustworthy performance data.

Purchasing a camera for high-performance imaging applications can be confusing and time-consuming. Manufacturers lack clear and consistently defined specifications, which makes it difficult to compare one camera with another based on specs alone. For example, a camera specified as 12 bits by one manufacturer means that the root-mean-square background noise is less than one analog-to-digital count and that the camera has a dynamic range of 72 dB. But to another vendor, 12 bits may simply imply that a 12-bit analog-to-digital converter is used, regardless of how many of those bits are consumed in noise.

The inability to perform a quantitative comparison based on technical specifications alone can be solved in two ways. The first and, unfortunately, most common approach is to do side-by-side comparisons of all cameras that "look" similar. The system integrator must coordinate the delivery of a camera, frame grabber, cables and power supply for each device to be evaluated, and then must become familiar with new software display packages and determine a suitable method for measuring performance.

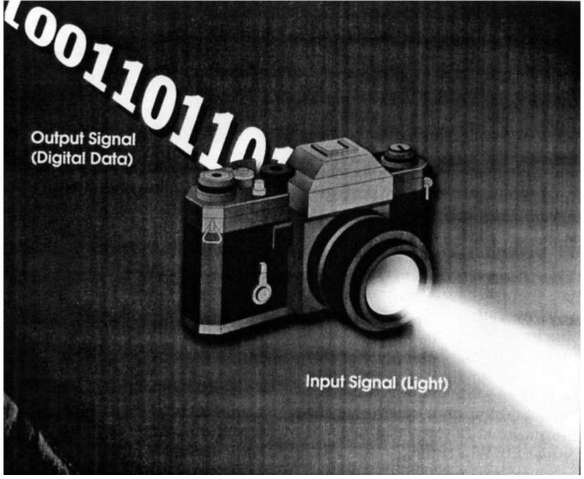

Figure 1. Output noise is compared with input noise to characterize a camera system.

Appropriate lighting sources and calibration test targets are required to quantitatively compare camera performance. Although this approach might be intriguing as a doctoral thesis topic, it is expensive and time-consuming for the customer.

An alternative approach places the burden of technical proof on the manufacturer. With this plan, a standardized test procedure is used during camera manufacturing to provide consistent, quantitative and verifiable performance data such as read noise, dark current, full-well capacity, sensitivity, dynamic range, gain and linearity. Fortunately, a test method of this type has existed for well over a decade. Known as the photon transfer curve, it is used by NASA's Goddard Space Flight Center and Jet Propulsion Labs and leading camera manufacturers around the world to enable an apples-to-apples comparison of key performance parameters. The fundamentals of photon-transfer-curve calibration, along with a discussion about how each measured parameter affects imaging performance follow. The test methods work equally well for both CMOS and CCD cameras and are applicable in area-scan, line-scan, time-delay and integration, or essentially any other architecture.

How the curve works

From a basic measurement point of view, the photon transfer curve works as follows:

- The camera itself is a system block with light as an input and digital data as an output (Figure 1).
- Because of the character of photons, we know that the only noise introduced at the input is shot noise, and we can predict exactly what that noise will be at any specified illumination level.
- Any difference between the noise at the input and output must have been caused by the camera (or sensor) electronics.

The use of noise as a test stimulus is convenient because the natural input signal for an imager is light, and the noise characteristics of light are well-known. The shot-noise-characteristics of light are plotted as a function of illumination level on a Log-Log graph (Figure 2). The root-mean-square value of shot noise is equal to the square root of the mean number of photons incident on a given pixel. Thus, the shot noise profile becomes a straight line with a slope of one-half on the Log-Log curve (Log $X^{½}$ = ½ Log X). This noise is inherent in the nature of light itself and has nothing to do with the camera design.

In contrast to Figure 2, which shows only the noise associated with the input signal (light), Figure 3 shows the photon transfer curve that contains the typical noise profile seen at the output of a digital camera. Here you can see three distinct noise regions of the CCD camera system: read noise, shot noise and fixed-pattern noise. The photon transfer curve compares the differences in Figures 2 and 3 to determine the operational characteristics of the camera. The input and output noise match only in the central region of the graph. At both high and low illumination levels the curves differ – and the camera causes this difference.

