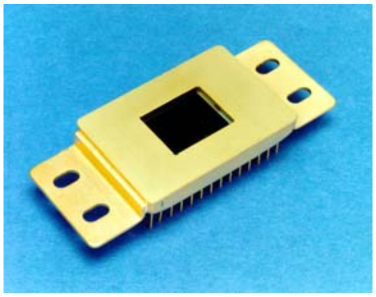
Application Note

The Sensitivity of Focal Plane Arrays and Cameras



1 Introduction

The sensitivity of a photodetector is essentially the amount of light required so that the *signal-to-noise ratio (SNR)* is 1:1. There are many units used to measure sensitivity and the appropriate choice depends of type of detector, the application, whether or not it is desirable to normalize application parameters such as measurement bandwidth or detector geometry. As often or not, tradition plays a role in choosing the appropriate unit. Just try asking for the detectivity, D*, of a visible detector or the noise-equivalent-power, NEP, of an infrared detector. In this Technical Note, we will define and describe the units commonly used to specify the sensitivity of focal plane arrays and cameras.

Focal plane arrays and cameras have added complications due to the interplay between the photodiode array, the readout integrated circuit (ROIC or multiplexer), and the external camera electronics. This is complicated further as the noise of the photodiode array depends on the exposure time while that of the ROIC is independent of exposure time. The sensitivity of a focal plane array and camera, therefore, depends on the measurement conditions and is expressed in a variety of units. The purpose of this Note is to describe the considerations that go into an analysis of a focal plane array and camera and to describe the various units used for sensitivity.

2 The Signal of Photodetectors

The "signal" in the SNR of a photodetector fundamentally depends on its *quantum efficiency,* often denoted with the symbol □, and is defined as the percentage of photons that generate electron-hole pairs. The *external quantum efficiency* is the percentage of incident photons that generate electron-hole pairs collected at the electrodes of the detector. This is reduced from the *internal quantum efficiency* by the photons that either reflect from the detector surface or transmit through the detector. A typical InGaAs PIN photodiode has an external quantum efficiency greater than 80% for photons at a wavelength of 1.55 μm.

A more practical unit of signal is *photoresponse* measured in Amperes per Watt (A/W). This measures the current (1 Ampere = 1 Coulomb per second = 6.24×10^{18} electrons/s) generated by an incident optical flux (1 Watt = 1 Joule/s = N photons per second where N depends on the energy or wavelength of the photon). A photon with a wavelength of λ (μm) has an energy of

$$E[J] = \frac{1.985\, x 10^{-19}}{\lambda[\mu m]} \qquad (1)$$

An electron has a charge of 1.602×10^{-19} C. A photon flux of N photons per second will produce a current of η x N x 1.6×10^{-19} A. Thus the relationship between *photoresponse* and *external quantum efficiency* is

$$PR[A/W] = \eta \frac{\lambda[\mu m]}{1.239} \qquad (2)$$

The $\eta = 80\%$ of InGaAs at $\lambda = 1.55\ \mu m$ corresponds to a photoresponse of 1.0 A/W. It is interesting to note that a silicon photodetector with the same 80% quantum efficiency at 0.5 μm has a photoresponse of only 0.32 A/W yet is an equally “good” device. *Quantum Efficiency* is thus the more fundamental measure of response while *Photoresponse* is an engineering unit that is often more useful in determining how a photodetector will respond in an application.

3 Noise in Photodetectors

There are several sources of noise in photodetectors. These include *shot noise* from the detector dark current, *shot noise* from the photocurrent, *Johnson noise* from thermal fluctuations in the detector impedance, and *flicker noise* that is inversely proportional to the measurement frequency (also referred to as “1/f” noise). Avalanche photodiodes also have *“excess noise”* that depends on the ratio of the ionization coefficients for electrons and holes and the avalanche gain. In this Note, we are concerned with focal plane arrays and cameras. These also contain noise contributions from the focal plane array’s readout integrated circuit (multiplexer) as well as from external camera electronics.

