Keep the Noise Down!

Low Noise: An Integral Part of High-Performance CCD (HCCD) Camera Systems

Noise is composed of undesirable signal components that arise from various sources in an electronic imaging system. The figure of merit that dictates the ultimate performance of a system is *signal-to-noise ratio* (*SNR*), which describes the quality of a measurement (see Figure 1). In CCD imagine, SNR refers to the relative magnitude of the signal compared to the uncertainty in that signal on a per-pixel basis. Specifically, it is the ratio of the measured signal to the overall measured noise (frame-to-frame) at that pixel. High SNR is particularly important in applications requiring precise light measurements.

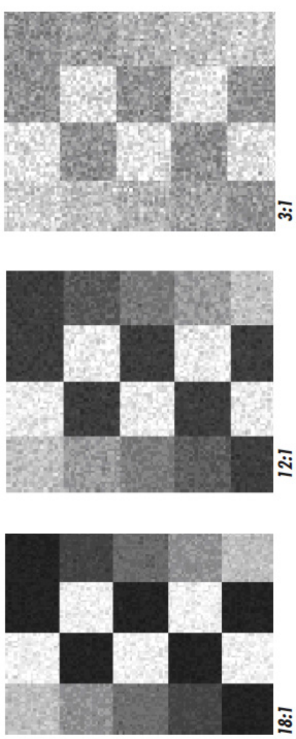

Figure 1. This series of test patterns depicts various signal-to-noise ratios.

When calculating overall SNR, all noise sources must be taken into consideration. The three primary sources of noise in a CCD imaging system are *photon noise, dark noise*, and *read noise*.

Photon Noise

Photons incident on the CCD convert to photoelectrons within the device's silicon layer. These photoelectrons constitute the signal but also carry statistical variation in the photo arrival rate at a given point. Photon noise, also known as *photon-shot noise*, refers to the inherent natural variation of the incident photon flux. The number of photoelectrons collected by a CCD pixel exhibits a Poisson distribution and has a square root relationship between signal and noise. Photon noise cannot be reduced via camera design.

$$\textit{photon noise} = \sqrt{\textit{signal}}$$

Dark Noise

Dark noise arises from the statistical variation of thermally generated electrons within the silicon constituting the CCD. Dark current describes the rate of generation of thermal electrons at a given CCD temperature. Dark noise, which like photon noise exhibits a Poisson distribution, is the square root of the number of thermal electrons generated within a given exposure time.

$$\textit{dark noise} = \sqrt{\textit{(dark current) (integration time)}}$$

High-performance CCD camera systems reduce dark noise by cooling the CCD with either thermoelectric coolers (TECs), liquid nitrogen (LN_2), or cryogenic refrigeration during camera operation. To further reduce dark current, many CCDs operate in multi-pinned-phase (MPP) mode. The largest contribution to dark current results from the interface between the silicon dioxide and the epitaxial silicon layer within the CCD. MPP devices are fabricated and operated in such a way as to significantly reduce this source of thermal charge generation. In practical terms, the noise arising from dark current should be reduced by cooling the CCD to a point at which its contribution is negligible over a typical exposure time.

Read Noise

Electronic noise sources inherent to the camera system and the CCD also introduce uncertainty in the measured signal. Collectively these noise components are referred to as read noise and represent the error introduced during the process of quantifying the electronic signal on the CCD. The major component of read noise arises from the on-chip preamplifier. Spurious charge also contributes to the overall read noise of the imaging system.

HCCD camera systems are able to lower read noise by employing carefully designed electronics. For instance, to lessen CCD preamplifier noise, CCD designers employ the latest advances in high-resolution photolithography to reduce the feature sizes of on-chip amplifiers, a step that directly reduces capacitance and thus allows more sensitivity. Additionally, dual-slope integrators or correlated double sampling methods are used to filter out specific components of read noise, such as kTC noise and 1/f noise.

