Noise in Cameras and Photodiodes
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An study focused on the origins of noise in the field of experimental optics, technological and statistical sources will be assessed and evaluated for different hardware and software configurations for the case of the CCD camera and the Photodiode.

I. INTRODUCTION

The present report consists of an exploration of the meaning and the different sources of noise in two kind of sensors, the photodiode and the CCD (charge-coupled device) camera. The first section will list some of the theoretical concepts and tools that will be reference as the pages go by. After this, in the Procedure and Results section, the methodology and results of the experiments will be explained and interpreted.

For the first experiment, the case of a CCD sensor is studied, a dark image will be taken an analyzed to characterize the camera's readout noise, and then a series of photos will be taking with the same configurations altering only the exposition time to experimentally verify the noise dependence on photon number. After this, some alternatives such as binning will be tested to see how resolution and the SNR are affected.

During the second experiment, the focus will be shifted towards the photodiode, exploring mainly how the reverse bias voltage affects the I-V curve, and later an analysis will be run for different resistors to see how the SNR changes.

Finally in the discussion section the team will make a summary of the results and some limitations and comparisons will be acknowledged.

II. THEORY

Noise is every undesired signal in a measurement, and in terms of optical detection, it has different sources:

1. Photon shot noise: Comes from the random distribution of photon energy in light. The introduced deviation is the expressed by
$$\sigma_{shot} = \sqrt{\overline{N}}$$
with $\overline{N}$ the average number of photons.

2. Readout noise: Characteristic of the detector, since it does not depend on the signal, it's a constant.
$$\sigma_{read} = const.$$

3. Fixed pattern noise: Comes from specific errors in the detector that are not random. e.g. Dust in the lens, low-amplification in certain pixels, etc. It scales with the amount of signal. (P_N is a FPN quality factor)
$$\sigma_{FPN} = P_N \cdot S$$

4. Dark current noise: As technology has been improved, this noise has become insignificant, it comes from thermally excited electrons that mix into the signal and alter the readings, it depends then on the measurement time t and a thermal excitation constant D.
$$\sigma_{dark} = \sqrt{\overline{N}_{dark}} = \sqrt{Dt}$$

An important concept that givesinformation of the quality or "cleanliness" of a measurement is the SNR (Signal to Noise Ratio). This adimensional quantity is defined by the part of the signal that represents just noise. In Equation 1, $\overline{S}$ is the mean pixel value, and σ the standard deviation. The mean signal value is related to the mean number of photons.

$$SNR = \frac{\overline{S}}{\sigma} \tag{1}$$

However in the case of the photodiode the noise definition is a bit different since it no longer depends on the captured photons, but on the read current i and its standard deviation.

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

On the other hand, the shot-noise analog also takes the shape of a standard deviation of traveling particles' energies. expressed as in Equation 3, where B is the bandwidth $B = \frac{1}{2t}$.

$$\sigma_{shot} = \sqrt{2eiB}$$

or

$$\sigma_{shot} = \sqrt{2eGiFB} \tag{3}$$

by adding a gain G and a gain noise F.

Finally getting to a Signal to Noise Ratio expression (starting from Equation 2 and using $i = eG\eta\phi$ for a photon flux ϕ and a quantum efficiency η):

$$SNR = \frac{(eG\eta\phi)^2}{(2e^2G^2\eta\phi FB) + \sigma_{JN}^2} \tag{4}$$

In this case there are also thermally excited particles that produce undesired thermal noise (σ_{JN}), also known as Johnson-Nyquist noise defined in Equation 5 where k_b is Boltzmann constant

$$\sigma_{JN} = \sqrt{\frac{4k_BTB}{R}} \tag{5}$$

III. PROCEDURE AND RESULTS

A. Noise in a CCD Camera

1. Readout Noise

The read noise comes from the circuit, when converting the charges into a voltage signal. During this practice it was characterized by blinding the camera with a lens cap and taking a picture. The mean value was around 250 counts resulting from the readout noise, while the standard deviation of 9. Then a dark image was taken, meaning that this mean value was going to be subtracted from all images but this increased the standard deviation to 12, value that matches the RMS theoretical value of the camera. This is shown in figure (1).

