White paper

Comparison between SPAD and sCMOS cameras in low-light conditions

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Introduction

Single-Photon Avalanche Diodes (SPADs) and sCMOS cameras are both essential tools in the field of imaging, each offering unique capabilities suited to different applications. Understanding their differences and strengths is crucial for selecting the right tool for a given task. While sCMOS cameras are interesting due to their versatility, low cost, and high resolution, SPADs are capable of detecting single photons, making them ideal for low-light and photon-counting applications. Besides having great capabilities in low-light conditions, SPADs also offer high dynamic range, and high speed imaging. Fields of applications are discussed in section ***Applications of SPAD512² cameras***.

One of the main challenges in single-photon camera development is the search for the best trade-off between the sensitivity of the camera, and its noise. To reach this best trade-off is to reach the best signal-to-noise ratio (SNR) of the camera. This SNR quantifies and compares the strength of the desired light signal to the background noise. It is a critical metric in imaging: high SNR indicates that the signal of interest is strong relative to the noise, resulting in clear and accurate image representation.

The goal of this paper is to demonstrate the capabilities of a SPAD camera (SPAD512² [1]) in low light-conditions, and to compare its SNR to a scientific sCMOS camera. Several parameters have an impact on the evolution of the SNR as function of the intensity of incoming light: they will be discussed and analysed in this paper.

Theory

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

In the field of imaging, the noise is defined as the 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 SPAD512² and the sCMOS 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. Its contribution will be the same for both SPADs and sCMOS cameras.
- **Readout noise:** When a photon is detected by a sCMOS or a SPAD camera, it interacts with the semiconductor material, typically silicon, causing the generation of electron-hole pairs through the photoelectric effect. Then, the process of amplifying electrical charge generates noise called readout noise. Readout noise is due to shot, thermal, and 1/f noise of charge amplifiers and output amplifiers. If high frame rates are needed, thermal noise from the source follower acting as the charge amplifier is the major readout noise source. sCMOS implements charge amplification within the pixel and column parallel readout. 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]. In contrast, the sCMOS camera used in the following comparison has a readout noise of 1.38 e^-. This is the main advantage of SPAD technologies over other cameras in low-light conditions.
- **Dark noise:** It is the generation of carriers without incident light, due to thermal effects. SPAD512² produces 24 counts per second (cps) of dark noise whereas the sCMOS camera used for the comparison produces 7.4 cps.

The specifications of the two cameras that are compared in the section below are shown in table (1). Due to the readout noise of the sCMOS camera, we expect to get a higher SNR with the SPAD512² camera in low-light condition.

	sCMOS camera	SPAD512^2
Sensor size	9.2 mm	8.4 mm
Resolution	812 × 620 px	512 × 512 px
Pixel active area size	9.0 µm × 9.0 µm	6 µm × 6 µm
Peak QE (at 530nm)	73 %	50 %
Readout noise	1.38 e^-	0
Median dark noise	7.4 cps	24 cps
Maximum frame rate		
1 bit	x	100,000 fps
5 bits	x	6,500 fps
10 bits	166 fps	400 fps
12 bits	140 fps	100 fps
Minimum integration time		
1 bit	x	0.02 µs
5 bits	x	0.32 µs
10 bits	14 µs	5 µs
12 bits	14 µs	20 µs

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: 200 images are taken with illumination from the signal of interest. Maps of the mean intensity I and their standard deviation STD are computed. Then 200 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 is the comparison of USAF target images with increasing intensities of light. Details of the set-up are given in section ***Experimental setup***. Figure (1) shows the images taken by both cameras.