When the noise sources are independent of each other, they add in quadrature, i.e.

$$\begin{aligned} &Noise_{total} = \\ &\sqrt{Noise_1^2 + Noise_2^2 + \Lambda\ + Noise_n^2} \end{aligned} \qquad (3)$$

4 Noise in Focal Plane Arrays

Focal plane arrays integrate signal for an exposure time, ET. The effective measurement bandwidth associated with this exposure time is

$$B \approx \frac{1}{2ET} \qquad (4)$$

In general, one noise source will tend to dominate or, at most, there will be interplay between two sources. Focal plane arrays do not contain avalanche photodiodes so excess noise can be neglected. Exposure times tend to be 100 ms or less so the effective bandwidth is greater than 5 Hz. For InGaAs, 1/f or flicker noise only begins to be noticeable at frequencies less than 1 Hz. Since sensitivity is defined for low light levels (i.e. the minimum amount of light such that the signal equals the noise), signal shot noise can be ignored. Also, in a well-designed camera, the noise from the external electronics should be negligibly small.

This leaves as the dominant noise sources dark noise (both shot and Johnson) and readout noise from the multiplexer. Shot noise and Johnson noise are given by

$$\begin{aligned} \left\langle I_S^2 \right\rangle^{1/2} &= \sqrt{2qBI_{dark}} \\ \left\langle I_J^2 \right\rangle^{1/2} &= \sqrt{\frac{4k_B TB}{R}} \end{aligned} \qquad (5)$$

where

q	Charge of electron, $1.602\text{x}10^{-19}$ C
k_B	Boltzmann’s Constant, $1.380\text{x}10^{-23}$ J/K
B	Measurement bandwidth
T	Temperature, K
R	Photodiode impedance, Ω
I_{dark}	Photodiode dark current, A=C/s

If, in the focal plane array, the photodiodes are operated at zero bias then there is no dark current and the primary source of noise is Johnson noise. On the other hand, if the photodiodes are reversed biased, the diode impedance increases decreasing the Johnson noise while the dark current increases so that the shot noise dominates.

Consider the special case of shot noise in an integrating detector. Combining Equation 5 for noise current, Equation 4 for measurement bandwidth, and noting that the integrated noise charge is the noise current multiplied by the integration time,

$$\begin{aligned} Q_S &= ET\left\langle I_S^2 \right\rangle^{1/2} \\ &= ET\sqrt{2q\frac{1}{2ET}I_{dark}} \\ &= \sqrt{qETI_{dark}} \\ &= \sqrt{qQ_{dark}} \end{aligned} \qquad (6)$$

The accumulated charge from the dark current, Q_{dark}, can be expressed as the number of accumulated electrons multiplied by the charge of a single electron, $Q_{dark}=Nq$, therefore

$$\begin{aligned} Q_S &= N_S q = \sqrt{qN_{dark}q} \\ N_S &= \sqrt{N_{dark}} \end{aligned} \tag{7}$$

This simple relationship makes it easy to estimate shot noise from a FPA. In Sensors Unlimited's SU320M-1.7RT InGaAs MiniCamera, the dark current per pixel is approximately 500 fA or 3×10^6 electrons per second. During its maximum 16.3 ms exposure time, 50,000 electrons are accumulated with a resulting noise of 225 electrons. The camera has a full well capacity of 10^6 electrons per pixel which is digitized to 12-bit precision or 245 electrons per count. The dark noise, therefore, is equivalent to 1 ADC count.

In a focal plane array, the photodiode array is mated to a readout integrated circuit, ROIC. The contribution of this device to the total noise is the *readout noise*. This is a noise voltage that happens once per readout. ROICs have a *transcapacitance* that expresses how the integrated charge is amplified and output as a voltage: $V_{out}=Q/C$. Due to the convenience of Equation 7, it is conventional to express this noise voltage as "noise equivalent electrons." The readout noise of the SU320M-1.7RT MiniCamera, for example, is less than 500 electrons.

