Lab Report Noise in Cameras and Photodiodes

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1 Purpose

Noise in cameras and photodiodes and other electrical devices have a big effect on the performance of these devices. There are several types of noise that have different physical origin. In this lab, the different types of noise was to be isolated to measure their individual effect as well as to use different methods to increase performance, such as binning and electron multiplication gain.

2 Theory

In the lab the noise and performance will be measured to make conclusions about the camera and photodiode. The performance will be determined by calculating the SNR, the signal to noise ratio as well as the noise levels. The noise in photodiodes will be measured in two different ways, that is the shot noise, σ_{Shot} and the thermal noise, $\sigma_{Thermal}$. The shot noise is current dependant and is described the the following equation

$$\sigma_{Shot} = \sqrt{2eiB}. \tag{1}$$

Where the e is the electron charge, i is the current and B is the bandwidth. In cameras this is called photon shot noise, and is the square root of the mean pixel value $\bar{S}$,

$$\sigma_{shot} = \sqrt{\bar{S}} \tag{2}$$

The thermal noise is dependant on the load and its resistance which is described by the equation

$$\sigma_{Thermal} = \sqrt{\frac{4kTB}{R}} \tag{3}$$

where R is the resistance, T is the temperature, k is Boltzmans constant and B is the bandwidth. The SNR is measured in relative power intensities which in simplification leads to a current and noise ratio, depicted as the following equation

$$SNR = \frac{i^2}{\sigma_i^2}. \tag{4}$$

In the camera, there are also a three other noise sources present, such as read noise, σ_{read}, which is constant. The second camera-only noise is fixed pattern noise which originates from the fabrication imperfections of the sensor. This noise also scales with the signal

$$\sigma_{FPN} = P_N * S \tag{5}$$

where P_N is the FPN quality factor. The last source of noise in cameras is dark current noise and originates from thermally generated electrons. This noise will only be noticeably present when using long exposure times.

$$\sigma_{dark} = \sqrt{D * t} \tag{6}$$

3 Method

In the first part of the laboration the noise of a photodiode was to be measured. With the photodiode connected to a voltmeter and ampere meter, together with a potentiometer. This circuit also used a 100 $k\Omega$ resistor where the potential drop were measured. The current of the photodiode were increased in steps and the voltage drop measured over the resistor load. An bias was also applied to the photodiode to measure the change. After this was done, the thermal noise of the resistor was measured using a lock-in amplifier and then the noise was measured once again with the lock-in amplifier using the first circuit used.

In the second exercise the noise of a CCD camera was measured using a setup of the camera itself, an object and a computer program to make different measurement. Using different exposure times, EM gain settings and binning to examine the effects on noise and performance.

4 Result

4.1 CCD Camera

4.1.1 SNR as a function of exposure time

Our first task is to evaluate the cameras performance, thus one looks at a dark image. From this image we can determine the read noise since its all the background detection we are not interested in. From this measurement we determine that the average photon count $\bar{N}$ was 500.3 with a RMS $\sigma_r = 8.48$ that is well inside the expected read noise range 1-15 RMS in the specifications of the camera.

With the average photon count we can remove this expected value to have a clearer background. We take a set of twelve images with different exposure times T with in the range of 0.5 ms- 1.02 s. From this data we can find the average number of photons per pixel in a second

$$\bar{S}(T) = 17.06 \cdot 10^3 \frac{photons}{Px \cdot s} \tag{7}$$

From the data sheet we know that the sensor size is 658×496 pixels of a total size of 10×10 μ which gives off that each pixel has and area of $3.06 \cdot 10^{-16}$ m^2. From this one can find the photon flux density:

$$\phi = \frac{17.06 \cdot 10^3 \frac{photons}{Px \cdot s}}{3.06 \cdot 10^{-16} \frac{m^2}{Px}} = 5.58 \cdot 10^{-16} \frac{1}{Px \cdot m^2} \tag{8}$$

Since we have data point for multiple exposure times one could be interested in that the noise has over different signals, this is show in Fig.1. In this figure one can tell ta for large signals that we get less noise than the read noise which is expected since we are correcting for it but we don't go higher than the upper limit which is the shot noise.