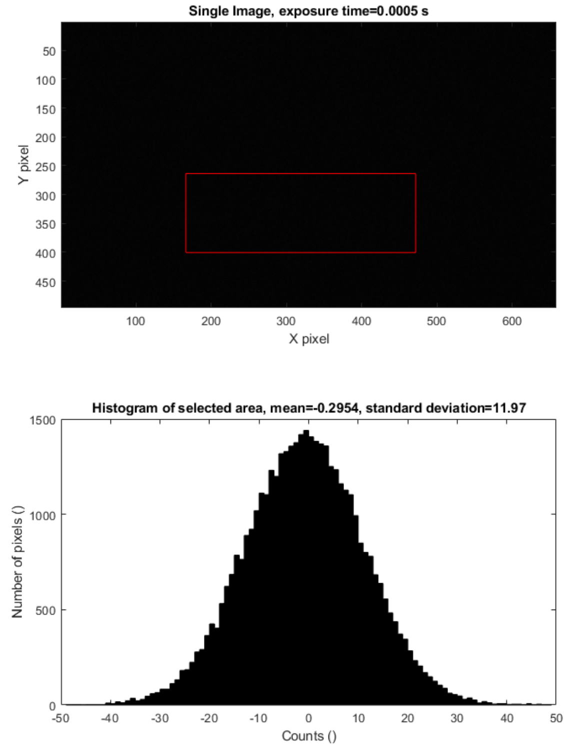

Figure 1: Screenshot of the dark image work, noticing that the mean value went to zero.

2. SNR as function of Exposure time

Exposure time is an alterable variable in the software, through this option will take a series of photographs and measure the change in the Signal to Noise ratio.

8 pictures were taken with different exposure times being [0.0005, 0.00134, 0.0036, 0.0096, 0.0258, 0.0694, 0.1863, 0.5]s. The reason of this shape of the data was to obtain a better log-log plot for the SNR. From Labview data obtained, the photon flux for each exposure time was [28213.7, 27228.6, 27320.9, 27496.2, 27621.4, 27613.8, 27672.1, 27144.6] photons/s*um in

average. It is visible from this data that due the slow variation it can be concluded that the light source is stable.

The SNR was plotted as a function of the signal, resulting in figure (2), from this plot it can be seen that the noise tend to be reduced as the signal grows.

Plotting the SNR vs the photon shot noise to see the ideal behavior it was obtained the following plot (2). It can be observed that the SNR never is equal to the photon shot noise limit, this can be due the fact that additional noise is contributing like the readout noise, the dark current noise, although it gets really close to it in the interval of $[10^2, 10^3]$.

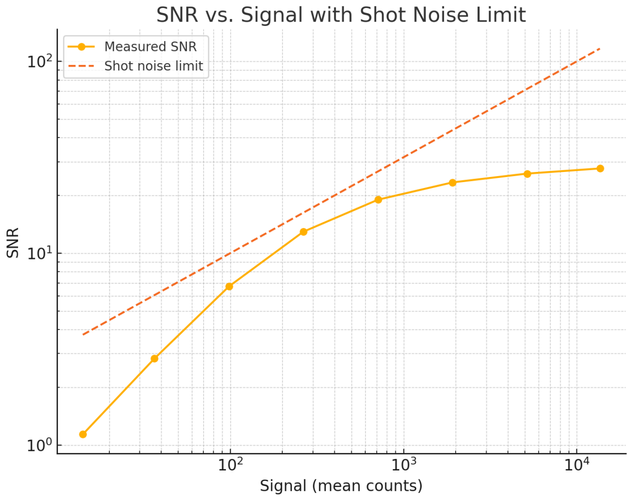

Figure 2: Signal to Noise Ratio compared to the photon shot noise.

From this data and knowing the value of the $\sigma_{read} = 12$, the expected noise is given by $\sigma_{expected} = \sqrt{\sigma_{shot}^2 + \sigma_{read}^2}$. The following table stablishes the mean value of each exposure time, it's standard deviation (noise of that exposure time) and the expected noise theoretical value:

It can be seen that at the beninging for short times (because the signal scales linearly with time) the experimental noise is close to the theoretical one, implying that the readout noise and the photon shot noise dominate, but for prolonged times the error separated completely from the theoretical value, implying the contribution of other sources of noise in the measurements.

