APDCAM Setup Considerations for Optimal Signal to Noise Ratio

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The APDCAM family of detector cameras is not off-the-shelf product but are built considering the needs of each individual customer and their applications. This document describes considerations for achieveing an optimal Signal to Noise (SNR) ratio at the planned input light intensity.

Noise sources

During the measurement process in which the input light is converted to the digitized signal several noise sources are present:

- **Photon statistics.** The incoming light radiation arrives in photons each having $h\nu$ energy, where h is Planck's constant and ν is the frequency. Collecting N photons in a given time the photon statistical noise of N will be $\sqrt{N}$, provided N is much larger than 1. This means the SNR of the measurement will be $1/\sqrt{N}$. The number of collected photons is affected by the Quantum Efficiency (QE) of the detector, which gives the probability (in %) of detecting a photon. From the above it is clear that SNR is proportional to $1/\sqrt{QE}$. Photon statistical noise has a flat frequency spectrum it has the same power at all frequencies.
- **Detector noise.** Detectors convert the incoming photons to electrons thus producing an electric current. Some detectors multiply the number of electrons and this multiplication process (internal gain) has some statistical noise. The amount and nature of the noise depends on the detector technology but often this noise is indistinguishable from the photon statistical noise, therefore the result can be considered as a decreased effective QE. The detector gain is typically dependent on temperature, therefore the temperature of a detector with internal gain should be kept constant, which is a standard feature of APDCAMs.
- **Dark current.** The detector might produce a finite output electron current even at zero input light. This current consists of electrons and, similarly to the photons, the number of electrons is also subject to statistical fluctuations. The amount of the dark current depends on detector technology but typically it can be reduced by cooling the detectors.
- **Amplifier noise.** The current from the detector is amplified and converted to voltage to be measured by the Analog to Digital Converter (ADC). Generally for detectors with higher internal gain lower gain amplifier is needed which produces less noise. The amplifier has several noise sources:
    - **Voltage noise.** This noise produces a frequency dependent noise spectrum. Without going into detail it can be stated that the voltage noise is increased at high frequency if the detector has higher capacitance. This is called *noise gain*.
    - **Resistor noise.** The current sensing resistor has thermal current noise which might be important if the detector current is comparable to it.
    - **Current noise.** The amplifier might have a current noise which adds to the detector current. In most APDCAM devices the current noise is negligible.

  - **Pick-up noise**. Radio waves, power lines and other laboratory equipment generate electric and magnetic fields which might couple to the low detector signal. APDCAM has multiple shielding layers against environmental noise but improper grounding, power connection or strong sources around the detector might cause some additional noise. Often these noises appear at distinct frequencies (e.g. 50Hz). Please consider the proposed grounding scheme in the APDCAM User's Guides.
- **Digitizer noise.** The ADCs convert the amplified detector signal to numbers. The standard resolution of the APDCAM ADCs is 14 bits, meaning the SNR resulting from finite resolution is over 10^4, typically much higher than the SNR from other noise sources. However, if the signal is very low and/or the resolution is reduced to 8 bits to increase the maximum sampling frequency the digitizer noise might appear in the finite SNR.

Most of the above noise sources generate flat power spectrum. In this case reducing the bandwidth of the amplifier increased SNR as $1/\sqrt{BW}$. This can also be done in the computer after the measurement, thus it makes no sense to reduce the bandwidth of the amplifier. However, in some cases the reduction of the bandwidth offers additional possibilities for optimizing the amplifier noise, therefore in such cases Fusion Instruments will propose a reduced amplifier bandwidth.

Choices for optimizing SNR in APDCAM

The above noise sources can be affected by the choice of components and settings of APDCAM. In most cases the best result is achieved by balancing various factors while keeping in mind the expected input photon flux and the desired bandwidth. In this section were consider the most important choices and their consequences.