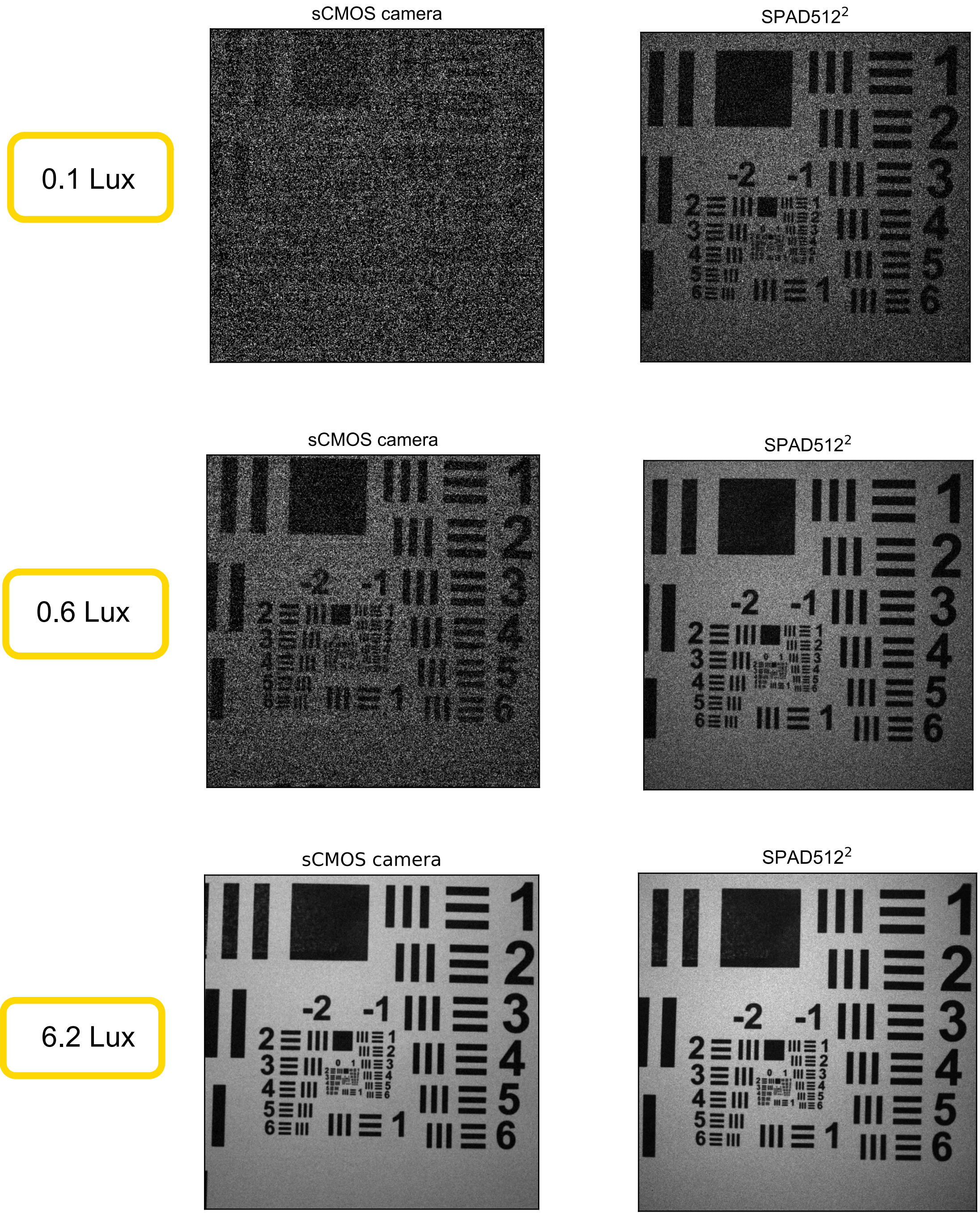

Figure 1: sCMOS camera vs SPAD512² with increasing light conditions.

As a reference:

- 0.1 Lux corresponds to the illuminance perceived during a full moon on a clear night. For this intensity of light, black and white parts of the images are almost non-distinguishable with the sCMOS camera, while the numbers can be clearly seen with the SPAD512².
- 0.6 Lux could correspond to the light from a television screen in a dark room. One can notice that the sCMOS camera image is still more noisy than the one taken with the SPAD512².
- 6.2 Lux could be compared to the situation of twilight under a clear sky. At this intensity, images from both cameras seem to be of similar quality.