The SNR was plotted now in function of the exposure time, resulting in plot (3), the photon shot noise is equal to the readout noise at about $3.6ms$. The SNR will

Mean Count	Measured Noise (std dev)	Expected Noise
14.11	12.41	12.57
36.49	12.93	13.43
98.36	14.65	15.57
263.96	20.41	20.20
712.63	37.49	29.27
1916.40	81.95	45.39
5155.32	198.38	72.80
13572.28	490.99	117.12

Table I: Comparison between measured noise and expected noise.

never exceed the photon shot noise because this only considers this noise source and it's ideal, other noise sources contribute experimentally to the data measured, leading to a lower SNR.

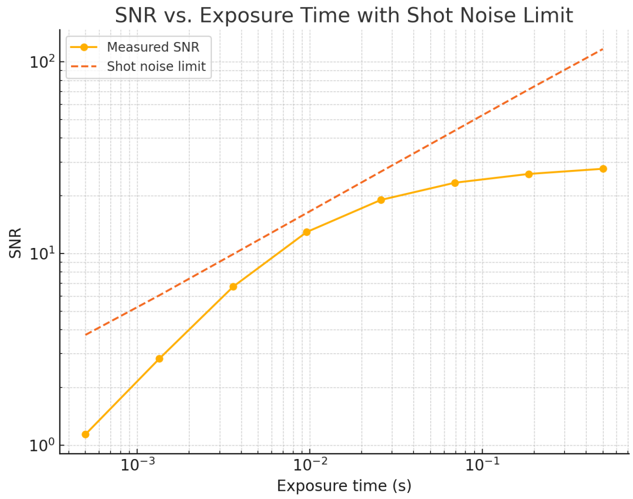

Figure 3: Signal to Noise Ratio vs exposure time compared to the photon shot noise.

3. *Binning*

Two binning measures were studied, one for a 2x1 binning (2 pixels in the x axis merge with only 1 in y axis) so it has a binning factor of 2 and for a 2x2 binnning (2 pixels from the x axis merge with 2 pixels of the y axis) which binning factor is 4. The binning factor is the number of pixels that are combined to form the bigger super-pixel.

The SNR values obtained are resumed in the following table:

It can be seen that the binning factor is not followed exactly, this could be due a lack of a linear response of the sensor. The SNR values were plotted with their respective photon shot noise limit, resulting in

Exp. Time (s)	SNR (No Bin)	SNR (2x1)	Prop. (2x1)	SNR (2x2)	Prop. (2x2)
0.00050	1.14	2.68	2.35	6.62	5.83
0.00134	2.82	4.82	1.71	10.98	3.89
0.00360	6.71	8.57	1.28	16.32	2.43
0.00960	12.93	17.23	1.33	23.05	1.78
0.02580	19.01	23.90	1.26	26.09	1.37
0.06940	23.38	27.65	1.18	28.18	1.21
0.18630	25.99	28.71	1.10	29.23	1.12
0.50000	27.64	30.48	1.10	38.58	1.40

Table II: Comparison of SNR values and binning proportion.

Figure 4. It can be observed that as the binning factor rises, the faster the SNR reaches the photon shot limit but for lower exposure times.

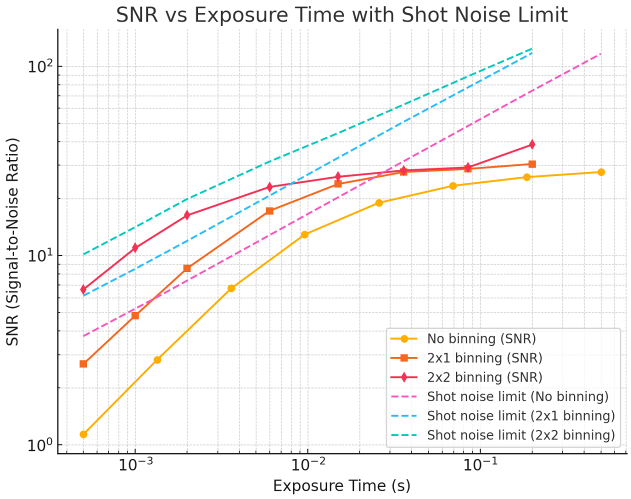

Figure 4: Signal to Noise Ratio vs exposure time compared to the photon shot noise limit for different binning configurations, no binnning, 2x1 binning and 2x2 binning, respectively.

A comparison of images with and without binning are given in figure (Figure 5). From the comparison of the same image it is noticed that as the binning factor gets higher, the resolution is getting lower but the image gets smoother meaning a reduction in noise.

Figure 5: Image with different binning configurations, no binning, 2x1 binning and 2x2 binning, top to bottom respectively.

