Lower Read Noise with Correlated Multi-Sampling

In the simplest of terms, pixel values in a CMOS image sensor represent photoelectrons collected in each pixel during an exposure. The collected electrons are first converted to a voltage inside the pixel which is subsequently measured using an Analog-to-Digital Converter (ADC).

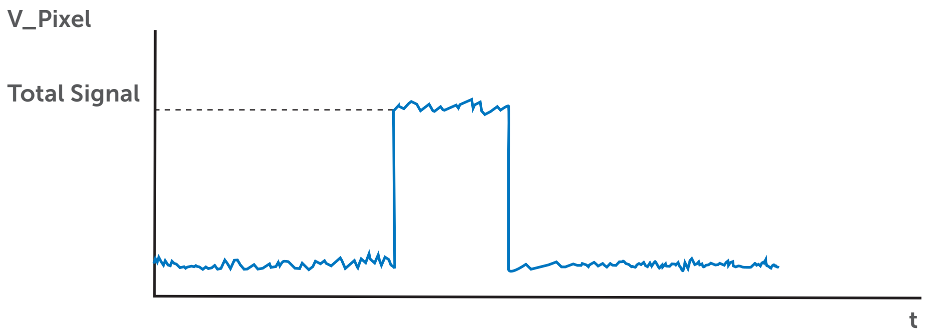

Figure 1: Peak of the voltage for the pixel indicates how much signal was measured. The pixel integrates the signal for the length of the exposure time, building up the voltage in the pixel

Unfortunately, the process of measuring the pixel contributes a small amount of additional noise known as read noise, impacting precision at low light levels.

Two of the main components of read noise are "reset noise" (also known as kTC noise) and "amplifier noise". Reset noise is a random offset created when a pixel is cleared of previous charge. Reset noise can largely be eliminated using Correlated Double Sampling (CDS). CDS measures both the offset and the signal level and subtracts the two in order to obtain an accurate measurement.

With reset noise largely eliminated by using CDS, amplifier noise becomes the dominant source of read noise. Amplifier noise has a high frequency white noise component and a low frequency "1/f" component. This low frequency component is particularly difficult to remove. One solution is to sample the offset and signal levels multiple times and average the results. This special implementation of CDS is called Correlated Multi-Sampling (CMS), and can be done with two or more samples.

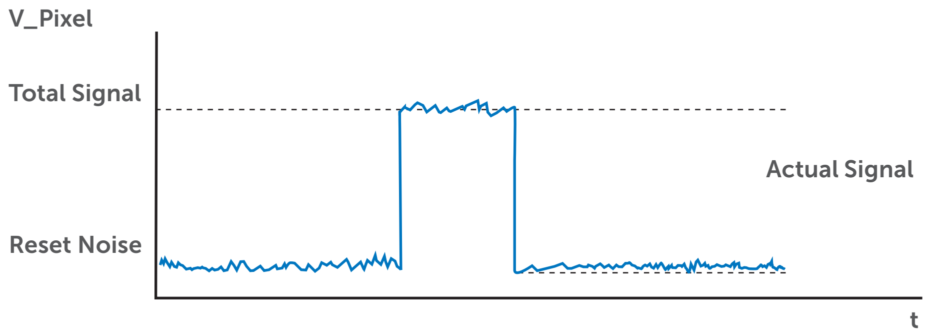

Figure 2: The actual measured signal is the voltage of the signal minus the reset noise.
Actual Signal = Total Signal – Reset Noise

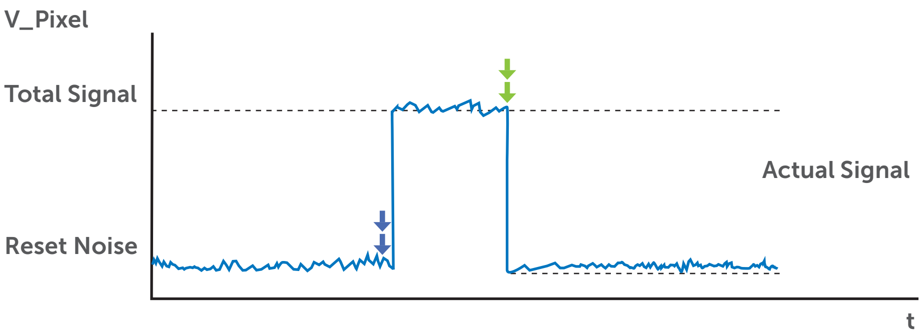

Figure 3: Sampling the reset and the integrated signal twice

Using the Signal to Noise equation to determine the impact on read noise, the calculation for a CDS based acquisition is as follows. Other noise sources such as shot noise are omitted as they do not contribute and are not affected by CDS.

$$SNR_{1x\ CDS} = \frac{Signal}{\sqrt{Noise^2}}$$

Using CMS and sampling the measured signal twice results in the signal to noise calculation becoming:

$$SNR_{2x\ CMS} = \frac{2\ x\ Signal}{\sqrt{2\ x\ Noise^2}}$$

$$SNR_{2x\ CMS} = \frac{1.414\ x\ Signal}{\sqrt{Noise^2}}$$

A two-times sampling of the signal provides a theoretical √2 improvement in the SNR of the measurement and, as the signal level itself is not changing, this corresponds primarily to the reduction of the amplifier noise component of the read noise. This makes it possible to achieve read noise levels close to 1 electron with CMS capable sCMOS sensors.

Typically, sampling the integrated signal level multiple times comes with a negative impact to frame rate, as each sampling introduces a delay to the readout process. This delay is equal to the time it takes to digitize a pixel. To minimize this delay, some CMOS sensors can use two separate signal chains to simultaneously perform 2X CMS.

Typically, these two signal chains are used for sampling with high sensitivity (high-gain) for low signal levels, and a low sensitivity (low-gain) for higher signal levels, to provide dynamic range. The high-gain and low-gain data is combined to provide an image with both high sensitivity and a large dynamic range.

In some sensors it is possible to reconfigure the low-gain amplifier as a second high-gain amplifier. Instead of using a high-gain and a low-gain to combine into an image, it is now two high-gain images being combined. This enables the multi-sampling of the signal level to reduce the read noise in the measurement without a trade-off in frame rate. The trade-off comes in the form of a lack of significant dynamic range as the full-well capacity in this implementation is limited.