ASTRO 4410 LAB 1

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1 Objectives

1. Understand the way a charged couple device (CCD) works.
2. Become familiar with the operation of a CCD and the way it captures images.
3. Gather image data by direct operation of a CCD in a laboratory setting.
4. Analyze data obtained through the use of a CCD in order to understand sources of error present in the capture of astronomical data and the ways to compensate for them.
5. Calculate the read noise, bias, dark current, the gain factor G for converting from data numbers into electrons, linearity, and blooming for a CCD.

2 Setup

The experiment was performed using an Andor IDus 440 CCD mounted on a flat table and attached to a camera lens. The first three results were obtained by placing the CCD some 50 cm away from a white piece of paper. This white piece of paper was pasted to a wooden bar in order to keep it flat and upright. A light bulb connected to a variable power source was placed directly behind the paper and the bar. In an effort to create a flat field from which to acquire data from, the brightness of the light bulb was adjusted and the variable power source was set at a constant voltage for all measurements. The lights of the room were turned off for the duration of the exposure time on each occasion data was acquired. Results for the blooming part were obtained using a different setup, with the white piece of paper replaced by a pigeon hole that was placed around the lightbulb in order to create a point source. The CCD was connected to a computer that was used to control it and receive the data it obtained. The computer's screen was also turned off whenever measurements were made. The CCD was set to a temperature of -40 řC. The software used to obtain and save the data was the 'Andor Solis' package developed by the CCD's manufacturers.

3 Results

3.1 Read noise and bias

Data for this part of the lab was acquired from five exposures timed to be as short as possible, which in practice corresponded to 0.00001 seconds. The camera lens cap was kept in its covering position.

The read noise was calculated by taking the standard deviation of the values of the pixels contained in the image obtained by the CCD and averaging over the values recovered for each of the exposures. The bias was calculated by measuring the average value of the pixels contained in the images, and again averaging over the five exposures. All of these results can be seen on Table 1.

Table 1: Standard deviation and bias for zero second exposures

Exposure #	Standard deviation (σ_R) (DN)	Bias (DN)
1	1.1899	188.7861
2	1.1931	189.0550
3	1.2006	188.9735
4	1.2649	188.6766
5	1.2130	188.6830
Average	1.2123	188.8349

3.2 Dark current

The dark current is the current that flows through a CCD that is not due to photon collisions but to thermal fluctuations in it. Its value is given by the slope of the line obtained by graphing the average number of counts DN per pixel in terms of the respective exposure time. The average number of counts per image was calculated using all of the image's pixels, and nine different images were taken, each using a different exposure time. The results are shown in Table 2 and Figure 1. The value of the dark current was calculated as

$$\frac{d(DN)}{dt} = 0.01990\,\frac{DN}{s}$$

Table 2: Dark Current

Exposure time (s)	Average counts per pixel (DN)
0.1	189.4229
1	189.4311
5	189.5149
10	189.8589
20	189.8461
40	190.4565
80	191.4351
160	193.1236
320	195.6770

