White paper

Comparison between SPAD and EMCCD cameras in low-light conditions

Maxime Berchet, Cyril Saudan, Michel Antolovic

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Introduction

Single-photon avalanche diode (SPAD) and electron-multiplying charge-coupled device (EMCCD) cameras are both important technologies in the field of imaging, each offering distinct benefits suited to specific applications. While EMCCD cameras are interesting due to their low dark current and their ability to amplify weak signals, SPADs offer extremely high readout speeds and are capable of detecting single photons, making them ideal for low-light and high-speed applications.

Understanding the differences and strengths is crucial for selecting the right tool for a given task. Besides having great capabilities in low-light conditions, SPADs also offer high dynamic range and high speed imaging not achievable with EMCCD technology. Finally, SPAD 512 features time gating to study time varying signals of interest, such as fluorescence lifetime imaging (FLIM), enabling molecule identification by their timing footprint. Such fields of applications are discussed in section *Applications of SPAD 512 cameras*.

One of the main challenges in single-photon camera development is the search for the best sensitivity of the camera, and its lowest noise, leading to a high signal-to-noise ratio (SNR) of the camera. The goal of this paper is first to demonstrate the capabilities of a SPAD camera (SPAD 512 [1]) in low light conditions, and to compare its SNR to an EMCCD camera. As a second step, the high-speed advantages of SPAD 512 will be discussed through a study of moving fluorescent beads.

Theory

The SNR is a key metric widely used in the context of imaging, and allows to determine whether the image is dominated by the signal of interest or by noise.

In the field of imaging, noise is defined as unwanted random variations or fluctuations in pixel values that obscure the true signal. These variations can arise from various sources and depend on the technology used to detect photons. We discuss the main noise sources below, and the impact they will have on the measurements with the SPAD 512 and the EMCCD camera:

- **Shot noise:** Also called **Poisson noise**, it is the inevitable noise source in every particle based measurement defined by $\sigma_{shot\,noise} = \sqrt{n_i}$ with n_i being the number of detected photons. The higher the sensitivity, the smaller the relative effect of shot noise on the SNR.
- **Dark noise:** It is the generation of carriers without incident light, due to thermal effects. SPAD 512 typically produces 10 counts per second (cps) of dark noise (at room temperature) whereas the EMCCD camera used for the comparison produces a dark current of 0.0003 e-/pix/sec (cooled at -80°C).
- **Readout noise:** As SPADs use a direct photon to digital transformation, their readout noise is irrelevant because the pulse amplitude is usually 10000 higher than the readout noise [2]. Read noise of EMCCD is also close to zero: while the sensor does have a read noise, the electron multiplication step boosts the signal before the readout, reducing the readout noise from 89 e- to 1 e-.
- **Clock induced charged noise:** This noise occurs only in EMCCD cameras. It arises from unwanted charge generation during the clocking process, which can be seen as spurious spikes in the image, particularly at high EM gain. While this noise is masked in standard CCD's by other noise sources like readout and thermal noises, it becomes significant in EMCCDs due to the EM gain, especially in low-light conditions.
- **Excess noise:** The electron multiplication in EMCCD cameras creates an excess noise factor of approximately 1.4 (square root of 2) over a wide range of gain levels.

The specifications of the two cameras that are compared in the section below are shown in table (1).

	EMCCD camera	SPAD 512
Sensor size	8.2 mm	8.4 mm
Resolution	512 × 512 px	512 × 512 px
Pixel active area size	16 µm × 16 µm	16 µm × 16 µm
Peak QE (at 520nm)	95%	50%
Excess noise factor	1.4	x
Readout noise	89 e-	0
Median dark noise	0.00030 e-/pix/sec	10 cps
Maximum frame rate		
1 bit	x	100'000 fps
5 bits	x	6'500 fps
10 bits	x	400 fps
12 bits	x	100 fps
16 bits	56 fps	x
Minimum integration time		
1 bit	x	0.02 µs
5 bits	x	0.32 µs
10 bits	x	5 µs
12 bits	x	20 µs
16 bits	100 µs	x

Table 1: Specifications of the two cameras.

