COMPARING CAMERA SENSITIVITY WITH NOISE EQUIVALENT IRRADIANCE

Jean-Edouard Communal

Raptor Photonics Ltd.

ABSTRACT

It can be difficult to compare the merits of cameras using different sensor technologies using only the specifications typically provided by the manufacturers. The Noise Equivalent Irradiance (NEI) provides a normalized and unique parameter allowing a direct comparison. It is also fairly simple to calculate from the commercial specifications for a given wavelength and exposure time of interest. We compare the merits between typical CCD, EMCCD, CMOS and InGaAs FPA cameras.

***Index Terms*—** CCD, EMCCD, CMOS, InGaAS, SWIR, NEI, noise, signal to noise, irradiance, detectivity

1. INTRODUCTION: SIGNAL TO NOISE IMPORTANCE TO HYPERSPECTRAL IMAGING

In hyper spectral imaging, each pixel holds important spatial and spectral information. Large datasets must process in order to automate sorting with the highest possible confidence. There are many papers outlining how to improve image quality [1] and reducing noise [2], [3], [4]. However, starting with a good quality raw dataset with high signal to noise ratio goes a long way to make subsequent data processing easier, faster and more reliable.

Selecting the right camera is the first step to obtain good raw data, make the processing easier and reach reliable results.

2. PERFORMANCE PARAMETERS AND TRADEOFFS

Before considering the expense of integrating a camera, the first step is usually to evaluate how it will perform. The capacity of a camera to detect light is determined by the following parameters:

- **Quantum efficiency**, the probability for a photon of a given wavelength to produce a pair electron/hole
- **Pixel size**
- **Full well capacity in electrons**
- **Exposure time or frame rate**
- **Readout noise per pixel**
- **Dark current per pixel per second**

Essentially, on one hand, the higher the quantum efficiency, the larger the pixel size, the longer the exposure time, and the bigger the pixel well depth, the more signal can be gathered.

On the other hand, the lower the readout and dark current noise, then the smaller the detection threshold will be. Finally, the dynamic range within a single exposure will depend on the pixel full well capacity and detection threshold.

In theory, an ideal detector would be able to count the exact position and timing of every single photon to offer perfect image quality. In practice, one must balance sometimes conflicting parameters varying for different sensor types:

- **Quantum efficiency**, suffers no tradeoffs. The higher it is over the larger spectral range the better.
- **Pixel size and full well capacity**; smaller pixel result in higher spatial resolution at the expense of sensitivity and full well capacity.
- **Exposure time** and frame rate are linked to the readout noise and dark current. Higher frame rate is desirable to have a high temporal resolution; however, with high frame rate readout noise can increase. Similarly, if temporal resolution is irrelevant, then long exposure times are desirable, but in this case, the dark current will increase correspondingly.

Each application has its own set of compromises, for example for hyper spectral imaging the camera characteristics translates as follows:

- **Quantum efficiency** combines to the grating efficiency of the spectrometer to give a total spectral range and efficiency of the instrument.
- **Pixel size**, translates into spectral resolution according to the spectral dispersion.
- **Exposure time** or frame rate, translate into spatial resolution according to the scanning speed.

The choice of a suitable camera for hyper spectral imaging is therefore often driven mostly by these three parameters.

3. SENSOR TECHNOLOGIES

CCD, EMCCD and CMOS are all silicon based detectors, as such are typically sensitive in the UV, visible

Authorized licensed use limited to: MIT Libraries. Downloaded on November 07,2022 at 19:09:54 UTC from IEEE Xplore. Restrictions apply.

and near infra-red areas of the spectrum. SWIR cameras are InGaAs focal plan arrays which as their name suggest are sensitive in the Short Wave Infra-Red area of the spectrum. Furthermore, each sensor technology has its own particularities:

- On a CCD, all pixels are read through one A/D output and the readout noise increases with frame rate but can be reduced by binning. Sensitivity, speed and spatial resolution are linked and subject to compromises and tradeoffs.
- On an EMCCD, the readout noise can be compensated by the electron multiplication gain before the A/D output. This makes EMCCD the most sensitive silicon based device and removes the link between sensitivity, speed and spatial resolution. Unfortunately, very few EMCCD chips are available on the market.
- With a CMOS, all pixels can be read simultaneously since each has its own A/D converter. This also removes the link between sensitivity, speed and spatial resolution. However, each pixel's A/D has slightly different offset, gain, and dark current characteristics which require a non-uniformity correction to emulate the image quality of a single output device. In addition, binning won't reduce the readout noise.