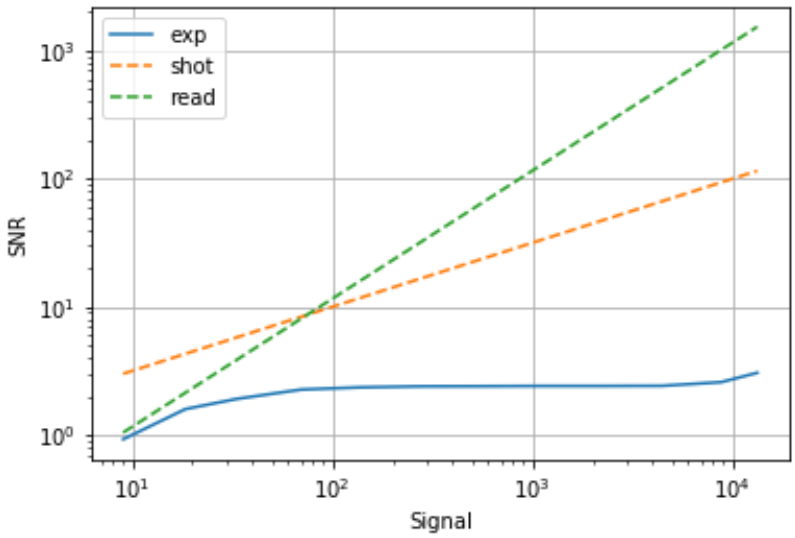


Figure 1: SNR for different exposure times, where we plot the read noise, the shot noise and the real SNR

we can calculate the value of the photon shot noise by using what we already know from our system. we can proceed to compute the following:

$$\sigma_{shot} = \sigma_{read} \rightarrow \sigma_{shot} = \sqrt{\bar{S}} = 8.48 \rightarrow \bar{S} = 71.9 \tag{9}$$

Which we can see in Fig.1 also matches up with what we expect theoretically.

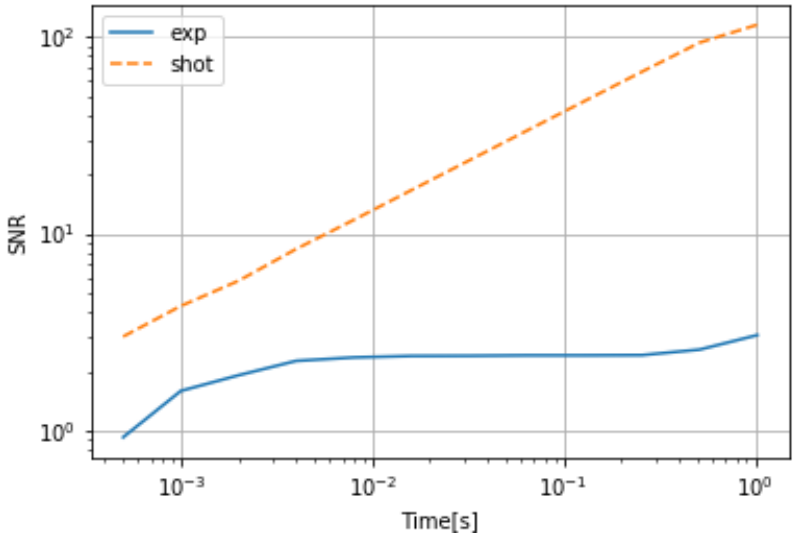


Figure 2: SNR for VS. exposure time, where we plot the shot noise and the experimental SNR

We can take a similar approach to find the theoretical value where the shot noise is equal to the read noise. We can compute in a direct way as follows:

$$\sigma_{shot} = \sigma_{read} \rightarrow \bar{S}(T)T = 8.48^2 \rightarrow T = 4.2\ ms \tag{10}$$

Which is exactly what we expect from looking at Fig.2. Its worth to mention that we can't over come the photon shot noise since it is intrinsically connect to the stochastic nature of light thus we are always going to have this noise in our system.