5 The Total Noise of a Focal Plane Array

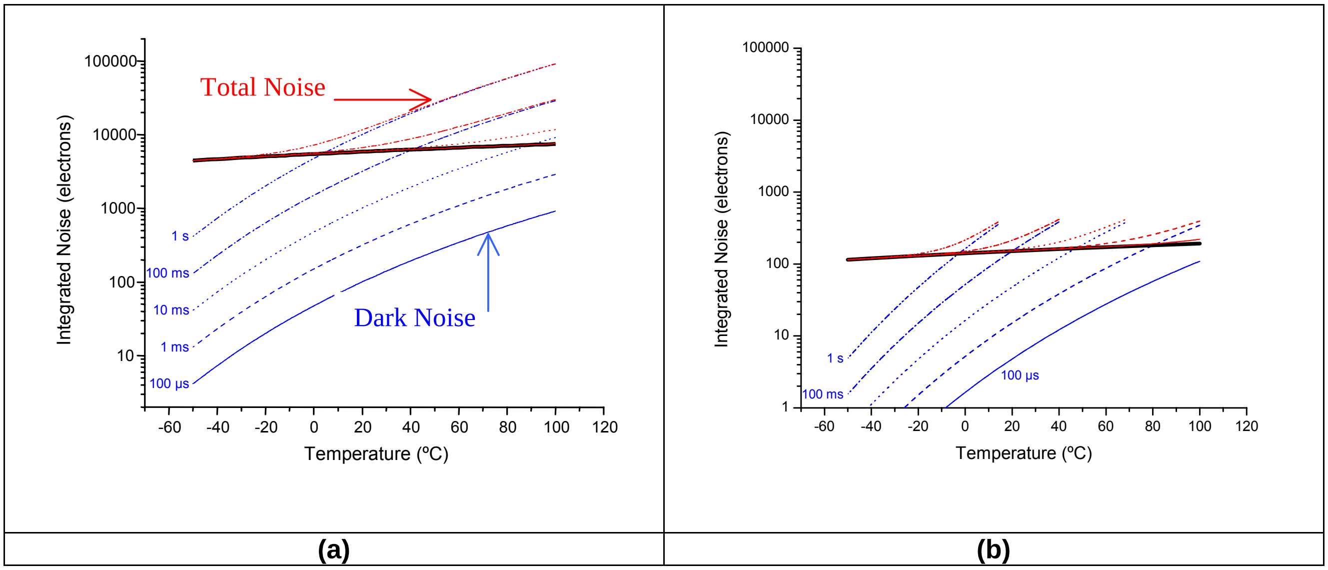
The total noise of a focal plane array consists of the shot noise due to the dark current (Equation 7), the shot noise of the photocurrent (Equation 7 with N_{dark} replaced by N_{signal}) and the readout noise in equivalent electrons. They add in quadrature as per Equation 3. An important point to note is that readout noise only occurs once per read while shot noise increases with the total measurement time, i.e. the total number of integrated dark and signal electrons. Focal plane arrays exhibit *reciprocity*. The total signal is the incoming flux (photons per second) multiplied by the quantum efficiency (electrons per photon) times the total integration time. It doesn't matter if the total integration time occurs during one integration or if multiple exposures are added.

By the same token, shot noise also exhibits reciprocity. In a single exposure, the number of integrated dark or signal electrons increase linearly with the exposure time so that the shot noise (Equation 7) increases with the square root of the exposure time. When multiple scans are added, the noise increases as the square root of the number of scans, which is equivalent to the square root of the total integration time. Readout noise, on the other hand, only occurs once per scan.

Figure 1 illustrates the temperature dependence of the interaction between dark current shot noise and readout noise in two Sensors Unlimited focal plane arrays. The first is a SU512LD-1.7T1-0500 linear array in which the photodiodes are held at zero bias so that Johnson noise dominates. The room temperature readout noise is just under 6000 electrons, the full well capacity is over 150 million electrons and the photodiode shunt resistance is about 3 GΩ. The second is a Sensors Unlimited SU320-1.7MX high sensitivity InGaAs two-dimensional focal plane array and camera. In this device, the photodiodes are reverse-biased so that shot noise dominates. The readout noise is 150 electrons, the full well capacity is 200,000 electrons and the dark current is 30 fA/pixel at 20°C.

As the temperature is lowered, the readout noise decreases roughly linearly in temperature (as it is primarily k_BTC/q noise). The dark current decreases exponentially in temperature. The messages contained in the figure are:

- The way to increase the signal-to-noise ratio is to increase the total measurement time.
- The dark signal can be subtracted from the total signal leaving behind the dark noise (either Johnson or shot noise) plus readout noise. Since the dark noise, in electrons, is the square root of the integrated dark current (in electrons), care must be taken not to saturate the detectors – i.e. exceed the full well capacity.
- The way to minimize the noise – and thus maximize the sensitivity – is to minimize the shot noise so that readout noise is the dominant noise source.
- Lowering the temperature reduces the dark current and allows the total measurement to be made up of fewer individual scans. The dark noise is independent of whether there was one long scan or many short scans but the total readout noise depends on the number of scans. To minimize the total system noise, the fewer scans the better.