Table 1 below summarizes characteristics of cameras using these various sensor technologies

	CCD	EMCCD	CMOS	SWIR
Quantum Efficiency	50 to 90%	50 to 90%	50 to 70%	70% to 90%
Spectral Range	350-1000nm	180-1000nm	400-1000nm	400-1700nm
Pixel size	4.54µm	8-10µm	5.5µm	15-30µm
Resolution	Large, up to 9MP	Small, <1MP	Large up to 4MP	Very Small, <0.32MP
Exposure time	Very Long 1ms to hours	Long 1ms to min	Short 1ms to sec	Very Short 500ns to sec
Frame rate	6Hz	50Hz	50Hz	346Hz
Readout noise	low 3-7e$^-$	Very low <1e$^-$	low 7e$^-$	medium 50-150e$^-$
Dark current	Very low 10^{-6}e$^-$/p/s	Low 1e$^-$/p/s	Medium 9e$^-$/p/s	High 30,000e$^-$/p/s
Pixel well depth	Small 12,000e$^-$	Medium 30,000e$^-$	Small 12,000e$^-$	Large 170,000e$^-$

Table 1: typical characteristics of various sensor types

4. IRRADIANCE, ONE NORMALIZED VALUE

With so many parameters it can be difficult to estimate which camera to select in order to obtain the best possible performances for a given application. A few basic questions regarding the spectral range, spatial and temporal resolution required can already help to narrow down the choice.

For example, the choice of a suitable camera for hyper spectral imaging is therefore often driven mostly by these three parameters, QE, pixel size and exposure time. However, it would be useful to reduce all these parameters to a single one.

Noise Equivalent Power (NEP) is the minimum power that can be detected, measured in watts. It doesn't take into account the pixel surface area. It is usually used for photo detectors and normalized for one hertz output bandwidth or half a second integration time [5]. As such it is not a convenient parameter to compare cameras with widely different pixel size and covering a range or exposure time. The lower the NEP is, the higher the sensitivity.

Specific Detectivity (D*): is the reciprocal of the NEP normalized over the square root of the photosensitive area. It is expressed in cm√Hz/W or Jones [6][7], unlike the NEP the higher the specific detectivity is, the higher the sensitivity. However, it still doesn't reflect the wide range of possible exposure times.

Irradiance is the power of electromagnetic radiation per unit area (radiative flux) incident on a surface its SI unit is watts per square meter (W/m^2). The Noise Equivalent Irradiance (NEI) is the light flux density required to be equal to the noise of the camera. NEI is usually expressed in W/cm^2 or in $Photons/(cm^2 \cdot s)$[8].

The benefit of NEI is that it offers a single normalized quantity representing the sensitivity which can be calculated from the specifications provided by the manufacturer. The lower the NEI is, the higher the sensitivity will be.

The general noise equation is the following:

$$Noise_{total} = \sqrt{Noise_{readout}{}^2 + Noise_{darkcurrent}{}^2 + Noise_{shot}{}^2}$$

Since only the readout and dark current noises are camera dependent. We can define the NEI at a given wavelength as follows.

$$NEI(Photons/cm^2 \cdot s) = \frac{\sqrt{Noise_{readout}{}^2 + Noise_{darkcurrent}{}^2}}{Pixel\ Size \times Exposure\ time \times Quantum\ efficiency}$$

4.1. Numerical example:

For a 640x512 Vis-SWIR camera in High Gain mode at 1550nm, the typical values are the following:

- QE is 80% at 1550nm
- Pixel size is 15x15µm
- Full well capacity, 12,000 e$^-$
- readout noise is 50 e$^-$/pixel RMS;
- dark current is 2.5fA/pixel (at 15°C sensor temperature)

Authorized licensed use limited to: MIT Libraries. Downloaded on November 07,2022 at 19:09:54 UTC from IEEE Xplore. Restrictions apply.

Remembering that:

- $1C_{oulomb} = 1(A \cdot s) = 6.241\,509\,629\,152\,65 \times 10^{18}(e^-)$
- $Dark\ current(e^-) = Dark\ current(A) \times C$
- $Noise_{dark\ current} = \sqrt{Dark\ current}$

Using an exposure time of 33ms the NEI at 1550nm will be:

$$NEI = \frac{\sqrt{50^2 + \left(\sqrt{2.5 \times 6.241 \times 10^{15-18} \times 0.033}\right)^2}}{(15 \times 10^6)^2 \times 0.033 \times 80\%} \times 10^{-4}$$
$$\simeq 9.2 \times 10^8 \left(Photons/(cm^2 \cdot s)\right)$$