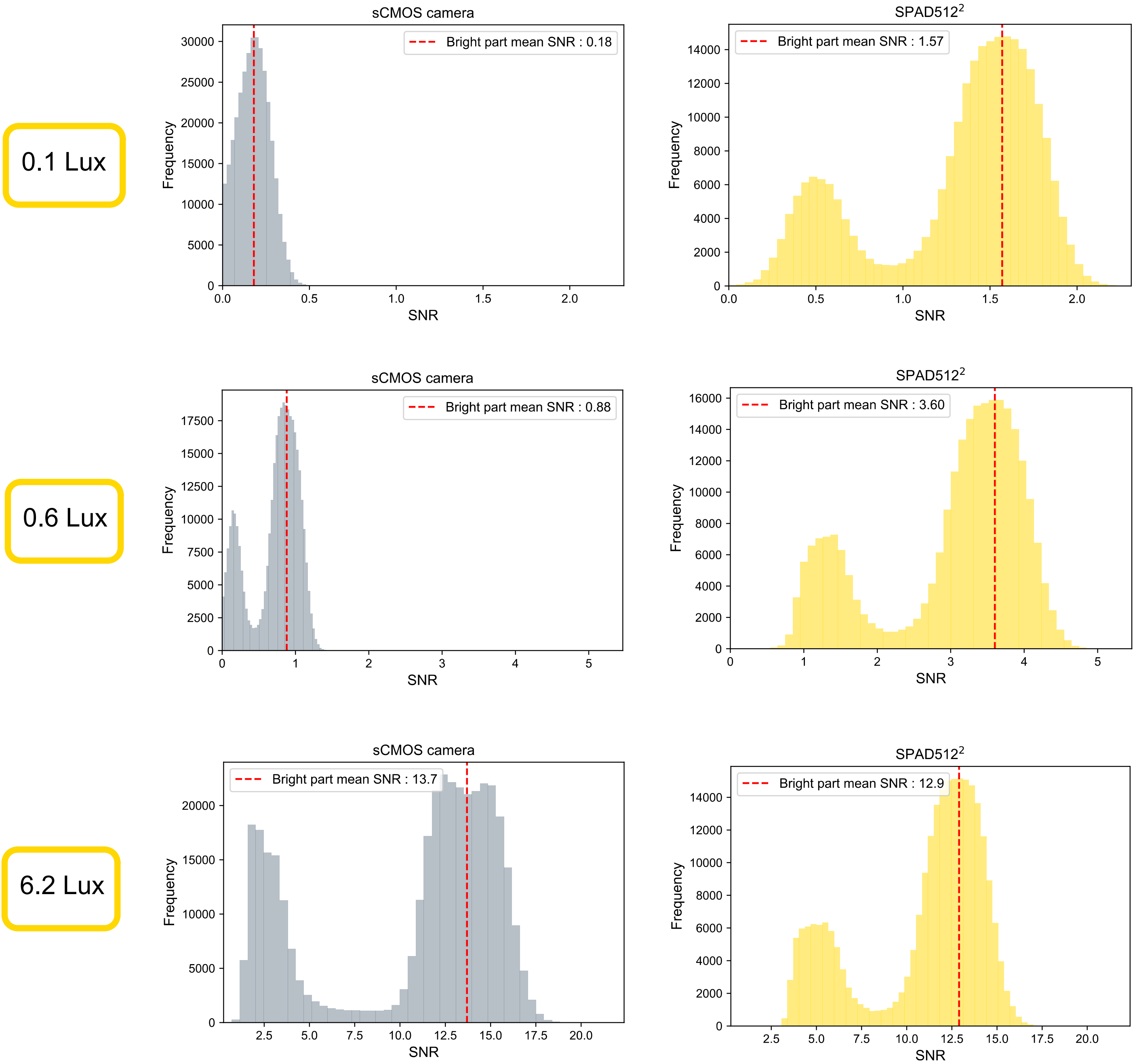

Figure 2: Resulting SNR from the images of figure (1), with sCMOS camera and SPAD512². The value given for the mean SNR is the mean value of the SNR for the white parts of the image (i.e. the 2nd peak), showed by the red dashed line.

These images are consistent with the SNR values computed and shown in figure (2). Histograms are directly computed from the images above.

Two peaks of SNR are present for each SNR histogram, except for the sCMOS with 0.1 Lux. These two peaks correspond to the black and white parts of the USAF target image. The fact that one cannot distinguish the black and white parts of the sCMOS image at 0.1 Lux is then consistent with this one-peak histogram.

For 0.1 and 0.6 Lux, we clearly see a better SNR for the SPAD512² camera. Then for the last image, at 6.2 Lux, the histograms show SNR peaks at similar values: 13.7 for the sCMOS camera, 12.9 for the SPAD512².