The binning must be used for low-light conditions or faster adquisition of images due the fast reach of the photon shot noise limit that increases with the binning.

4. *Gain*

For this experiment, three sets of data were taken to observe the behavior of the electron multiplication (EM) gain. It was taken image measurements for a gain of 0 (gain function disabled), gain of 25 and 80. The following table shows the data for different exposure times:

Exp. Time (s)	Mean Count (Gain 0)	Mean Count (Gain 25)	Signal Gain (25)	Mean Count (Gain 80)	Signal Gain (80)
0.00050	19.86	43.30	2.18	74.36	3.74
0.00100	38.48	85.89	2.23	153.85	4.00
0.00350	134.39	171.81	1.28	306.53	2.28
0.00960	370.55	428.33	1.16	760.81	2.05
0.02500	968.93	855.78	0.88	1516.69	1.57
0.06900	2680.81	1707.40	0.64	3019.67	1.13
0.18000	6960.80	4231.95	0.61	7421.88	1.07
0.50000	15882.69	8329.19	0.52	14412.23	0.91

Table III: Comparison of signal gain for different EM gain settings.

As the table shows, the signal gain is not represented by the EM gain parameter, which varies being higher at low exposure times like for $t = 0.0005s$ the signal gain for the 25 EM gain is 2.18 and for the 80 EM gain 3.74. This signal gain decreases for long exposure times, for $t = 0.5s$ the signal gain is 0.52 for EM gain of 25 and 0.91 for EM gain of 80.

From this it is concluded that the signal gain is not a fixed value and depends on the time exposure, at short exposure it has larger effects while it's less effective for longer exposure times.

The SNR values were obtained resulting in Figure 6. From the plot it can be observed that the EM gain makes the SNR get more close to the photon shot noise limit faster but only for low exposure times, while for long exposure the EM gain is not so effective.

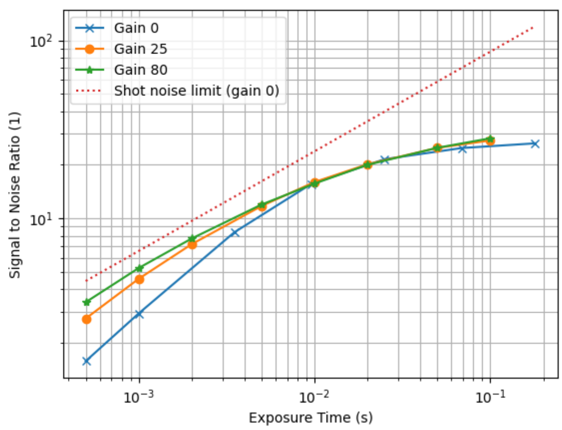

Figure 6: Signal to Noise Ratio behavior for different EM gain.

A comparison of the same image but with different EM gain at the low exposure time is given by Figure 7.

