Application Note

Published: 18 April 2023

Low-Light Imaging: Unraveling Signal, Sensitivity, Responsivity & Noise in High-Speed CMOS Sensors

K. D. Gilroy, PhD (Reviewed & Edited By: Saba Adabi, PhD; Matthew Vayner, PhD)

Vision Research, AMETEK

Background. One of the most commonly confused topics when assessing high-speed CMOS sensors is the concept of *sensitivity*. To date, it is often seen that the specification $\mathrm{ISO}_{\mathrm{sat}}$ 12232 is used in lieu of *spectral responsivity* and *read noise* when qualifying how well CMOS sensors perform in *low-light imaging applications*. In fact, it is often the case that a sensor with high ISO actually performs worse in low-light scenarios than a sensor with low ISO. In the discussions below, the origin of this confusion is highlighted followed by the key technical specifications that define quantitatively how well a sensor performs in low-light imaging applications.

The $\mathrm{ISO}_{\mathrm{sat}}$ Specification. Let us start by looking at **Figure 1**, where we have two different sensors imaging a chart & bulb under the same test lighting conditions. If you were to select a sensor that has better low-light performance, you would immediately select Sensor B because it is clearly brighter. However, you may be surprised to know that the low-light performance for sensor A and B are actually the same! Technically speaking, you *cannot* discern which sensor performs better, yet just that Sensor B saturated much faster. This example underscores the origin and importance for the upcoming discussion for how $\mathrm{ISO}_{\mathrm{sat}}$ can be easily perceived as a benchmark parameter.

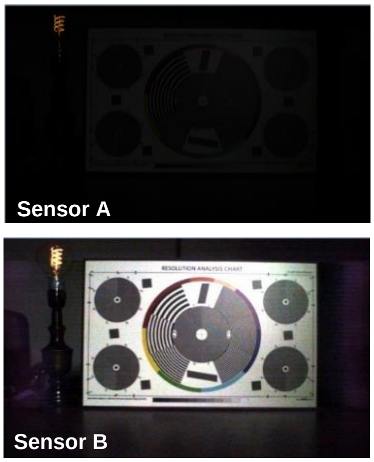


Figure 1. (Sensor A) Top image. (Sensor B) Bottom image.

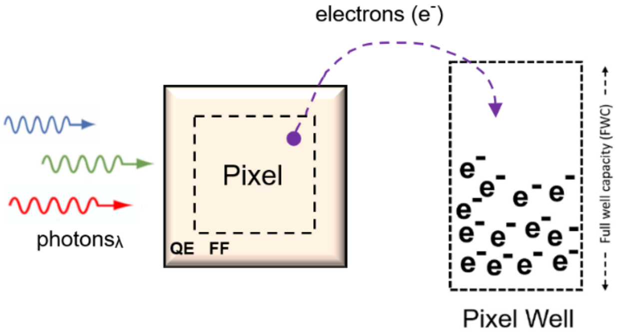
There are a few different types of 'ISO' measurements that can be performed,[1] but the most commonly used for high-speed CMOS sensors is called the *Saturation based method*, as defined using the equation:[1]

$$\mathrm{ISO}_{\mathrm{sat}} = \frac{78}{\text{Exposure Time} \times \text{Incident Lux}} \qquad \textbf{Eq. 1}$$

In Equation 1, *Exposure Time* describes how long a frame integrates (collects light), and the *Incident Lux* defines how much light hits the pixel (using either a daylight or tungsten illumination source). Therefore, terms in the denominator are increased until the pixel reaches saturation, and then once that occurs, those specific numbers are plugged into Equation 1 and $\mathrm{ISO}_{\mathrm{sat}}$ is determined. This number purely defines *how fast* a sensor reaches saturation, and thus could be defined as a measure for *apparent* sensitivity (or out of the box brightness), rather than a figure that defines actual or *scientific* sensitivity (namely responsivity) – which defines how responsive the sensor is in terms of electrons of signal to photons of incident irradiation.