- **Detector QE vs detector and amplifier gain.** Higher QE would be optimal in each case but often high QE is coupled to low detector gain. If the light level and detector gain is low the amplifier noise might dominate and a detector with higher internal gain but lower QE might give better SNR. The most often used detector in the APDCAM family is the 4x8 pixel S8555-02 Avalanche Photodiode Detector (APD) from Hamamatsu. It has over 80% Quantum efficiency in most of the visible spectrum while still offering reasonably high efficiency in the UV and near infrared. The internal gain is up to 150 and it can be changed continously between 1 and 150 by changing the bias voltage. .

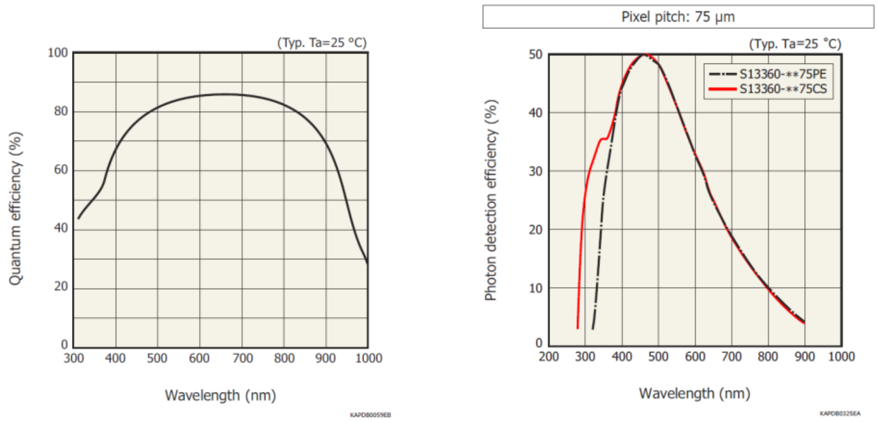


Fig. 1. Quantum efficiency of the S8850-02 APD detector and a typical MPPC.
(Source: Hamamatsu detector datasheets.)

An alternative is to use a Multi Pixel Photon Counting (MPPC) device which has lower QE, especially in the red part of the spectrum, but its gain is 10^6-10^7. On the other end of the gain scale are the photodiodes where the gain is unity and the QE is typically high. APDCAM can be equipped with all 3 types of detectors, Fusion Instruments can provide the detector type and arrangement matching the application need. The table below gives some guidelines for detector choice for APDCAMs operating in the 100 kHz-1 MHz bandwidth range. This in formation should be considered as illustration, the final detector choice might depend on other factors as well.

Input photon flux [ph/s]	Recommended detector type
$<10^8$-10^9	MPPC
10^8-10^9 $<$ 10^{11}-10^{12}	APD
10^{11}-10^{12} $<$	Photodiode

Please see typical SNR *vs* light flux curves in the next section.

- **Bandwidth vs. detector gain**
  If the light flux is sufficientyly high the noise is dominated by photon statistical noise. Reducing the light flux the effect of the amplifier noise appears. At this point the amplifier gain can be increased at the expense of a reduced bandwidth. In such cases it is essential to select the bandwidth to the minimum which fulfills the requirements so as to maximize the SNR.

- **Detector gain vs. light flux.** If the noise is dominated by the amplifier noise it is good strategy to increase the detector gain. However, as soon as the photon statistical noise dominates further increase of the detector gain just increases the detector noise, thus the SNR decreases. This means the detector gain should be increased only to the point where photon statistical noise dominates over amplifier noise. APDCAM can have up to 4 detector voltage generators, thus blocks of detectors can be driven from different voltage. The gain can be set differently for pixels receiving different light flux.

- **The role of detector temperature.** If the detector dark current is negligible the detector temperature does not play a role, it just changes the detector gain at a certain detector voltage. However, if the dark current is significant and its statitical noise plays a role in the SNR decreasing the detector temperature decreases the dark current statistical noise, thus improves the SNR. This situation is not typical and APDCAM is not prepared for cooling the detector below the condensation point. A separate whitepaper discusses the effect of reduced temperature operation in APDCAM.