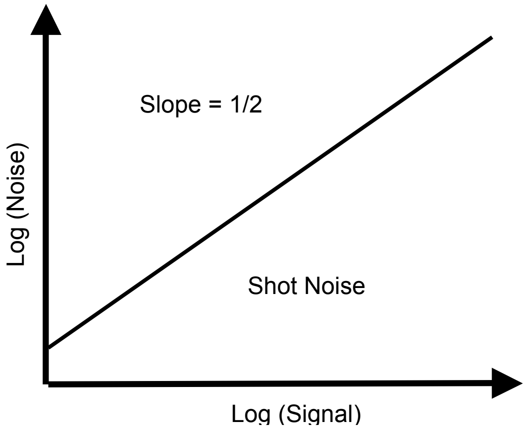

Figure 2. In an ideal world the camera would introduce no additional noise, and the output noise characteristics would look like this.

Camera performance

It's important to understand the characteristics of each of the regions along with their significance in characterizing camera performance. The characteristics are:

- Read noise: This is represented by the first (flat) region of the graph in Figure 3 and is the random noise that is associated with the CCD output amplifier and the camera's signal processing electronics. In a properly designed camera, the read noise should be around one analog-to-digital count root mean square or less. Any more than this, and an "8 bit" camera may be supplying, for example, only 6 bits.
- Shot noise: Shown in the second region of the graph in Figure 2, it is inherent in the light itself. The noise does not originate in the camera. As the input light level increases in amplitude, the noise at the camera output rises out of the read-noise region and becomes dominated by shot noise. Shot noise is directly related to the input illumination and is proportional to the square root of that signal.
- Fixed-pattern noise: The right-most region of the photon transfer curve represents the fixed-pattern noise, which becomes dominant at relatively high levels of illumination. This noise results from differences in sensitivity among individual pixels or from photo response non-uniformity (PRNU). Because it is directly proportional to input signal strength, the slope in this region of the Log-Log graph is 1.

$$N_{FP} \propto \left(S\,x\,PRNU \right)$$

Where S = optical input signal.

- Full well: As illumination levels are increased, the individual CCD pixels are unable to hold any additional charge without spilling over into adjacent wells. At this point on the noise curve, output noise abruptly drops because the signal value is clipped at the pixel's maximum saturation level. At the point where the photon transfer curve peaks, as shown in Figure 3, the CCD is said to have reached full-well capacity.

Making the measurements

During the photon-transfer-curve measurement, the CCD is exposed to a precisely controlled light source with a flat (uniform) illumination field. This is done with an integrating sphere with a monochromatic light source, such as LEDs or filtered white light. The use of monochromatic light is important for removing the effects of color temperature and quantum efficiency variations.

Prior to starting data collection, the operator adjusts the light source so that the camera is at its specified full-well illumination. The camera gain and offset are then adjusted such that the analog-to-digital converter full scale corresponds to the CCD full-well condition within about 100 analog-to-digital units. After this initial calibration has been completed, the light source is stepped from complete darkness to full-well illumination in precisely measured increments.

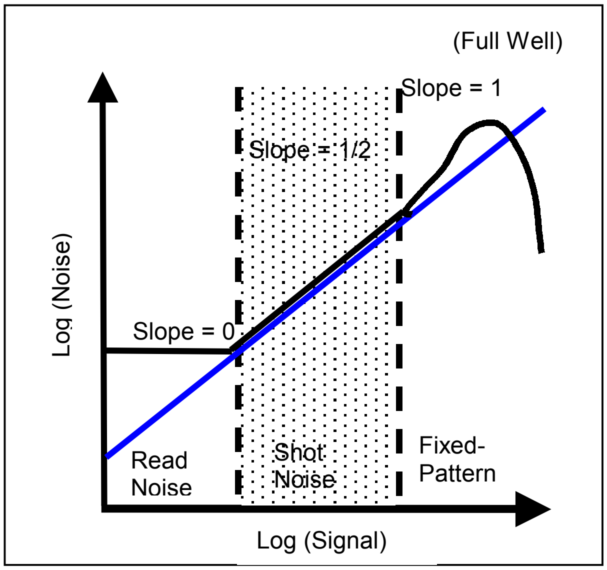

Figure 3; This photon transfer curve compares the input (noise) (blue) with the camera output noise (black). Comparing the ideal to the actual camera noise accurately determines characteristics such as dynamic range, full-well capacity and noise floor.