4.2. NEI conversion in W/cm^2:

In order to obtain the Noise Equivalent Irradiance in W/cm^2, we need to use the energy per photon which is determined by the wavelength according to the following relation:

$$E_{Photon}(J) = \frac{h \times c}{\lambda}$$

- Plank's constant h= 6.626 069 573×10^{-34} J·s
- Speed of light c= 299 792 458m/s

$$E_{Photon}(J) = \frac{6.626069573 \times 2.99792458}{\lambda(nm)} \times 10^{-34+8+9} \simeq \frac{1.986 \times 10^{-16}}{\lambda(nm)}$$

$$NEI(W \cdot cm^{-2}) = \frac{NEI\left(Photons/(cm^2 \cdot s)\right) \times 1.986 \times 10^{-16}}{\lambda(nm)}$$
$$\simeq \frac{9.2 \times 10^8 \times 1.986 \times 10^{-16}}{1550} \simeq 1.18 \times 10^{-10}(W \cdot cm^{-2})$$

5. CAMERAS SENSITIVITY COMPARISON

The NEI is a powerful way to compare wildly different cameras. Since the quantum efficiency is a function of wavelength and the dark current is a function of the exposure time, it is important to use the wavelength and exposure time of interest for the given application.

5.1. Silicon cameras

Table 2 and Figure 1 compare the NEI of typical EMCCD, CMOS and CCD at 550nm for exposure times ranging from 10ms up to about 15min.

EMCCDs are best for short exposure times (milliseconds) while CCDs are best for long exposure (minutes). For exposure times in seconds, all technologies are in a similar order of magnitude. Still the NEI allows for a precise comparison and ranking.

	EMCCD	CMOS	CCD
QE	47.3%	51.5%	78%
Pixel size (µm)	10	5.5	4.54
Full well capacity (e$^-$)	24,000	14,000	12,000
Readout noise (e$^-$/p)	<1	7	7
Dark current (e$^-$/p/s)	1	9	0.08
NEI (picoW/cm^2) @ 33ms	**38**	493	477
NEI (picoW/cm^2) @ 10s	1.6	2.7	**1.6**
NEI (picoW/cm^2) @ 15min	0.043	0.233	**0.027**

Table 2: Silicon based detectors NEI at 550nm

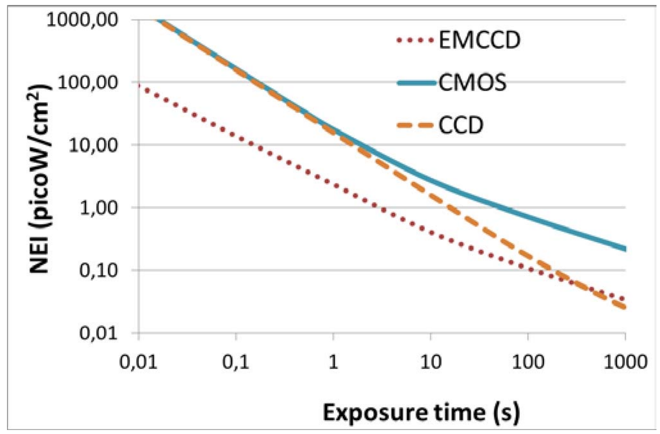

Figure 1: NEI of Silicon cameras at 550nm

5.2. InGaAs cameras

Table 3 and Figure 2 compare InGaAs FPA detectors NEI at 1550nm. Since the readout noise and dark current very large compared to silicon based detectors and are not compensated by the high QE and large pixel size. Long exposure times are also prohibited by the large dark current which fills up the full well capacity about one second. Notice how close all three cameras are despite the fact that the 640 Vis-SWIR has 4 times smaller pixels thanks to lower readout noise and dark current.

	320 SWIR	320 Vis-SWIR	640 Vis-SWIR
QE	72.9%	82.1%	80%
Pixel size (µm)	30	30	15
Full well capacity (e$^-$)	170,000	170,000	12,000
Readout noise (e$^-$/p)	150	150	50
Dark current (e$^-$/p/s)	190,000	190,000	15,000
NEI (picoW/cm^2) @ 33ms	100	**45**	118
NEI (picoW/cm^2) @ 0.5s	13	**11**	14

Table 3: InGaAs FPA detectors NEI at 1550nm

Authorized licensed use limited to: MIT Libraries. Downloaded on November 07,2022 at 19:09:54 UTC from IEEE Xplore. Restrictions apply.

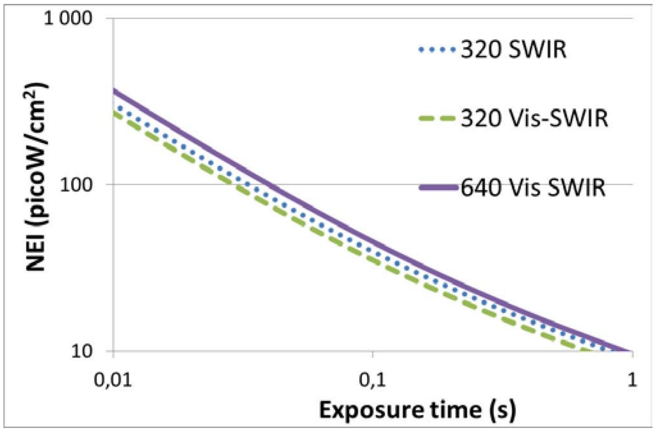

Figure 2: NEI of InGaAs cameras at 1550nm

5.3. General comparison

We can compare cameras equipped with Silicon and InGaAs FPA detectors, using wavelengths where both technologies are sensitive. Figure 3 represent the NEI vs Exposure time at 950nm. Of course, this wavelength puts the Silicon cameras at a disadvantage with much reduced quantum efficiency compared to InGaAs cameras. See Table 4 below