4.1.2 Binning

When we change the binning of the camera we effectively change the amount of pixels we are averaging our signal over. This reduced the resolution but it also give a improvement in signal clarity. We take two different bins and then compare to our original signal, we observe the the increment in the binning factor is proportional the the signal, which is expected since we are gathering more light per pixel.When we look at the SNR form different binning we can determine that the SNR follows the same tendency for any bin we can see this in Fig.3

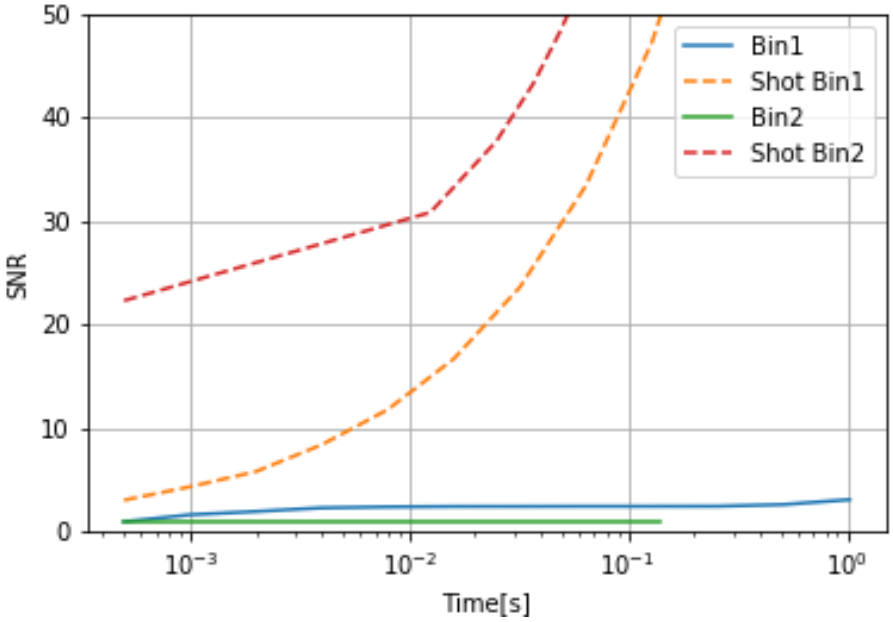


Figure 3: SNR for two sets 1x1 and 2x2 of binning and the correspondent shot noise.

With this we could also be interested in seeing the effect on the image of binning, we show two images of the same scenario with different bins in Fig.4. From this we can tell that there is a clear benefit to binning that we reduce the sharpens and the noise of the image, since we are averaging over more pixels we get a more homogeneous background. But one can also see how the resolution is decreased since the amount of pixels is also reduce.