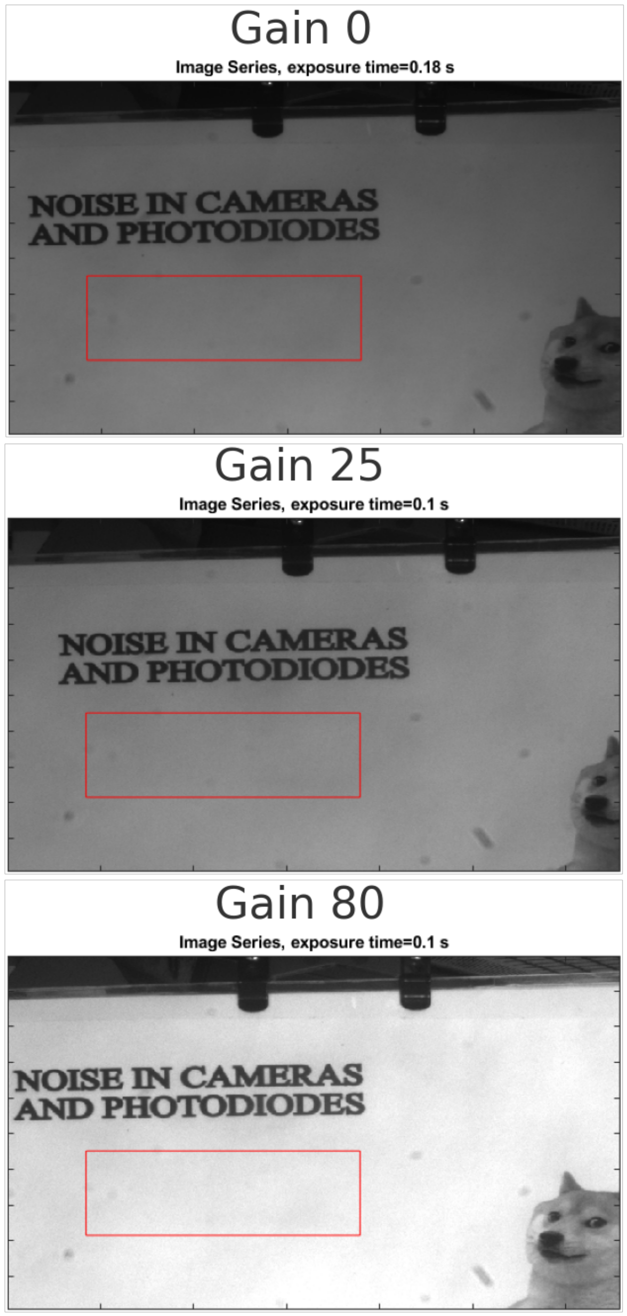

Figure 7: Image comparison for different EM gain values at the lower exposure time.

From all above, the EM gain observed behavior allows to conclude that this tool is useful for low exposure or low light situations for weak signals detection.

One important concept is the ionization probability which determines how effectively the EM register amplifies the signal. This is given by the relation:

$$G = X^t. \tag{6}$$

Where G is the signal gain, X the ionization probability and t the number of transfers. If the number of transfers is 536, the following table gives the value of the ionization probability by taking the 80 EM gain value:

Exposure Time (s)	**Ionization Probability (X)**
0.00050	1.00247
0.00100	1.00259
0.00350	1.00154
0.00960	1.00134
0.02500	1.00084
0.06900	1.00022
0.18000	1.00012
0.50000	0.99982

Table IV: Ionization probability per transfer (X) for different exposure times.

From this information it is observed that there is only a small chance of gaining an electron by EM multiplication at lower exposure times, and this probability decreases for long exposure times.

5. *Fixed Pattern Noise*

For this part of the experiment two dark images were taken. One with 10 s exposure time and one with 500 ms exposure time. These are shown in figures 8 and 9 respectively.

Dark noise was assumed to be negligible, so we only investigate fixed pattern noise. Fixed pattern noise is due to pixels not having the exact same sensitivity. When a very long exposure time is used, the extra sensitive or damaged pixels will accumulate lots of false detections. This shows up clearly as white specks on a dark image. These are constant between images. Figure 8 shows this phenomenon clearly. Fixed pattern noise isn't as visible when other noise is of comparable amplitude in the same image, but is still there. Figure 9 shows this. It is still discernable, but one would probably need to know the pattern from looking at a longer exposure time image to make it out. If long enough time has passed so that the FPN affected pixels are saturated and the others are not, it sticks out. More subtle extra sensitivity can be harder to detect and must be found by looking at common patterns between different images.