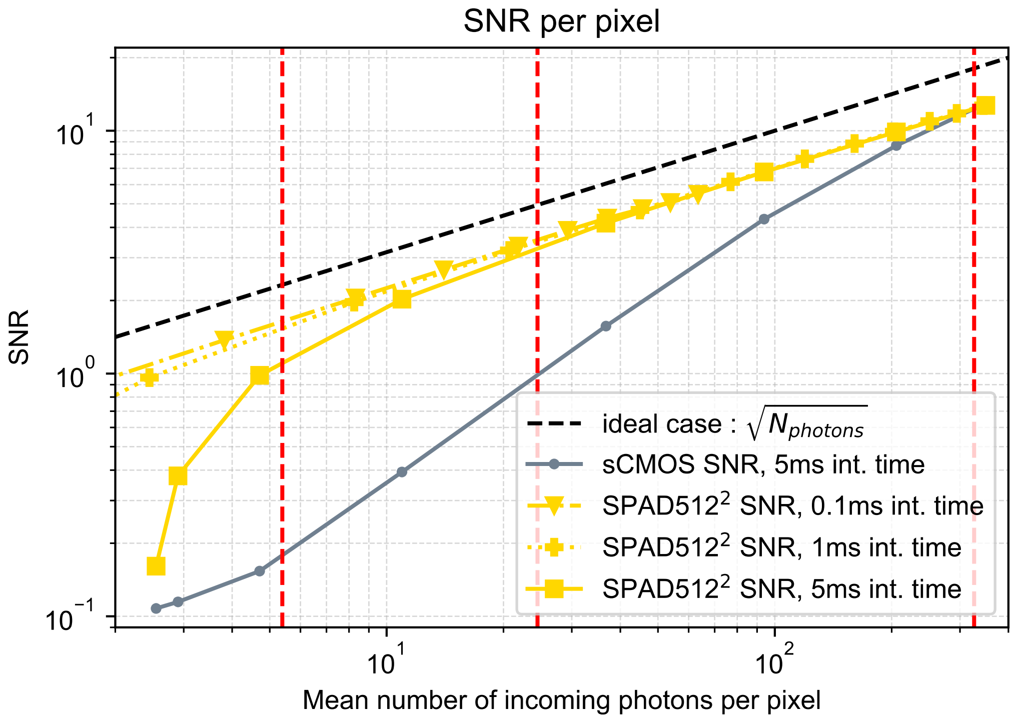

Figure 3: SNR comparison between sCMOS camera and SPAD512². The 3 red lines corresponds to similar incoming photons per pixel as the images of figure (2) taken with 0.1, 0.6 and 6.2 Lux.

Experiment B consists of putting both cameras in front of a diffused green LED, leading to homogeneous intensity of light on the whole camera. Once again, technical details are given in the section ***Experimental setup***.

Results are shown in figure (3). As expected, the SPAD512² camera presents higher SNR values in low-light conditions, in particular because of the readout noise of the sCMOS camera. Until 300 impinging photons on the SPAD/sCMOS, SPAD512² offers a better SNR value than the sCMOS camera.

Experimental setup

This section describes the parameters and conditions of the two experiments that compare SPAD512² and sCMOS cameras. Here are the parameters that are common for both set-ups. The illumination source is a green LED (530 nm). To do a fair comparison between the two cameras, as the sensor sizes are different, the integration times must be adapted. The pixel pitch of the sCMOS sensor is 9.0 µm × 9.0 µm, while the SPAD's pixel active area is 6 µm × 6 µm. This ratio is then taken into account in the following calculation: if $t_{SPAD\,512^2}$ is the chosen integration time of the SPAD512², then the integration time t_{sCMOS} of the sCMOS camera is given by the following equation:

$$t_{sCMOS} = \frac{Area\,SPAD}{Area\,sCMOS} \cdot t_{SPAD\,512^2} = \frac{6^2}{9^2} \cdot t_{SPAD\,51\,2^2}$$

This way, we ensure that for the same illumination conditions, the number of photons that hit the sCMOS/SPAD is the same. For both experiments, $t_{SPAD\,512^2} = 5$ ms and $t_{sCMOS} = 2.2$ ms. A gain of 30 was used for the sCMOS camera. Finally, a bit depth of 12 bits was used for the sCMOS camera. A pile-up correction for the SPAD512² was applied: 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 SPAD512² camera to count up to 7098 photons instead of 1024 after pile-up correction, thus increasing the bit depth to 12. Our 14-bit mode allows for a dynamic range up to 90 dB.

Experiment A: Both cameras were put in front of a USAF target, illuminated by the green LED. Images were taken with increasing LED intensities. To obtain a similar field of view, the sCMOS images were cropped by taking 612 × 612 pixels.

Experiment B: Both cameras were put directly in front of the diffused green light, leading to homogeneous intensity of light on the whole camera. In this experiment, the sCMOS images were cropped by taking 512 × 512 pixels, the same number of pixels as the SPAD512².

Applications of SPAD512² cameras

Here are a few examples of fields of applications SPAD512² 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 visualise 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.

Surveillance: SPAD cameras excel in scenarios requiring high-speed and low-light imaging, such as night vision surveillance, perimeter security, and object tracking. Their fast response time allows for rapid capture of moving objects, minimising motion blur and ensuring clear image acquisition in dynamic environments.

Automotive: Tracking moving scenes under low light conditions require a high SNR at low light conditions coupled with high frame rate capability. SPAD cameras reduce its main noise component (dark counts) while imaging faster. In contrast, sCMOS camera increase the readout noise at higher frame rates [5].

Conclusion

The challenge of imaging under low-light conditions is the battle between detecting a signal of interest that can be very weak, against all sorts of noise components. The Signal-to-Noise Ratio is an important value to understand the capabilities of single-photon imagers. The analysis of the different types of noise that are present in SPADs cameras or sCMOS cameras led to the following result: SPADs showed better SNR values under low-light conditions, mostly thanks to the absence of readout noise in SPAD512². Figure (3) showed an SNR more than 6 times higher for SPAD512² than for the sCMOS camera.

While sCMOS cameras offer general-purpose imaging capabilities suitable for a wide range of applications, SPAD cameras provide specialised functionality for demanding low-light and photon-counting scenarios where traditional cameras fall short. Therefore, SPAD512² excels in applications like biomedical imaging, quantum computing, or surveillance in low-light conditions.

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.

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