From the above factors the amplifier gain, bandwidth and sensitivity is set at factory and cannot be changed by the user. The detector gain and the detector temperature can be changed by software control at any time.

Typical SNR curves

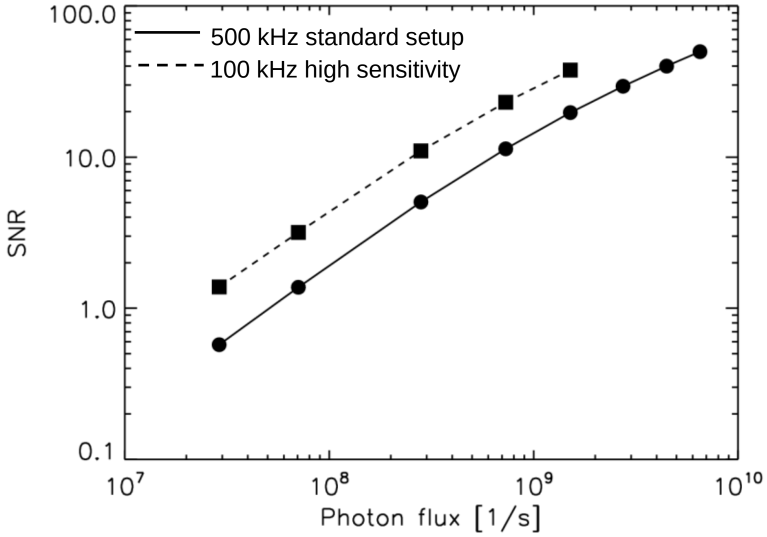
This section compares the APDCAM SNR as a function of light for different configurations. The presented situations should be considered as typical examples which illustrate the effect of different options.

These measurement were done in a test APDCAM where different detectors and different amplifier settings were used.

APD detector with different bandwidth and gain

Fig. 2. compares the standard 500 kHz APD amplifier setup at a detector gain of 120 and 25 C detector temperature to a reduced bandwidth setup optimized to yield optimal SNR at low photon flux. In the reduced bandwidth setup the noise is affected by the dark current, therefore cooling the detector further improves SNR. At the low light part of the curve the SNR changes proportionally to the light flux as the SNR is dominated by the fixed amplifier noise. At the highest photon fluxes the dependency becomes close to the square root of the light flux which indicates that photon statistical noise dominates.

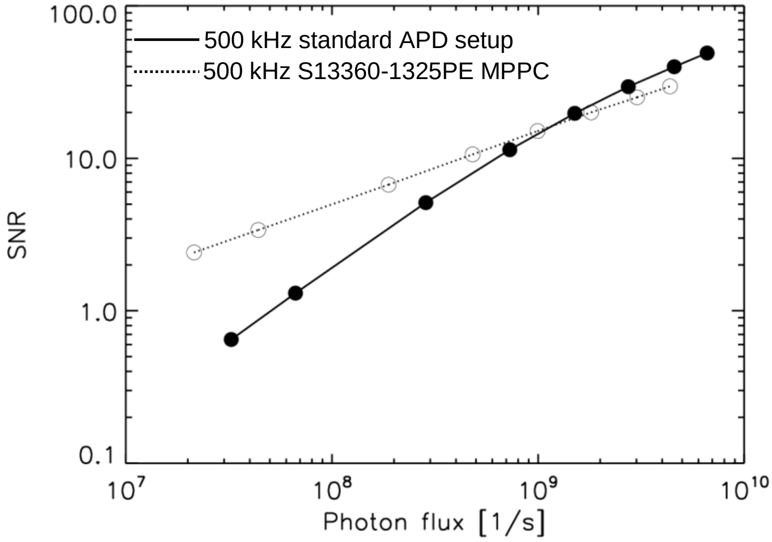
Fig. 2. Comparison of two amplifier settings for the S8550 APD matrix.