SNR calculation method: Finally, we present here the method for computing the ***SNR*** [3]. The process is the following: 100 images are taken with illumination from the signal of interest. Maps of the mean intensity ***I*** and their standard deviation ***STD*** are computed. Then 100 images are taken with no incoming light to compute the mean bias ***B***. This way, the real part of the signal of interest ***I-B*** can be found. The ***SNR*** is then defined by the following equation:

$$SNR = \frac{I - B}{STD}$$

Results and discussion

Experiment A consists of illuminating both cameras with a green light signal, leading to homogeneous intensity of light on the whole camera. Technical details are given in the section ***Experimental setup***.

Results are shown in Figure (1). With low gain (20), the EMCCD's SNR drops for low-light applications because of its readout noise (5.5 e- according to simulated data). Once the EM gain is increased to 50 and 100, the readout noise decreases to ~1 e-, becoming competitive with SPAD 512 at low-light exposures. However, increasing the EM gain results in a much lower dynamic range, as the effects of saturation of the camera can be observed around 5,000 incident photons for a gain of 50, and at only 2,000 incident photons for a gain of 100.

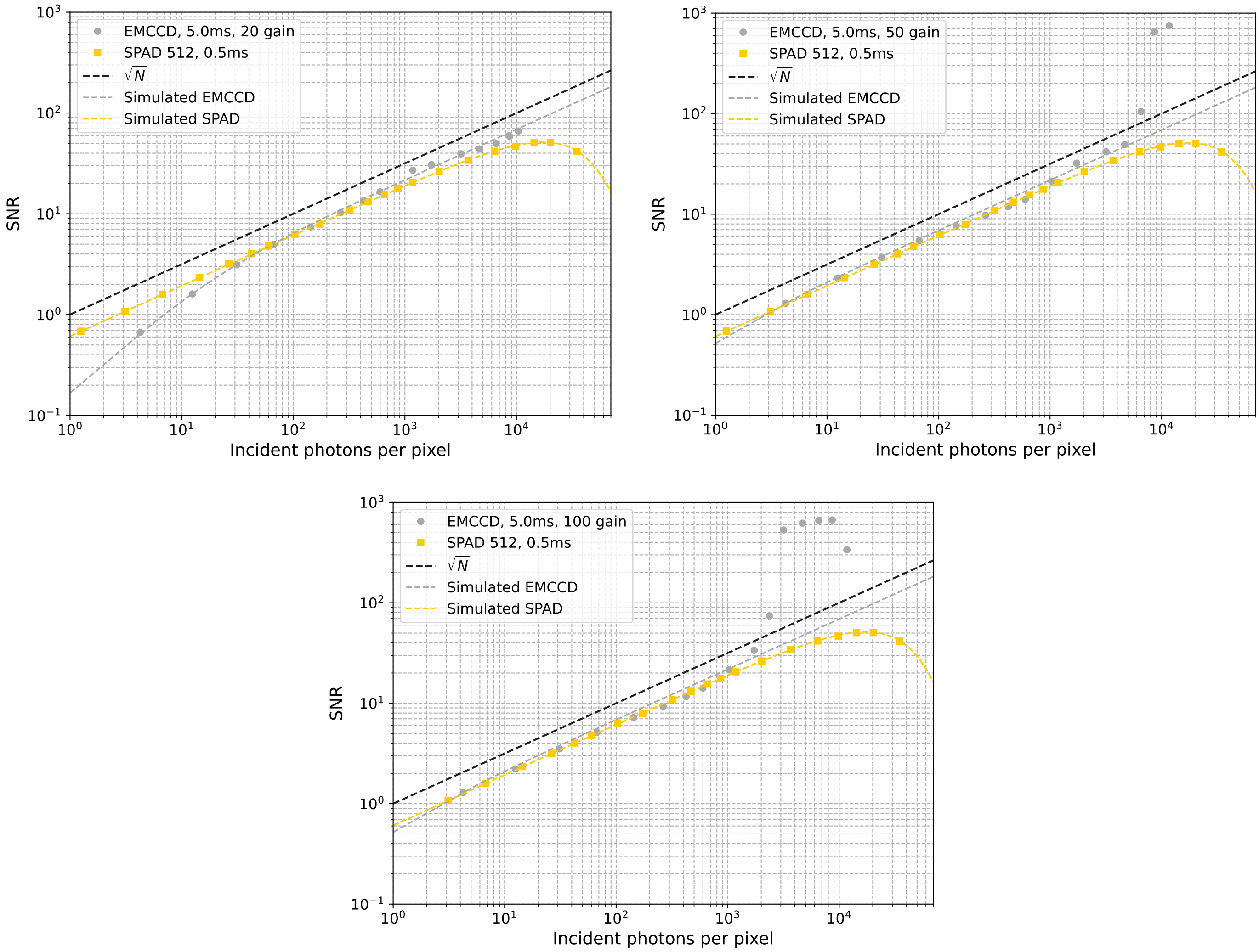

Figure (1): SNR comparison between EMCCD camera and SPAD 512, using 3 different gains for EMCCD (20, 50 and 100). Grey and yellow dashed lines correspond to the simulated response from both technologies. Readout noise for simulated EMCCD is 5.5 e- for a gain of 20, and 1.2 e- for gains of 50 and 100.