(a) **(b)**

Figure 1. The interplay between dark noise and readout noise as a function of temperature. (a) represents a linear array. At high temperature and long exposure times, the dark noise dominates the total noise. Maximum signal-to-noise is achieved by averaging as many scans as time permits. At low temperatures, readout noise dominates so that the maximum signal-to-noise is achieved with the fewest scans. (b) represents a two-dimensional array that is 50 times more sensitive (lower noise) than the linear array. In this device, the readout noise dominates at all temperatures and exposure times.

6 Units for Expressing Sensitivity

The most common unit of sensitivity for visible photodiodes is noise equivalent power, or NEP. In the infrared, detectivity, D*, is used. Specific applications often have their own notation. In optical communications, for example, sensitivity is defined as the power required to assure a maximum error rate at a specified data rate. In this section, we define various units of sensitivity and the relationships between them.

6.1 Noise Equivalent Power/NEP

NEP is the optical power that generates sufficient photocurrent (via the photoresponse, Equation 2) to equal the noise current (Equation 5). The units of NEP are W/√Hz. This assumes that the noise spectral density is “white,” i.e. constant as a function of frequency. A low NEP indicates a more sensitive detector. The definition of NEP excludes the detector area. This can be misleading. Consider two detectors identical except that one has double the area. It will have double the dark current and, thus, √2 more noise current. This will increase the NEP implying less sensitivity. The issue of normalizing detector performance by area is addressed by the concept of detectivity.

*6.2 Detectivity/D**

For NEP to more accurately describe detector performance, it is necessary to eliminate the area dependence of the noise current (Equation 5) by dividing by the square root of the area. Two InGaAs photodiodes, for example, identical in every way except for photosensitive area will now have the same normalized NEP. As with NEP, a <u>low</u> normalized NEP means a <u>high</u> sensitivity. Detectivity is simply the inverse of the normalized NEP, i.e.

$$D^* = \frac{\sqrt{Area}}{NEP} \qquad (8)$$

The units of D* are cm-√Hz/W which is often referred to as a “Jones” after R.C. Jones who suggested this figure of merit in 1952. Detectivity is not only independent of detector area, but a <u>high</u> detectivity implies a <u>high</u> sensitivity.

6.3 Noise Equivalent Irradiance/NEI

Irradiance is measured in Watts of optical power per cm^2 of area per nm of spectral bandwidth. This is useful when describing the sensitivity of a photodiode to a broadband light source.

Irradiance is measured at the detector surface. NEI is related to NEP by

$$NEI = \frac{NEP\sqrt{B}}{\Delta\lambda Area} \qquad (9)$$

6.4 Noise Equivalent Photon Flux/NEPF

The units of NEPF are photons per cm^2 of area per second or photons per pixel per second. This is most useful when the incident light is monochromatic.

6.5 Noise Equivalent Electrons/NEE

This is probably the most useful (and easiest to use) measure of sensitivity for a focal plane array. The Units of NEE are electrons per root scan. In a well-designed high sensitivity measurement, the dominant noise source should be the readout noise. Readout noise is independent of exposure time (and hence, bandwidth) and occurs once per scan. If multiple scans are added to increase SNR, the signal increases with the number of integrated scans while the readout noise increases with the square root of the number of scans. As described in the discussion leading to Equation 7, the readout noise is a fixed number of electrons (per root scan) and the dark noise is simply the square root of the number of integrated dark electrons. The number of signal electrons is simply the photon flux times the quantum efficiency times the exposure time of a single scan.

If you need further technical support, please contact our sales department via email sui_support@goodrich.com or call us at 609-520-0610.

About Goodrich's SUI Team: Founded in 1991, SUI (Sensors Unlimited, Inc.) is the leading manufacturer of indium gallium arsenide (InGaAs) PIN and avalanche photodiode arrays that are used in shortwave and near infrared imaging for military, industrial, spectroscopic, machine vision, and telecommunications applications. SUI provides InGaAs photodiode array processing as a foundry service and designs custom readout integrated circuits for unique imaging applications within its ISO 9001 certified facility. For more information, visit www.oss.goodrich.com/sui.