	QE	Pixel size (µm)	Readout noise (e^-)	Dark current (e^-/pixel/sec)
EMCCD	5.2%	8	<1	1
CMOS	8.9%	5.5	7	9
CCD	6.0%	4.54	7	0.08
320 SWIR	18.5%	30	150	190,000
320 Vis-SWIR	83.8%	30	150	190,000
640 Vis-SWIR	72.0%	15	150	15,000

Table 4: Sensor specification at 950nm

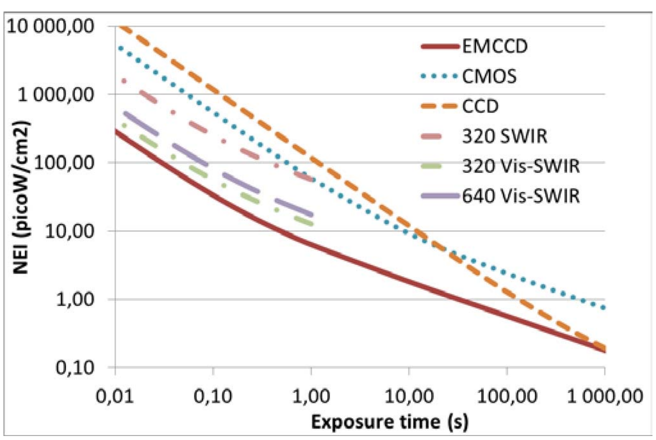

Figure 3: NEI of Silicon and InGaAs cameras at 950nm

From Figure 3, in the NIR up to one second exposure time, EMCCD is the most sensitive technology, followed by Vis-SWIR and SWIR cameras, finally, CMOS and CCD differentiate mostly through the difference in QE between otherwise very similar specifications.

6. CONCLUSION

Noise Equivalent Irradiance allows to precisely evaluate the sensitivity of wildly different cameras and to rank them for a given exposure time and wavelength. In the visible at short exposure time, EMCCD is the most sensitive technology followed by CCD and CMOS. In the NIR InGaAs cameras have the edge over CMOS and CCD while in the SWIR, InGaAs is still the only existing possibility.

6. REFERENCES

[1] Yuntao Qian ; Minchao Ye, "Hyperspectral Imagery Restoration Using Nonlocal Spectral-Spatial Structured Sparse Representation With Noise Estimation", *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, , Volume: 6 , Issue: 2 , Part: 2, 2013 , Page(s): 499 - 515*

[2] Lianru Gao ; Qian Du ; Bing Zhang ; Wei Yang ; Yuanfeng Wu, "A Comparative Study on Linear Regression-Based Noise Estimation for Hyperspectral Imagery", *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Volume: 6 , Issue: 2 , Part: 2, 2013 , Page(s): 488 - 498*

[3] Chen, C. ; Li, W. ; Tramel, E.W. ; Cui, M. ; Prasad, S. ; Fowler, J.E., "Spectral–Spatial Preprocessing Using Multihypothesis Prediction for Noise-Robust Hyperspectral Image Classification", *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Volume: 7 , Issue: 4, 2014 , Page(s): 1047 - 1059*

[4] Latorre-Carmona, P. ; Martinez Sotoca, J. ; Pla, F. ; Bioucas-Dias, J. ; Ferre, C.J., "Effect of Denoising in Band Selection for Regression Tasks in Hyperspectral Datasets", *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Volume: 6 , Issue: 2 , Part: 2, 2013 , Page(s): 473 - 481*

[5] P.L. Richards, "Bolometers for infrared and millimeter waves," *Journal of Applied Physics* **76**, 1 (1994), doi:10.1063/1.357128

[6] R. C. Jones, "Quantum efficiency of photoconductors," *Proc. IRIS* **2**, 9 (1957)

[7] R. C. Jones, "Proposal of the detectivity D** for detectors limited by radiation noise," *J. Opt. Soc. Am.* **50**, 1058 (1960), doi:10.1364/JOSA.50.001058

[8] Malacara, Daniel (1988). *Physical Optics and Light Measurements*. Academic Press. p. 247. ISBN 9780124759718.

Authorized licensed use limited to: MIT Libraries. Downloaded on November 07,2022 at 19:09:54 UTC from IEEE Xplore. Restrictions apply.