Despite the higher sensitivity, the EMCCD camera offers comparable SNR due to the excess noise of its EM process, effectively lowering the sensitivity by 2×. In contrast to EMCCD, the SPAD 512 offers intrinsic single-photon sensitivity with negligible readout noise, without requiring any gain adjustment. It thus maintains excellent SNR at low light levels without compromising its dynamic range. This makes SPAD 512 especially well-suited for scenes with variable lighting conditions, where both low-light performance and the ability to capture bright features are critical. Additionally, the SPAD 512 benefits from faster readout and photon timing capabilities, further extending its applicability in advanced imaging scenarios where temporal resolution is key.

Experiment B is the study of moving fluorescent beads with both cameras. The goal is to show how SPAD 512 can be beneficial for studying dynamic scenes such as single-molecule tracking or rapid biological process. Technical details are given in the section ***Experimental setup***.

Figure (2) show the comparison between the EMCCD camera and SPAD 512 when fluorescent beads are moving on a mechanical stage. While blurry images are observed for the EMCCD camera, due to a maximum frame rate of 56 fps, the high-speed capabilities of SPAD 512 allow to very easily keep track of the beads, reaching a frame rate of 1’600 fps for 8-bit images in this case. This speed can reach 6’500 fps for 5-bit, and 100’000 fps for 1-bit.