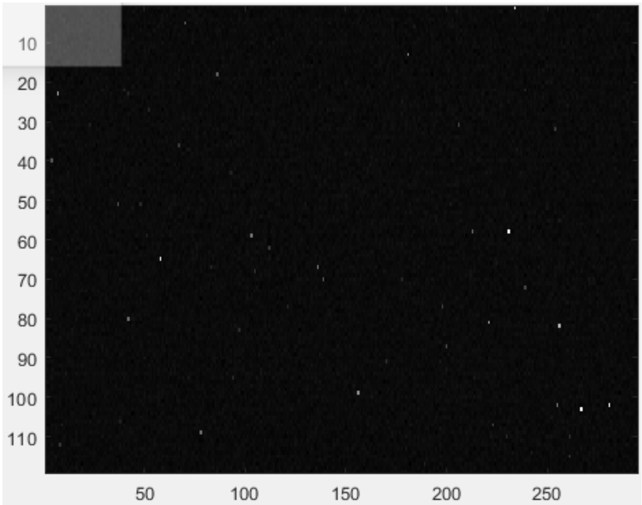

Figure 8: Dark image at 10 s exposure time

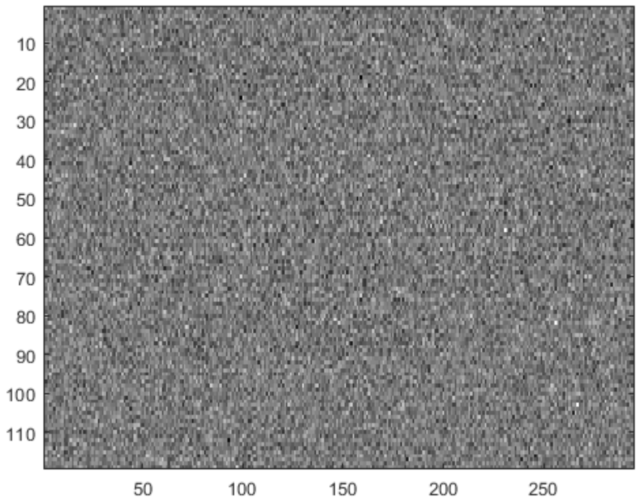

Figure 9: Dark image at 500 ms exposure time

The dark noise for this experiment was also assumed to be irrelevant, this is a reasonable assumption since

The choice of having the dark current noise as insignificant is justified by taking into account the amount of generated dark signal

Replacing the values form Figure 1 in ethe expression for the dark current noise, one gets the quantity:

$$\sigma_{dark} = \sqrt{m} = \sqrt{Dt} \implies$$

$$\sigma_{dark} \propto \sqrt{t}$$

Unfortunately we do not have the standard deviation measurement for the 10 s dark image (figure 8). We can however reason that dark noise will be very small in comparison due to it being proportional to the square root of the exposure time, whereas fixed pattern noise is proportional to exposure time as a constant error, and will thus grow much faster.

B. Noise in a Photodiode

1. *With and Without Reverse Bias*

Figure 10 shows the measured relationship between resistor voltage and LED current with and without biasing. The resistor voltage is proportional to the generated photo current.

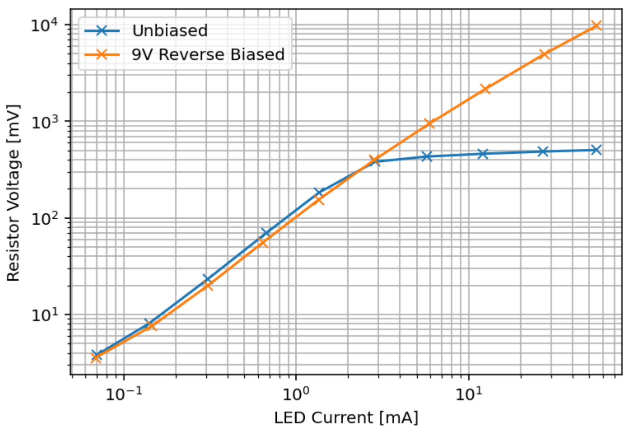

Figure 10: Measured resistor voltage vs. LED current with and without biasing

One can see in Figure 10 that a saturation intensity is reached way earlier for the unbiased measurements, this can be made sense of with the help of Figure 11. The reversed biased system will simply have more room to increase the intensity before running into saturation, opposed to the unbiased one, which will face this problem early on.

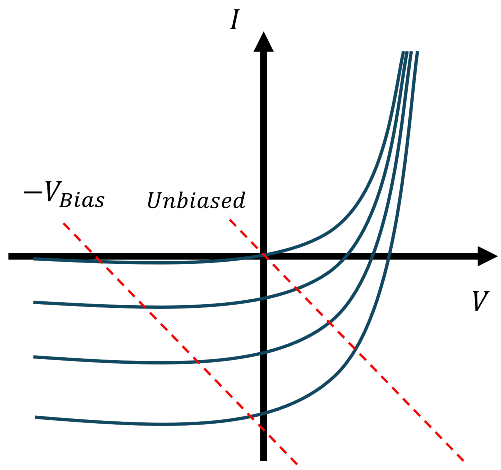

Figure 11: Characteristic IV curves of the photodiode for different resistances, the interrupted lines represent the measurement path taken for this experiment experiment.