If one wanted to boost $\mathrm{ISO}_{\mathrm{sat}}$, for example, there are a hand-full of methods. For example, one could simply (*a*) lower full well capacity (*via* sensor design), (*b*) select only to map the lower bits to display (i.e., *via* software or hardware), and/or (*c*) increase pixel responsivity (discussed later). Very often, the former two are decreased in order increase that apparent sensitivity. While this indeed will make the sensor appear brighter with out of the box settings, it directly reduces overall signal-to-noise performance. On the other hand, increasing the pixel *responsivity* is the only one of these three that will influence the *actual* sensitivity of the sensor in terms of photons-in, and electrons-out to impact overall sensor performance. Therefore, lets take a look at how signals are generated and how responsivity plays into low-light performance.

How Signal is Generated? When photons hit the surface of a pixel, a signal is generated in the form of electrons (or charge). The rate at which electrons are generated is directly proportional to the number and type of incident photons per area per time – called photon flux (Φ_λ). The photon flux, together with the quantum efficiency (QE_λ), fill factor (FF), and pixel area (PA) define how much signal can be generated over time. Note that QE_λ is the ratio of the number of electrons generated to photons of wavelength – λ; PA is the total area of an individual pixel, and FF is the ratio between the active (or photosensitive) pixel area to the entire pixel area. In many cases, the QE and FF are combined into one term called $QE_\lambda \times FF$. Schematic 1 shows how one can calculate how many electrons are generated from a given number of incident photons simply by knowing how many photons hit the pixel.



Schematic 1. Conversion of incident photons to electrons, and electrons filling a pixel's well to create signal.

Pixel Responsivity Calculation. The magnitude of pixel responsivity is directly defined by the rate at which a given photon flux is converted to signal in the form of electrons. The key parameters include the pixel area, quantum efficiency, and fill factor. Therefore, a quick calculation can be done to compare the responsivity of CMOS sensors at a given wavelength of λ using Equation 2:

$$\text{Responsivity}\left[\frac{e^-}{s}\right] = \Phi_\lambda\left[\frac{photons}{\mu s\cdot \mu m^2}\right] \times \text{PA}\ (\mu m^2) \times \text{QE}_\lambda\left[\frac{e^-}{photons}\right] \times \text{FF}\left[\frac{Inactive\ Pixel\ Area}{Active\ Pixel\ Area}\right] \qquad \textbf{Eq. 2}$$

Outside from direct calculation using the above equation, the most efficient way to *compare* sensors in terms of responsivity is to simply overlay the respective spectral response curves as provided by the sensor manufacturer, see **Figure 2** as a sample. These plots describe exactly how responsive the sensor is to light across the visible and NIR spectrum, in units of amps of signal per watts of incident light. This directly correlates to electron rate to photon rate. Note that the gray curve represents a monochrome pixel, and the red, green, and blue curves represent the responsivity from colored pixels.

Low-Light Performance. While the above discussion gives quantitative insight into how *responsive* a sensor will be, we still do not know how well a given sensor will perform during low-light imaging applications. To better understand that aspect, we must determine if the signal generated (from the

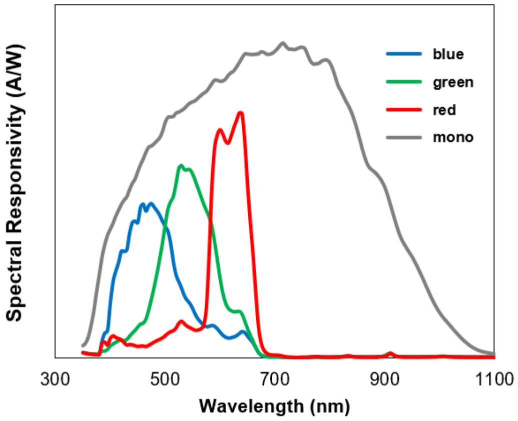


Figure 2. Spectral responsivity plot.