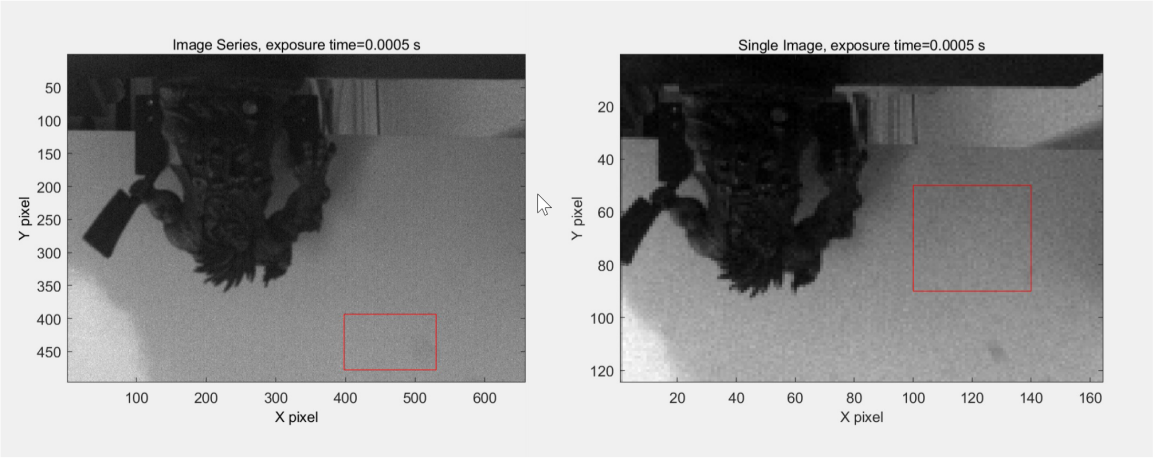


Figure 4: Two set of images with different binning where we can see the reduction of pixels on the axis of the plots

It makes sense to use binning when we need a smooth image which doesn't need the highest resolution but you are more interested in having a softer looking image.

4.1.3 Electron multiplication gain

From here we study the gain function in our CCD camera, for this we select two different gains and the zero gain reference. The signal gain is done by multiplying the amount of electrons that have been detected in each pixel, this is not a linear gain system.

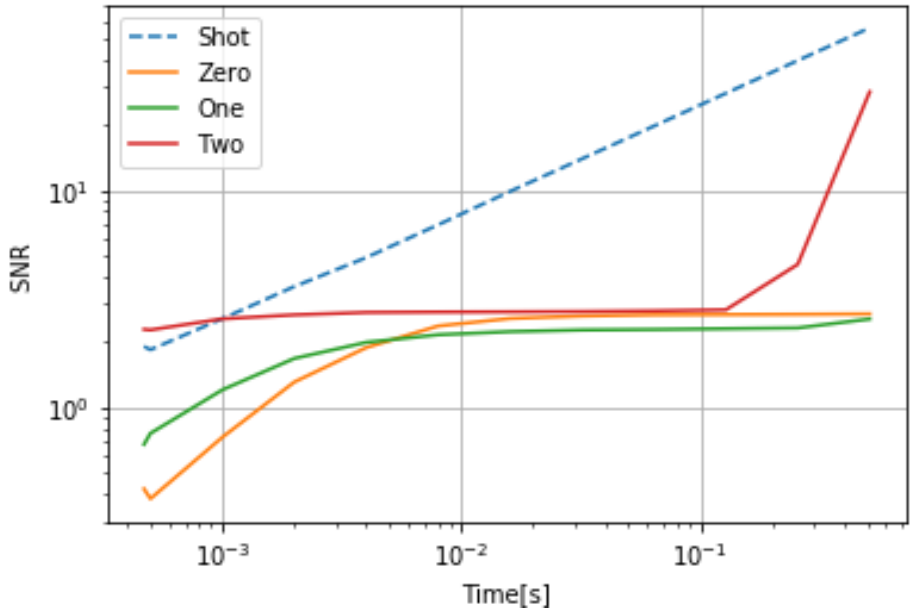


Figure 5: SNR for three set of gain values in a CCD camera, compared with the shot noise.

Form the data shown in Fig.5 we can see that for each increment in the gain we can actually match the shot noise of the sensor. This is done looking at the shot noise of the zero gain system its clear that for each gain the corresponding shot noise would also increase. As our final analysis we can look at the ionization probability threw the gain of the SNR measured, we assume the case where we have 563 defections. From this we can relate our gain factor $G = 2.57$ computed from the data shown in Fig.5, resolving for the probability as follows:

$$G = (p+1)^{536} \rightarrow p = 0.0018 \tag{11}$$

with this we conclude this part of experiment. In our time in the lab we were only able to collect data up to this task and as discussed in class we finish our analysis here.

4.2 Photodiode

Figure 6 showing log-log plot of both reverse biased and unbiased photodiode with logarithmically scaled set of current values.