Comparison of APD and MPPC

APD detectors have limited (50-150) gain, therefore below a certain photon flux the fixed amplifier noise dominates the noise and the SNR is proportional to the light flux. An MPPC has much higher gain (10^6-10^7) therefore the amplifier noise becomes negligible and the photon statistical and detector noise dominates. This means square root dependency on the light flux. As a result at low light flux the MPPC has significantly higher SNR. In contrast to this at high light intensity, where the photon noise dominates the APD noise as well, the latter has higher SNR due to the higher QE. It has to be noted that the QE of the MPPC is strongly dependent on the wavelength (see *Fig.1*) , therefore at shorter wavelength the crossing point of the APD and MPPC curve shifts to higher photon flux.

Fig. 3. Comparison of 500 kHz APD with gain 120 and an MPPC around 660 nm light input.

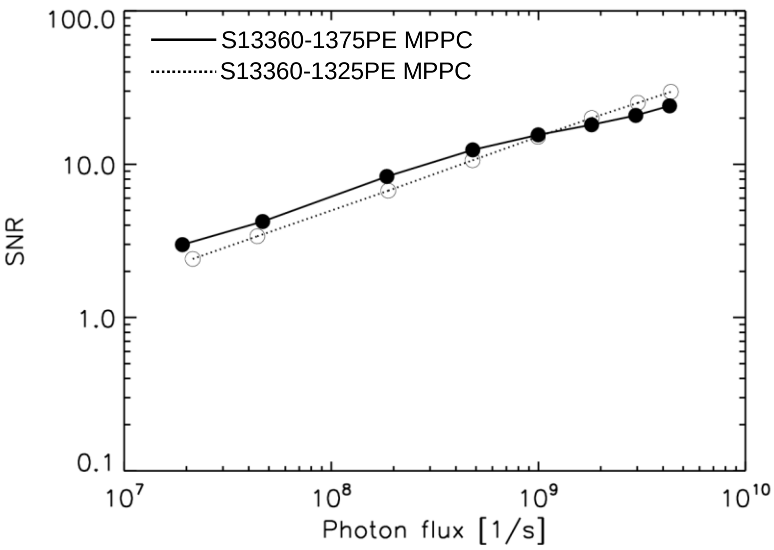


Comparison of MPPCs with different pixel size

An MPPC detector is composed of an array of small pixels connected in parallel. When a photon hits a pixel it fires a fixed amount of charge to the common output and it becomes insensitive to further photons for 10-100 ns. This means an MPPC detector gradually goes to saturation when the chance that a photon hits an insensitive pixel becomes significant. If the pixel size is small there are more pixels and the chance for this is smaller than for large pixels, meaning that the small pixel MPPC goes to saturation at higher photon flux. On the other hand the smaller pixel means more area between pixel, not sensitive to photons, thus the overall QE of the small pixel MPPC is lower than for the large pixel version. This behavior is shown in *Fig. 4.* Both curves are corrected for the nonlinearity of the MPPC.

At low photon flux the SNR depends on the square root of the light flux for both MPPCs but the large area version has higher SNR due to better QE. At higher photon flux the large area MPPC starts to saturate. In this range the output signal drops faster than the noise, thus after nonlinearity correction the SNR drops relative to the square root dependency and the small pixel MPPC becomes more efficient.

Fig. 4. Comparison of two MPPC types around 660 nm light input. S13360-1325 has 25 micron pixel size, while the other has 75 micron. 500 kHz amplifier bandwidth. Both curves are corrected for the nonlinearity of the MPPC.



High sensitivity detectors at 100 kHz bandwidth

Fig. 5. compares an APD and MPPC setup for high sensitivity at 100 kHz bandwidth. The APD is in dark current limited mode therefore at low light the SNR depends linearly on the light flux. The large pixel MPPC is in photon statistics limit therefore its SNR depends on the square root of the light flux, and thus it is superior at low light. At higher light flux the MPPC starts to saturate and becomes less efficient. It has to be noted that the crossing point shifts to the right at shorter wavelength.

Fig. 5. APD at gain 120 and large pixel MPPC. Both with 100 kHz bandwidth amplifiers. (~660 nm light input.)The MPPC curve is corrected for nonlinearity.