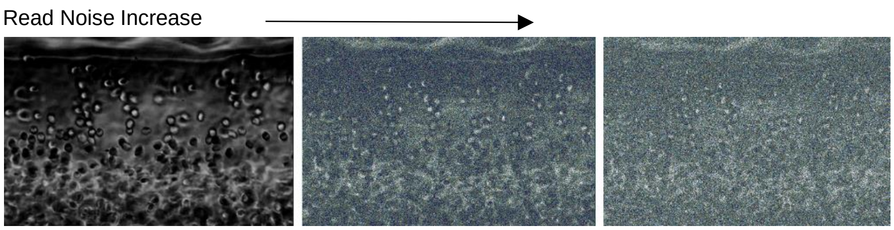
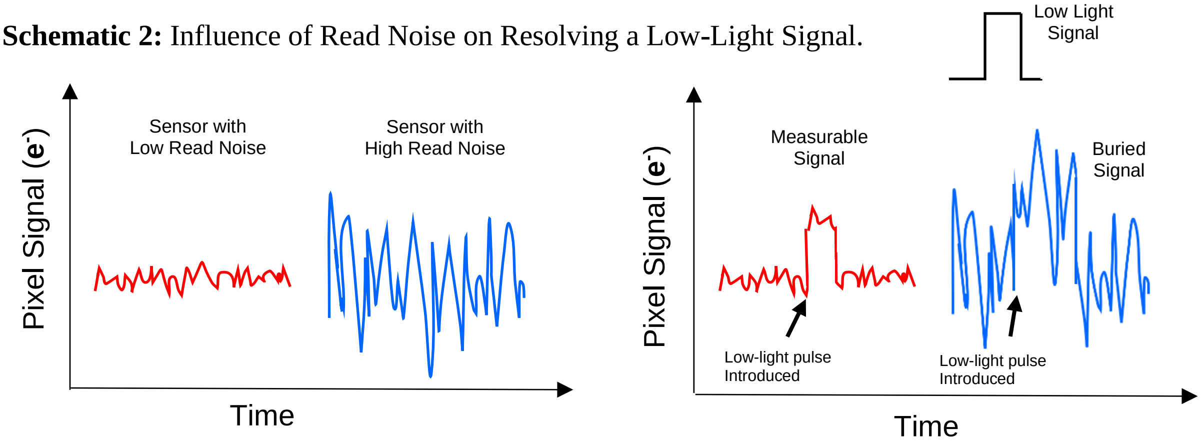


Figure 3. Sample low-light image data showing the influence of read noise on images captured of red blood-cells flowing through a microfluidic device. Images were captured at Newcastle University in the Laboratory of Prof. Andrew Filby. Note: read noise here added.

low-light signal) is capable of overcoming the sensors *read noise*. *Read noise*, also referred to as temporal dark noise, represents the noise present on the sensor without incident light. It therefore defines the number of electrons that need to be generated from the incident photon flux to create a viable electronic signal. In Figure 3, you can see that as the read noise on the sensor increases (from left to right), the image details become increasingly indiscernible from noise.

In the context of high-speed CMOS sensors, read noise is generally specified as frame-rate and sensor-resolution independent, and listed a single number generally in the range from 1 – 60 electrons (either RMS or median valued). In addition to read noise, another valuable specification is called absolute sensitivity threshold (AST), which directly provides a measure for how many photons are needed to generate a signal equal to the noise. In essence, any input signal (*i.e.*, low-light signal) that is less than the sensors AST cannot be discerned from the noise. This concept is illustrated in **Schematic 2**, where a low-light input signal is introduced into a pixel that has low read noise (red trace), and another that has a high read noise (blue trace). Note that the pixel signal with the red trace has a well-defined signal response, while the blue trace clearly buries it.

Schematic 2: Influence of Read Noise on Resolving a Low-Light Signal.



Concluding Remarks. In this application note, we illustrated why the ISO$_{sat}$ specification is a poor metric for gauging *sensitivity* for scientific low-light applications. In short, the ISO$_{sat}$ specification informs on how fast a sensor reaches saturation, rather than providing a precision measure for how many electrons are generated relative to the incident photon flux and sensor read noise. It is strongly encouraged that anyone benchmarking high-speed CMOS sensors in terms of overall image performance investigate the EMVA 1288 standards and guidelines, and how they impact to the imaging application and/or technique at hand.

References:

1. Photography — Electronic still-picture cameras — Determination of ISO speed Photographie ISO 12232:1998 https://standards.iteh.ai/catalog/standards/sist/7e29c0d9-dd5a-4b08-b396-9c6389decd9e/iso-12232-1998