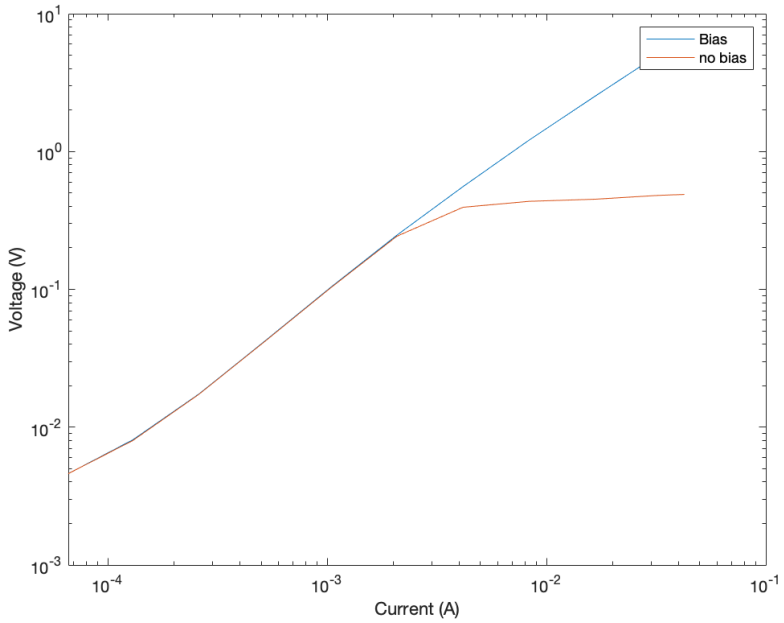


Figure 6: Measurement of reverse biased (blue) and unbiased photodiode (orange).

Measuring the thermal noise in the resistors resulted in a value of 0.113 μV for the 100 $k\Omega$ resistor and a value of 0.260 μV for the 1 $k\Omega$ resistor. The bandwidth was also calculated by comparing the noise level 100 $k\Omega$ resistors with the noise level per root square frequency. Where the value of the μV per root square frequency, $\mu V/\sqrt{Hz}$, was 0.046 resulting in a bandwidth, B, of about 25 Hz.

Figure 7 showing log-log plot of measured noise from the lock-in amplifier of the circuit with reverse bias as well as the calculated shot noise using equation 1 for the measures voltages.

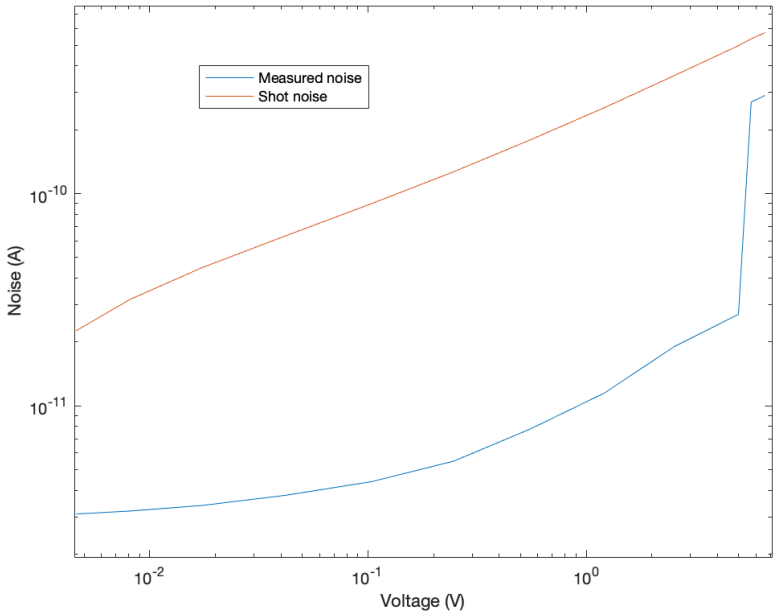


Figure 7: Measurement and calculations of noise in the circuit (blue) for swept voltages and calculated shot noise (orange).