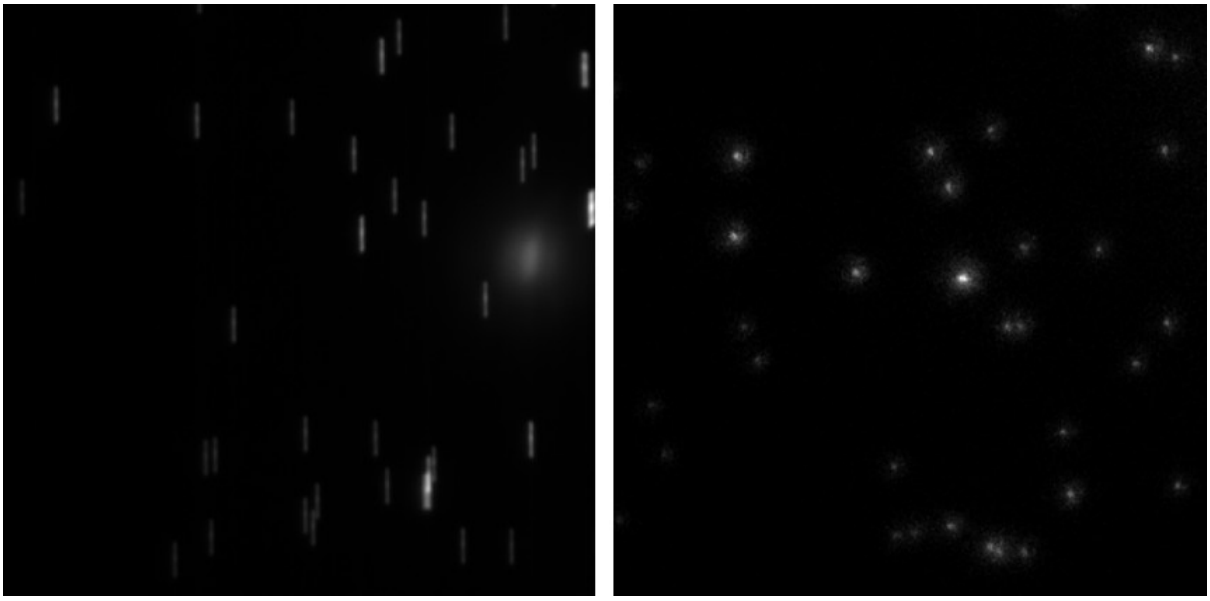

Figure (2): Images of moving fluorescent beads with EMCCD camera (56 fps) and SPAD 512 (1’600 fps).

Experimental setup

This section describes the parameters and conditions of the two experiments that compare SPAD 512 and EMCCD cameras. Here are some common parameters for both experiments. Both cameras were observing the same field of view and getting the same incoming light. A pile-up correction is used for the SPAD 512: since the camera has a non-linear response to light, the actual number of detected photons N_{actual} is higher than the number of photons measured $N_{measured}$. This effect is only noticeable for higher photon count rates, but the pile-up correction restores the linearity, transforming the measured amount of photons into the amount of photons that the SPAD detected [4], thanks to the following equation:

$$N_{actual} = -\ln\left(1.0 - \frac{N_{measured}}{2^{bitdepth} - 1}\right) \times \left(2^{bitdepth} - 1\right)$$

Thanks to this correction, an original counter bit depth of 10 will allow the SPAD 512 camera to count up to 7’098 photons instead of 1’024 after pile-up correction, thus increasing the bit depth to 12. Our 15-bit mode allows for a dynamic range up to 90 dB.

Experiment A: In the first experiment, both cameras are illuminated through a microscopy setup by homogeneous light coming from a reflected laser source shining at 520nm. A 5 ms and 0.5 ms integration time is used with the EMCCD and SPAD 512, respectively. 3 different gains were used with the EMCCD camera: 20, 50 and 100. Increasing the power of the laser, the number of incoming photons increases. To compute SPAD 512 incident photons I_{512}, we simply divide the number of detected photons by the PDE of the system. Then, as both cameras are exposed to the same light intensity, EMCCD’s incident photons I_{EMCCD} are computed using $I_{EMCCD} = I_{512} \times \frac{t_{EMCCD}}{t_{512}}$, where t_{EMCCD} and t_{512} are the integration times of the EMCCD camera, respectively SPAD 512.

The EMCCD camera is working under 16-bit mode, while the SPAD 512 is working with 12-bit mode (equivalent 15-bit mode after pile-up correction).

Simulated SNR curve for the EMCCD camera SNR_{EMCCD} in figure (1) is given by the following formula:

$$SNR_{EMCCD} = n \cdot PDE_{EMCCD} / \sqrt{(\kappa^2 \cdot n \cdot PDE_{EMCCD} + \sigma^2)}$$

where n is the number of incident photons, κ is the excess noise factor and σ is the readout noise. At low photon levels, the readout noise dominates, limiting the SNR. At higher light levels, the impact of readout noise becomes negligible, and the excess noise factor becomes the main limiting factor. κ is set to 1.4 and σ is set to 5.5 e- for a gain of 20, and is set to 1.2 e- for a gain of 50 and 100.

