

# Noise Sources in CMOS Image Sensors

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## INTRODUCTION

Until recently, CMOS image sensors have been plagued by poor image quality due to high fixed pattern noise (FPN), high dark current and poor sensitivity. Understanding the relationship between noise sources and the image output of a CMOS sensor will improve your ability to design high quality solutions with CMOS technology. Potential noise sources are present from the sensor photodiode through the column and programmable gain amplifiers (PGA) and analog-to-digital converters (ADC)

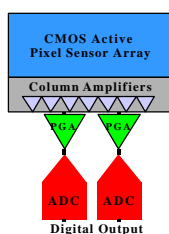


Figure 1 – Sensor Architecture

## TEMPORAL NOISE

Temporal noise refers to the time-dependent fluctuations in the signal level that are of fundamental origins, unlike FPN. Temporal noise can be introduced in the pixel, column amplifiers, programmable gain amplifiers and ADCs. Circuit-oriented temporal noise originating from substrate coupling or poor power supply rejection is not included in the discussion.

### Pixel Noise

Noise sources in the pixel include the photon shot noise, reset (kT/C) noise, dark current shot noise and the MOS device noise.

**Pixel Photon Shot Noise:** Photon detection is essentially a random process obeying Poisson statistics. This means that the standard deviation (or noise) and the photon noise limited Signal-to-Noise Ratio (SNR) associated with detecting a mean of ‘N’ photons are given by:

$$Noise (photon) = \sqrt{N}$$

$$SNR(photon) = \sqrt{N}$$

Photon shot noise limits the SNR when detected signals are large. This represents a fundamental limit and can only be improved by increasing the full well capacity of the sensor. The system noise floor limits dynamic range.

**Pixel Reset (kT/C) Noise:** The signal integrated on a pixel is measured relative to its reset level. The thermal noise uncertainty associated with this reset level is referred to as the reset or kT/C noise. Reset schemes can be devised so that this pixel-level noise is largely eliminated, either through correlated double sampling (CDS) techniques or by the use of uni-directional MOS reset switches in the pixel.

**Pixel Dark Current Shot Noise:** Pixel Shot Noise associated with the photodiode leakage current [I(dark)] is largely dependent on exposure time and is given by:

$$Noise = \frac{q}{C(pixel)} \times \sqrt{\frac{I(dark) \times t}{q}} \quad (Volts)$$

where C(pixel) is the total pixel capacitance and q is the electronic charge. The best CMOS processes tend to have extremely low dark currents (~100pA/cm<sup>2</sup>) for best image quality.

**MOS Device Noise:** The primary sources of amplifier noise in the pixels are the thermal and flicker (1/f) noise of the MOS transistors. 1/f noise can be largely eliminated through rapid double sampling of the pixel. Thermal noise in the MOS devices can also be largely suppressed by limiting the bandwidth of the in-pixel amplifiers, and that is generally the case on high-resolution sensors with large capacitive loads on the pixel amplifiers.

### Column Amplifier Noise

The column amplifier samples both the pixel reset and signal level, and then buffers or amplifies the difference signal. Major noise sources are the kT/C noise associated with the sampling process and the thermal and 1/f noise of the column amplifier MOS devices.

**Column Amplifier kT/C Noise:** The two un-correlated sampling operations associated with the signal and reset levels result in a thermal noise signal given by:

$$Noise = \sqrt{\frac{2kT}{C(Column)}} \quad (Volts)$$

C(column) is the column sampling capacitance; k is the Boltzmann’s constant; and T is the absolute temperature. A further 3dB increase in column kT/C noise is possible if dark reference columns are employed to reduce column fixed pattern noise.

Column Amplifier MOS Device Noise: Thermal and flicker noise sources are present in the column amplifier MOS devices but the effects are generally negligible when compared to the sampling operation  $kT/C$  noise.

### Programmable Gain Amplifier Noise

Noise sources in the programmable gain amplifiers are the  $kT/C$  thermal noise associated with sampling operations and programmable gain MOS device noise.