Figure 8 showing log-log plot of measured SNR of the circuit with reverse bias taken from the lock-in amplifier data and the calculated shot noise limited SNR for the measured currents. The shot noise limited SNR was calculated with the measured current together with equation 1 and 4.

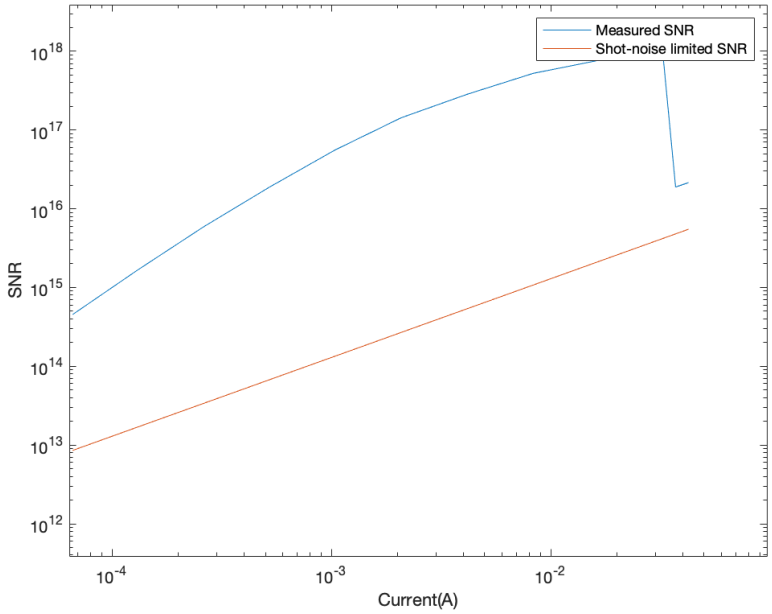


Figure 8: Measurement and calculations of SNR for the reverse biased circuit (blue) and calculated shot noise limited SNR (orange).

5 Discussion

5.1 CCD Camera

In this experiment we studied a large set of fundamental factors of CCD cameras. We looked at the different forms of noise, the effect of the exposure time and how the gain changes the received signal. We observed that the experimental signal to noise ratio is smaller than what is expected theoretically which is expected since we have more source of noise than just the ideal model. We also saw the benefits of changing the exposure time where we can get a well contrasted image from changing the exposure time but one can also over due it and saturate the sensor.

Most of what we have seen gives us a better understanding on how we should utilize a CCD camera and what parameters we can change to obtain a desired image. This is directly the idea behind looking at the binning of an image from this property we can chose if we want to have a better resolution or a smooth image, this is a choice one can take depending of the implementation. In general we learned what is the advantages of working with a CCD sensor and how to understand its physical limitation and optimal implementation.

5.2 Photodiode

As can be seen in figure 6, the reverse biased setup shows an increased voltage drop over the load for larger currents whereas the unbiased setup saturates much quicker.

Measuring the thermal noise, $\sigma_{thermal}$, the value for the 100 $k\Omega$ shows a noise of 0.113 μW, versus the noise of the 1 $k\Omega$ of 0.260 μW. This is in line with the theoretical relationship between the two according to equation 3. In theory the larger resistance would have a noise which is a tenth of the value of the smaller. The measured ratio of about 2 is not a expected value but might be explained with other noise sources.

In figure 7, the measured noise versus the theoretical shot noise value shows that the measured noise is much lower than the theoretical value. This is unusual since the measured data should consist of several noise sources and thus be larger than one theoretical value. For example, thermal noise in the load would be present as earlier mentioned.

Looking at the SNR plot in figure 8, the lower noise in the measured data is reflected here. The measured data showing a much better signal to noise ratio than the theoretical shot noise limited value. Again, this should not be the case since in reality there are several noise sources which together would exceed the theoretical value of a single noise source.