The signal-to-noise ratio for a CCD camera can be calculated as follows:

Equation 1

$$SNR = \frac{PQ_e t}{\sqrt{(P + B)\, Q_e t + Dt + N_r^2}}$$

- P = *photon flux incident on the CCD (photons/pixel/second)*
- B = *background photo flux incident on the CCD (photons/pixel/second) — background light can arise from many sources and is usually scattered light that is not of interest to the observer — when the signal is the only source of light, B equals 0*
- Q_e = *quantum efficiency of the CCD*
- t = *integration time (seconds)*
- D = *dark current (electrons/pixel/second) — as discussed earlier, dark noise equals the square root of Dt*
- N_r = *read noise (electrons rms/pixel)*

Photometrics can provide quantum efficiency, dark current, and read noise parameters for each CCD, camera head, and digitization rate offered. If the incident light levels are known, these parameters can be used to determine the SNR for any Roper Scientific camera system. Note that because incident photon flux, background photon flux, and quantum efficiency are each a function of wavelength, Equation 1 must be integrated over all wavelengths of interest when a CCD is exposed to a broad-band radiation source. Under low-light-level conditions, read noise exceeds photon noise and the image data is said to be read-noise limited. The integration time can be increased until photon noise exceeds both read noise and dark noise. At this point the image is said to be photon-noise limited.

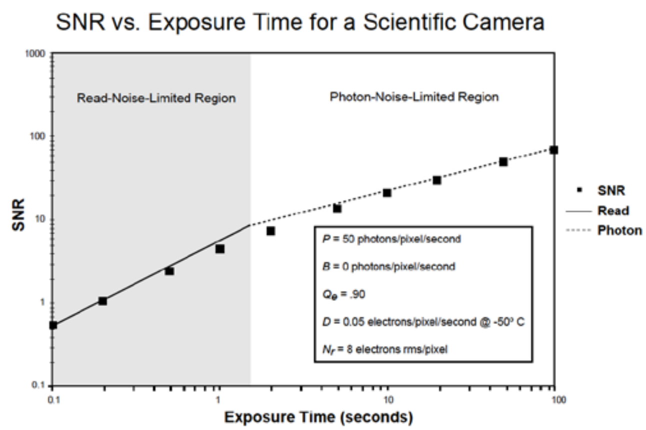

Figure 2. Under low-light-level conditions, high-performance CCD camera systems become photon-noise limited at shorter exposure times.

Figure 2 plots the SNR as a function of exposure time using Equation 1 with parameters typical of a high-performance camera designed for low-light-level imaging applications. In this example, read noise is the dominant noise source for short exposure times. For this region of the graph, Equation 1 can be simplified as shown in Equation 2.

Equation 2

$$SNR = \frac{PQ_e}{N_r}\, t$$

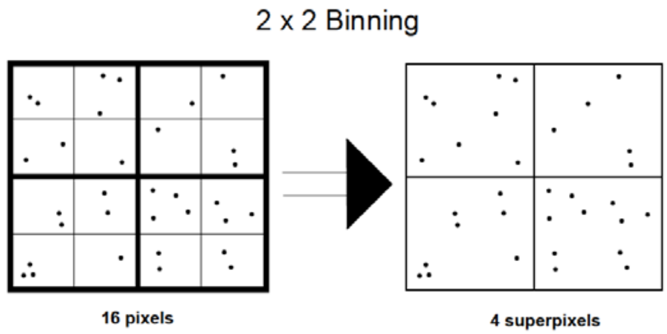

Figure 3. The charge from adjacent pixels in a CCD can be combined during readout to improve the signal-to-noise ratio. Note that the higher SNR comes at the expense of spatial resolution.

The detected photon signal increases with longer exposure times, which in turn makes photon noise the dominant noise source. For this region of the graph, Equation 1 can be simplified to Equation 3.