2. *Thermal Noise in Resistors*

For this step of the experiment, the lock-in amplifier will be used as a voltmeter in order to measure the noise related to each resistance value (1 and 100 $k\Omega$). the obtained values are summarized in table()

Resistance ($k\Omega$)	**Noise**(μV)
1	0.027
100	0.158

Table V: Thermal Noise produced from each of the resistors

The relationship between these quantities should follow the theory, so an analysis was made starting from the definition Equation 5.

$$\sigma_{JN_1}/\sigma_{JN_2} = \sqrt{\frac{R_1}{R_2}}$$

Substituting the resistance values gives a factor of 10, from which the experimental result of 5.85 is not so different. The same order of magnitude was obtained.

3. *Noise in The Photodiode Signal*

For the last experiment, the measured noise was compared against the theoretical expressed in Equation 3, with the same series of current values for i, a gain G and parameter F set to 1, and a Bandwidth B of 17.2. In order to change from current to Voltage in both series, Ohm's law was used $V = Ri$, with $R = 100k\Omega$.

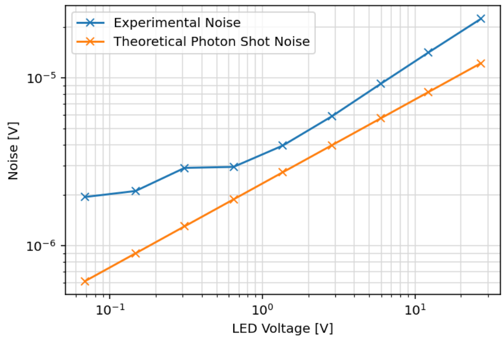

Figure 12: Noise voltage vs applied voltage, series for the experimental noise results and theoretical photon shot noise.

From figure Figure 12 it is visible that the measurements follow the same behavior as the applied voltage increases, however, the experimental noise is higher in value, this result is explained by taking into account other noise sources that were not modeled theoretically, such as, among others, thermal noise, circuit noise and light leakage.

Finally, the SNR was obtained using the newly obtained noise signal for the measured current in the previous biased vs unbiased section. The equation Equation 2 was used. Results are shown in Figure 13.

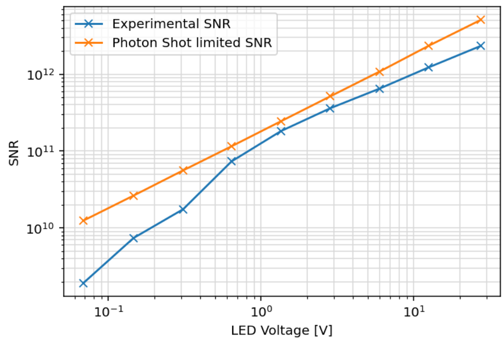

Figure 13: SNR vs applied voltage, experimental data and photon shot limited SNR are shown.

As the voltage increases, the experimental Signal to Noise Ratio gets closer to the photon shot limited value, this makes sense, since the other noise sources are not proportional to the signal, so they will fade away against the photon shot noise as the signal gets larger.

IV. CONCLUSIONS

The experiment allowed the team to observe and analyze the behavior of the different type of noise that arises while taking measurements of light with different sensors.

The first experiment with a CCD camera gave the opportunity to analyze the readout noise that come from the processing light-electricity signal which is constant over time. An analysis of the signal to noise ratio (SNR) was done for this CCD camera, with and without different tools like binning and electron multiplication gain. Measures without any amplification tool allowed the observation of the SNR and to compare it to the ideal photon shot noise, leading to the fact that other noises are contributing to the measurements, like the dark current or the readout noise.

The binning tool was used to observe how the relation between the SNR and the noise can be reduced by merging pixels, allowing them to work as a mega pixel, reducing the noise from the data measured with the drawback that resolution is lost. The electron multiplication gain showed how the signal gain is not given by this parameter, which does not give a linear response and reduces the signal gain over long exposure times but allowing to get a closer SNR to the photon shot limit for low exposure times.

This tools allowed to conclude that they are useful on low-light and low exposure situations for detecting weak signals for example.

On the other side, the photodiode experiment was a great way to understand the effects of the bias voltage in the system,increasing the possible intensity spectrum. After this, the noise was also well studied, the thermal noise was characterized for different resistance values and verified theoretically.

Finally, the actual noise was compared against the photon shot noise and the photon shot limited SNR, Through this, the hypothesis was verified, as the signal gets bigger, the other noise sources become negligible and only the photon shot noise becomes important.

This lab was a thorough study of noise sources and a great way for the team to understand better the technologies used.

[1] Bahaa E. A. Saleh , Malvin C. Teich *Fundamentals of Photonics*, 2019, *Wiley*.