The simulated SNR curve used for SPAD 512 is described in [5].

Experiment B: For the second experiment, fluorescent beads are observed while moving on a mechanical stage. The beads are microspheres of diameter 0.175 µm shining at 550 nm after excitation by the laser. Both cameras work at their maximum frame rates for the used bitdepth: 56 fps in 16-bit mode for the EMCCD, 1’600 fps with 8-bit mode with SPAD 512.

Applications of SPAD 512 cameras

Here are a few examples of fields of applications SPAD 512 is suitable for.

Research: For biomedical imaging, in fluorescence microscopy and in vivo imaging, SPAD cameras can detect weak fluorescence signals with high SNR, allowing researchers to visualize and study cellular and subcellular processes with exceptional detail. In quantum imaging and quantum cryptography, SPAD cameras play a crucial role in detecting individual photons and quantum states, enabling experiments in quantum communication and quantum computing.

Fluorescence lifetime imaging: FLIM is an advanced imaging technique that reveals both the structure and dynamic behavior of fluorescent samples. SPAD arrays eliminate pile-up, a limitation requiring conventional, point-scanning, FLIM detectors to have a 10% detection rate with respect to the laser repetition rate. Due to conventional instrumentation dead time, early photons are more likely to be detected and late photons are ignored, leading to a systematic error. SPAD arrays push this limitation by spreading photons to multiple pixels, thus allowing for more likely detection of late photons.

High-speed imaging: The high quality of today's digital cameras can quickly deteriorate in challenging conditions such as low light or fast motion. Single-photon avalanche diode (SPAD) image sensors address these challenges with zero read noise and the ability to detect individual photons with precise timing, enabling clearer and more accurate images even in low-light conditions. Finally, to resolve the tradeoff between image blur and image noise, an image burst is captured, collecting images with single photon precision and then correcting for movement occurring either in the scene or by the camera.

Learn more: https://piimaging.com/spad-512/

Conclusion

Whether in research or industry, the need for low-light and high-speed imaging is crucial in several advanced applications. The signal-to-noise ratio (SNR) is a critical metric for evaluating the performance of single-photon imagers. An analysis of the different types of noise present in SPAD and EMCCD cameras and experiment 1 revealed that SPADs demonstrated superior SNR values under low-light conditions, when using low gain with the EMCCD. Increasing this gain allows the EMCCD camera to remove its readout noise, but leads to a tradeoff with its dynamic range.

While EMCCD cameras offer high sensitivity and are effective in amplifying weak signals, SPAD cameras excel in specialized applications that demand exceptional low-light performance and high-speed capabilities. The second experiment highlighted that SPAD 512 can achieve high-speed imaging, outperforming EMCCD technology in scenarios requiring rapid and precise detection. Finally, the inclusion of time gating in SPAD 512 makes it well-suited not only for widefield, video-rate FLIM and accurate time-resolved imaging, but also for applications such as biomedical imaging, quantum computing, and various industrial uses where traditional cameras may fall short.

References

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About
Pi Imaging Technology

Pi Imaging Technology is fundamentally changing the way we detect light. We do that by creating photon-counting arrays with the highest sensitivity and lowest noise.

We enable our partners to introduce innovative products. The end-users of these products perform cutting-edge science, develop better products and services.

Pi Imaging Technology bases its technology on 11 years of dedicated work at TU Delft and EPFL. The core of it is a single-photon avalanche diode (SPAD) designed in standard semiconductor technology. This enables our photon-counting arrays to have an unlimited number of pixels and adaptable architectures.

Pi Imaging Technology
Bâtiment C
EPFL Innovation Park
1015 Lausanne
Switzerland
info@piimaging.com
www.piimaging.com