Programmable Gain  $kT/C$  Noise: As in the column amplifier case, two un-correlated sampling operations are generally performed, and the associated thermal noise signal is given by:

$$Noise = \sqrt{\frac{2kT}{C(pga)}} \quad (Volts)$$

Programmable Gain MOS Device Noise: MOS amplifier thermal and flicker noise can be designed to be much smaller than the sampling operation  $kT/C$  noise.

### ADC Noise

The primary source of noise in the ADC is the quantization noise. An ideal ADC's quantization noise is given by:

$$Noise = \frac{LSB}{\sqrt{12}} \quad (volts)$$

$$= 0.288 \times LSB \quad (volts)$$

A practical, but non-ideal ADC noise level will exceed  $0.288LSB$  due to other noise sources like thermal, amplifier and switching noise. In addition to random mismatches in ADC components contribute to Fixed Pattern Noise.

### Overall Temporal Noise

The overall temporal noise of the CMOS image sensor is the uncorrelated sum of the pixel, column amplifier, programmable gain amplifier and the ADC noise, and is given by:

$$Noise = \sqrt{(G \times N1)^2 + N2^2}$$

G, N1 and N2 are respectively the PGA gain, pre-PGA noise sources and post-PGA noise sources. N1 and N2 are computed by root-sum-square summation of the various noise sources in the analog signal path.

### Noise Floor (or Read Noise)

This refers to the residual noise of the image sensor if photon shot noise is excluded. The noise floor limits the image quality in the dark regions of an image, and increases with exposure time due to the pixel dark current shot noise.

## Dynamic Range & SNR

The dynamic range of a CMOS sensor is defined as the ratio of the largest detected signal to the smallest simultaneously detectable signal (or noise floor). Figure 2 shows the relationship between signal level and SNR of a typical CMOS image sensor, where the solid-blue represents the overall SNR, the dotted-green line is the photon noise limited SNR and the dashed-red line represents the noise floor limited SNR

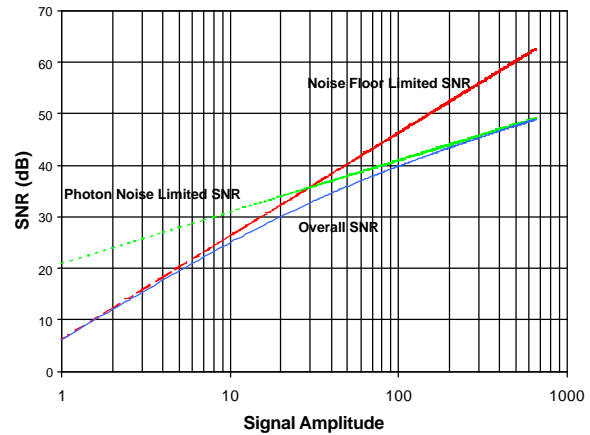


Figure 2 - SNR versus Signal Amplitude

## FIXED PATTERN (SPATIAL) NOISE

FPN refers to a non-temporal spatial noise and is due to device mismatches in the pixels & color filters, variations in column amplifiers, and mismatches between multiple PGAs and ADCs. FPN can be either coherent or non-coherent.

Dark current FPN due to mismatches in pixel photodiode leakage currents tends to dominate the non-coherent component of FPN, especially with long exposure times. Again, as with pixel dark current shot noise, low leakage photodiodes are preferable to reduce this FPN component. Dark frame subtraction is an option, but this tends to increase the read-out time of the sensor.

The most problematic FPN in image sensors is associated with easily detectable (or coherent) row-wise and column-wise artifacts due to mismatches in multiple signal paths, and un-correlated, row-wise operations in the image sensor. Coherent FPN offset components can generally be eliminated by reference frame subtraction. Gain mismatches are more difficult to remove since they require time or hardware intensive gain correction (e.g. multiplication).