Equation 3

$$SNR = \frac{PQ_e}{\sqrt{(P + B)\, Q_e + D}} \sqrt{t}$$

In Figure 2, the points computed using Equation 1 are represented by boxes. Notice that Equation 2 (the solid line) fits the computed points for shorter exposure times, while Equation 3 (the dashed line) fits the computed points for longer exposure times. The intersection of Equations 2 and 3 divide the graph into two sections, a read-noise-limited region and a photon-noise-limited region.

When imaging, it should be taken into consideration whether there is a difference in SNR if many short exposures are acquired and then added together, or if a single long exposure is acquired for that total length of time. The same number of photons is collected in either case, but the strategies for image optimization are different in the two regions of the graph.

The SNR increases linearly with time if the mean pixel value is within the read-noise-limited region. A single 1.0-second exposure has about ten times the SNR of a single 0.1-second exposure in this region. Adding together the multiple exposures, however, will increase the SNR by the square root of the number of exposures – in this instance, by about a factor of three when ten 0.1-second exposures are taken. Thus, one long exposure (on-chip integration) is better than many short exposures (frame averaging) in the read-noise-limited region.

Now consider the difference between ten exposures of 10-seconds duration and a single 100-second exposure. In the photon-noise-limited region, the SNR increases only as the square root of the exposure time – so both techniques give essentially the same SNR. There are other factors that should also be taken into account though, such as the effects of cosmic rays. Because cosmic rays do not impact the same pixels on multiple frames, these events can readily be removed from the sum by comparing the frames. Meanwhile, it can be very difficult to remove the effects of cosmic rays from a single frame, especially if there are point sources in the image that can be confused with these events.

An alternative means of raising the SNR is to use a technique known as *on-chip binning*. On-chip binning is the process of combining charge from adjacent pixels of a CCD array during readout into a single *superpixel* (see Figure 3). Consolidating the detected charge by binning neighboring pixels may allow a system to reach a photon-noise-limited signal more quickly (see Figure 4), with an inherent trade-off in spatial resolution. On-chip binning also increases the dark current per superpixel by the same factor.

Equation 1 can be modified to include binning, as shown in Equation 4, where M represents the number of binned pixels. Note that this equation assumes that the signal in each pixel is the same.

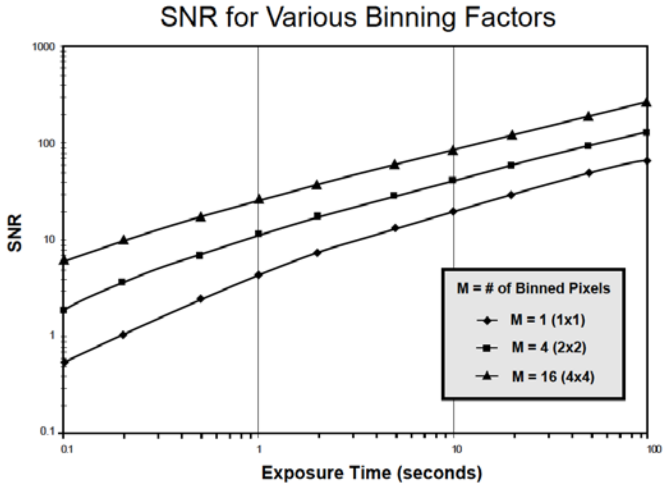

Figure 4. Binning can improve the SNR of a device, allowing the imaging system to reach a photon-noise-limited signal more quickly.

Equation 4

$$SNR = \frac{MPQ_e t}{\sqrt{(P + B)\ MQ_e t + MDt + N_r^2}}$$

High-performance CCD camera systems are designed specifically to be photon-noise limited at lower signal levels. In other words, by reducing read noise and dark noise, HCCD camera systems achieve higher signal-to-noise ratios and reach optimal noise-performance territory faster than other imaging systems – some of which never operate in the photon-noise-limited region under low-light-level conditions.

In conclusion, HCCD digital imaging system designs provide the high signal-to-noise ratios necessary for low-light-level applications. High-performance CCD camera systems also offer the flexibility to employ a wide range of image-acquisition strategies in order to optimize noise performance for any given set of conditions.