Time-varying noise

The noise is calculated at each measured light level by subtracting two sequential frames (to remove photo response non-uniformity and fixed pattern noise offsets), taking the sum of the squares of all pixels in the subtracted image and dividing the number of total pixels by two. The result is the statistical variance of the time-varying random noise in the image, where the factor of two in the divisor comes from the fact that the variance is initially doubled in the subtraction process.

Mathematically, this becomes:

$$Variance = \sigma^2 = \frac{\sum_{i=1}^{Np}([X1_i - X2_i])^2}{2 x N_p}$$

and *rms noise* = $\sigma = \sqrt{\sigma^2}$

This really comprises two equations, where:

$X1_i$ = the individual pixel values of the first frame, in analog-to-digital units.

$X2_i$= the individual pixel values of the second frame, in analog-to-digital units,

N_p = the number of pixels in the image.

Once the noise at each illumination level has been calculated, a photon transfer curve can be generated by plotting the camera's output root-mean-square noise vs. the average signal level on a Log-Log curve.

Let's take a look at each parameter and its relevance to the photon transfer curve plot:

- Read noise is directly available from the photon transfer curve by recording the noise level at zero illumination. On the photon transfer curve, the read noise is shown in terms of the number of analog-to-digital units of root-mean-square noise in darkness, which can be multiplied by the gain of the system to yield the noise floor in electrons.
- The gain of the camera system, or "*G*" is typically expressed in electrons per analog-to-digital units; that is, the number of photoelectrons that are required to change the analog-to-digital output by one count. By definition, modifying the illumination level produces a change of "*N*". Photoelectrons result in a change in the average analog-to-digital output level of *N/G* analog-to-digital units. The root-mean-square noise at the output of the camera in the shot noise region in analog-to-digital units is given by:

  $$rms\,noise = \sigma = \sqrt{N/G}$$

  And

  $$Variance = \sigma^2 = N/G$$

  Thus, if variance is plotted vs. average signal on a linear graph, *G* is obtained by fitting a line to this variance curve in the shot-noise-limited region and measuring the slope of that line. The inverse of this slope is equal to *G*.

- The dynamic range is calculated as full scale of the analog-to-digital range (ADU_{FS}) divided by the smallest detectable signal. Because the read noise (σ_R) sets this lower limit, the dynamic range is given by:

$$DR = \frac{ADU_{FS}}{\sigma_R}$$

The dynamic range, expressed in dB, becomes:

$$DR = 20 \log \frac{ADU_{FS}}{\sigma_R}$$

- Full well in electrons is derived from the maximum analog-to-digital output counts and the gain. The formula is:

  $$FW = S_{MAX}\ x\ G$$

  Where

  S_{MAX} = maximum analog-to-digital output before the photon transfer curve begins to slope downward.

  G = gain
  FW = full well (in electrons).

- Nonlinearity is based on the error between the best-fit straight line to the original data of the camera input vs. the camera mean response at each illumination level, in analog-to-digital units. The formula is:

$$INL = \frac{E_{MAX} - E_{MIN}}{AD_{FS}}\ x100$$

Where

INL = integral nonlinearity.
E_{MAX} = maximum (most positive) error from best-fit straight line
E_{MIN} = minimum (most negative) error from best-fit straight line.
AD_{FS} = analog-to-digital converter full-scale value (counts).

Note that (E_{MAX} – E_{MIN}) represents the worst-case peak-to-peak amplitude of the error. The analog-to-digital converter full-scale value is the value of the highest measurement taken that is still within the linear performance range. Normally, this is set as close to the actual full-scale capability of the converter as it practical during camera calibration.

- The effective number of bits (ENOB) is a standard term that indicates the useful number of digital bits that a system can deliver based on its dynamic range. The calculation basically converts the dynamic range, normally expressed as a $\log_{10}$ number, to $\log_2$:

$$ENOB = \frac{\left(\frac{ADU_{FS}}{\sigma_R}\right)}{\log(2)}$$

Summary

Specifications such as frame rate, trigger modes and data interfacing requirements can be extracted easily from most data sheets. In contrast, key parameters such as noise level, sensitivity and linearity are often either less obvious or nonexistent. Fortunately, a simple characterization technique is available that accurately measures these parameters and eliminates the time and money wasted on side-by-side shoot-offs. The photon transfer curve has been used by leading camera manufacturers for years because, without it, it is nearly impossible to guarantee adherence to printed technical specifications.