Program Memo Title: E2V Camera Signal Conditioning Analysis
Program Memo Number: 0013
Last Revision: 25-Feb-2010

Parameter		Symbol	Typical	Unit
Peak output voltage		Vsat	750	mV
Full well capacity	Area	Fw	500.00	ke^-
	Binning		1000.00	
CCD node sensitivity		Sv	1.8	uV / e^-
Dark Current	20º C	DS	1000	e^-/pixel/s
Readout noise [1]	-40º C	Nr	6	e^-rms

Table 1: Electrical Characteristics

(T_a = 25º C, unless otherwise noted)

Note:

1. *The Readout noise listed in Table 1 was measured by the manufacturer at an operating frequency of 20 KHz. The MityCCD-E3011BI camera is operated at 242 KHz. This number is used as an estimation of the performance of the sensor for doing a noise analysis. Given this, it is likely that the contribution of the MityCCD electronics to the total readout noise is in fact smaller than what is listed/calculated in this discussion.*

The above table shows the electrical characteristics of the CCD30-11 Back Illuminated CCD sensor.
The CCD30-11 datasheet specifies that the Typical Readout Noise is 6 e^- rms and the output gain sensitivity at 1.8 uV / e^-. The Readout Noise Level can be estimated using the following equation:

Readout Noise Level = Nr * Sv = 6 e^- rms * 1.8 uV / e^-
= 10.8 uV rms

The total gain through the amplifier circuitry at high gain is 104.4 and at low gain is 12. The 16-bit Analog to Digital converter (ADC) has an absolute range of 8.19 V and a resolution of 8.19V / 65536 = 125 uV per ADC count. Therefore, the resolution of the ADC at the input is:

High Gain:
Resolution = 125 uV per ADC count / 104.4 = 1.20 uV per ADC count
Low Gain:
Resolution = 125 uV per ADC count / 12 = 10.42 uV per ADC count

The CCD node sensitivity in terms of e^- per ADC count can now be determined:

High Gain:
CCD node sensitivity (e^- per ADC count) = 1.20 uV / Sv = 1.20 uV / 1.8 uV per e^-
= 0.67 e^- per ADC count
Low Gain:
CCD node sensitivity (e^- per ADC count) = 10.42 uV / Sv = 10.42 uV / 1.8 uV per e^-
= 5.8 e^- per ADC count

Given that the CCD node sensitivity is 0.67 e^- per ADC count at the high gain and 5.8 e^- per ADC count at the low gain, the ADC saturation levels can be calculated in terms of e^-. The gain in the low setting can be factory adjusted (contact Critical Link LLC for more information) to allow the ADC saturation level to match the horizontal summing register saturation levels. In most circumstances, this will not provide optimum performance.

High Gain:

ADC Saturation (e^-) = 0.67 e^- per ADC count * 65536
= 43.9 ke^-

Low Gain:

ADC Saturation (e^-) = 5.8 e^- per ADC count * 65536
= 380.1 ke^-

When performing noise calculations, the three contributions to noise across the camera are considered:

- CCD readout noise
- Electronics
- Shot noise from dark current

The theoretical readout noise level due to the CCD on-chip amplifier in terms of ADC counts is calculated using the following equation:

Readout Noise Level (counts rms) = Readout Noise Level / ADC input resolution

High Gain:

Readout Noise Level (counts rms) = 10.8 uV rms / 1.20 uV per ADC count
= 9 ADC counts rms

Low Gain:

Readout Noise Level (counts rms) = 10.8 uV rms / 10.42 uV per ADC count
= 1.04 ADC counts rms

The measured total rms noise level at high gain for a short exposure (i.e no dark current) is 10 ADC counts rms. From this result, the noise due to electronics can be calculated as follows:

If x = CCD Noise
y = Electronics Noise
z = Total

$$z^2 = (x^2 + y^2)$$
$$y^2 = z^2 - x^2$$
$$y = \sqrt{(10^2 - 9^2)}$$

Electronics Noise = 4.36 ADC counts rms

The shot noise due to dark current is approximately the square root of the number of electrons detected. The number of electrons detected is a function of the CCD temperature as well as the exposure time. Given that the dark current at 20º C is 1000 e^-/pixel/s, over a period of 10 seconds exposure time, the number of electrons accumulated would be 10000 e^-.

Typically, the CCD temperature during normal operation is cooled down to around -30º C and the dark current at -30º C is approximately 1 e^-/pixel/s. The shot noise level due to dark current over 10 second can then be calculated.

For Area Readout, where every pixel is read out individually, the shot noise for each pixel is:

Dark Current = 1 e^-/s * 10s = 10 e^-
Shot Noise = $\sqrt{10}$ e^- = 3.2 e^- rms

High Gain:
Shot Noise = 3.2 e^- rms / 0.67 e^- per ADC count
= 4.78 ADC count rms

Low Gain:
Shot Noise = 3.2 e^- rms / 5.8 e^- per ADC count
= 0.55 ADC count rms

During binning operations, the shot noise does not increase proportionally to the signal. For example, at 20º C with an exposure time of 1 second, the shot noise rms is $\sqrt{1000}$ e^-/s =32 e^-rms. If all 256 rows are binned, the shot noise in e^-rms is:

Binned Shot Noise = $\sqrt{(256 * 1000 e)}$ = 506 e^-rms

The above correct calculation is significantly lower than what is sometimes erroneously calculated as:

Binned Shot Noise = 256 * 32 e^-rms = 8192 e^-rms

This computation does not take into account that RMS signals have to be added in a root-sum-of-squares fashion.

The three sources of noise come into play differently, depending on the application.

For short exposures of up to several seconds, the shot noise of the dark current should be significantly below the signal level. If signal levels are very low, however, readout noise (the sum of the inherent CCD readout noise and the electronics noise) can be a source of poor images. Longer exposures will generally improve the signal-to-readout noise ratio very quickly. For each doubling of the exposure time, the signal to readout noise ratio will improve by 1.5dB. Because readout noise is only added when the data is read out of the CCD, binning charge within the CCD is a very effective way to reduce the effect of readout noise. For each doubling of the number of lines binned, the SNR of the resulting data will be improved by about 3dB.

Because the shot noise increases as the square-root of the signal (dark current or actual signal), longer exposures will produce better signal-to-noise ratios, in spite of the increase in dark current. The dark current represents a fixed-pattern noise, and is mostly deterministic. Subtraction of the average dark current at a given exposure setting can remove a very significant source of what would appear to be noise. This procedure leaves only the shot noise of the dark current, the shot noise of the signal, and the combined readout noise, in the image.

The electronic noise in the camera is lowest at high gain settings, since some of the noise in the output is introduced after the programmable gain stage. By increasing the gain, the electronics noise becomes a smaller portion of the overall noise, as compared to the inherent CCD readout noise.

In high light situations, the low gain setting will allow best use of the dynamic range of the CCD. Furthermore, binning in the DSP will increase the dynamic range significantly, at the cost of reduced readout speed. Noise in the high light application will be dominated by shot noise from the signal. This noise is improved by increasing the total number of electrons (photons) collected. Saturation should be avoided, of course, so once the amount of light binned gets close to saturation levels, additional SNR improvements must be obtained by averaging data from successive images.