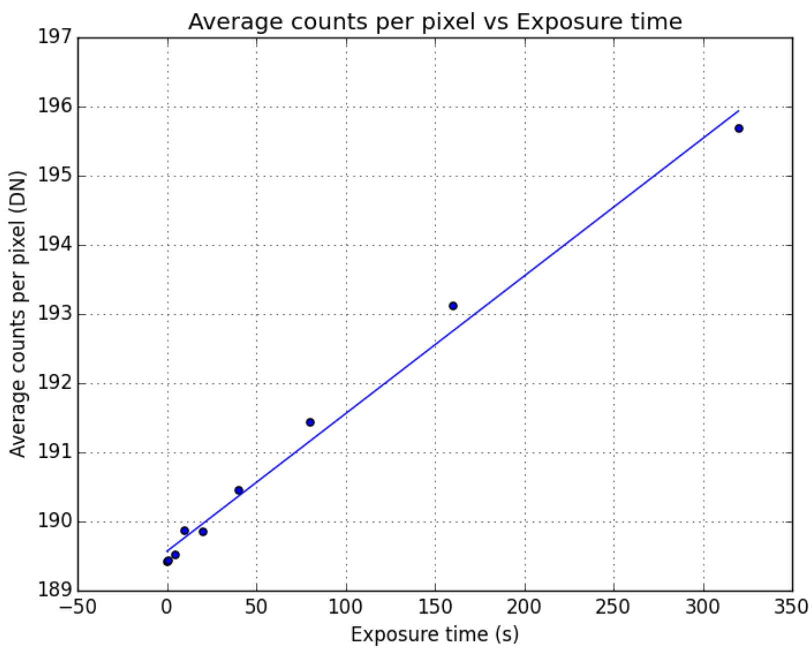

Figure 1: Average counts per pixel vs Exposure time

3.3 Gain factor and photon transfer curve

The gain factor G enables conversion from DN's to electrons. In this experiment, its value was calculated by taking several pictures of the white piece of paper with the light bulb behind it at constant brightness and varying the exposure time for each picture. In total, 18 pictures were taken, with exposure times ranging from 0.1 seconds to 100 seconds. Examination of each of the pictures determined that a fairly uniform region could be selected from the bottom right corner of each of them. A 20 by 20 pixel box corresponding to this region was used to calculate the noise and the signal for each of the pictures. Noise was calculated as the standard deviation of the group of pixels and the signal was calculated as its average value. Plotting the log of the noise obtained as a function of the log of the signal minus the bias obtained before results in the CCD photon transfer curve, shown in Figure 2. Removing the first five points of the photon transfer curve, which are dominated by read noise, produces Figure 3. In theory, the best fit line for Figure 3 should have a value of 1/2, because this part of the transfer curve is dominated by photon noise, and photon noise is proportional to the square root of N_e, the number of signal electrons in a well, while the signal is directly proportional to N_e. Thus this kind of graph can in theory be used to obtain the exact value of the gain factor G by extending the 1/2 slope line and would be given by the value of the point at which the line intercepts the x-axis. Unfortunately, the value of the best fit line for Figure 3 is not 1/2 but 0.618, which means that utilization of this method does not produce an accurate result. An attempt was made anyway and the value was found to be

$$G = 0.6369 \, \frac{e^-}{DN}$$

In order to obtain another estimation that would allow to get a more accurate value for the gain constant, an alternative approach was also tried, which relied on using the formula

$$G = \frac{S(DN)}{\sigma_S^2(DN) - \sigma_R^2(DN)}$$

So G was obtained by plotting the signal S(DN) vs the square of the noise minus the square of the read noise calculated earlier for each of the 20 by 20 pixel boxes obtained from the images. This method produced a value for G of

$$G = 0.5691 \, \frac{e^-}{DN}$$

That plot is shown by Graph 4. The average of the two values of G gives

$$G_{av} = 0.6030 \, \frac{e^-}{DN}$$

Using G_{av}as the gain constant, the value of the read noise can now be written as

$$\sigma_R = 0.7310 \, e^-$$

And the value of the dark current as

$$\frac{d(DN)}{dt} = 0.01200 \, \frac{e^-}{s}$$

The full well capacity cannot be calculated using this data for reasons that will be explained later.

It must be noted here that the fact that the value of the slope of Figure 3 is not 1/2 might be explained by an imperfect field produced during the experiment. In other words, the field measured by the CCD, with a physical basis on the illuminated part of the white piece of paper, was not a flat field, maybe because of experimental error. This is supported by the fact that when the size of the box used to calculate the signal and noise values is increased, the slope of Figure 3 increases, even though the selected area is still within what looks like a uniform region of the acquired image. The increase in slope implies an increase in the standard deviation of the pixels, which points towards the conclusion that the field produced in the experiment was not flat.

Figure 2 shows the complete photon transfer curve for the experiment, incorporating the points that were not plotted on Figures 3 and 4. In theory, this plot should have contained three different regimes characterized by three different curve shapes as exemplified by Figure 5. The first regime is dominated by read noise, the second by photon noise, and the third by fixed pattern noise. As can be immediately seen, Figure 2 shows only two different regimes, not three as was expected. This can be readily explained by the fact that the exposure times used were never high enough to reach the saturation level of the wells. We have already examined the second region, which was used to approximate the value of the gain constant. The discrepancy between the expected shape of the curve and the observed one for the first region is harder to explain. It might be possible that the read noise is not a constant and changed as a function of the signal, but it is not easy to see why this would be the case. Another, more plausible possibility is that the lack of flatness of the field might have affected the relationship between the noise and the signal for low values.

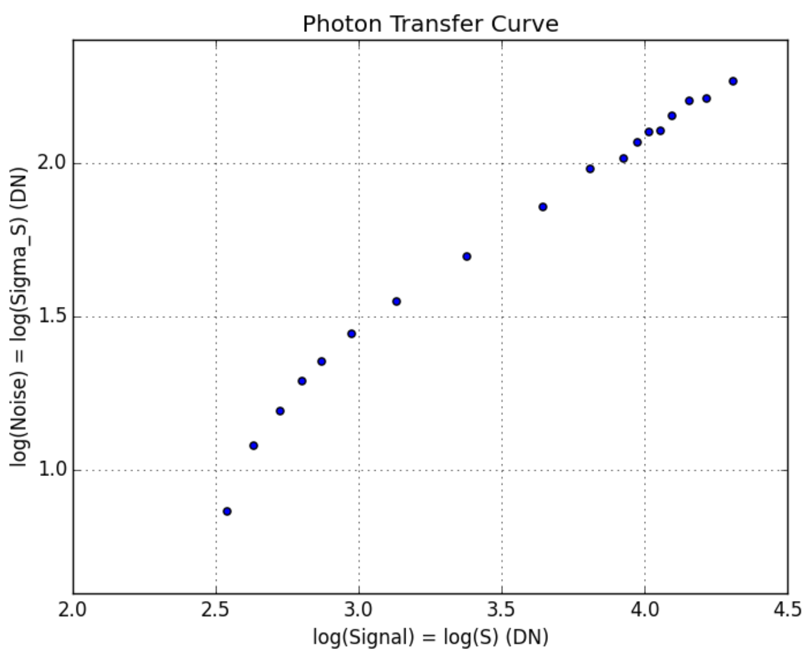

Figure 2: Full photon transfer curve

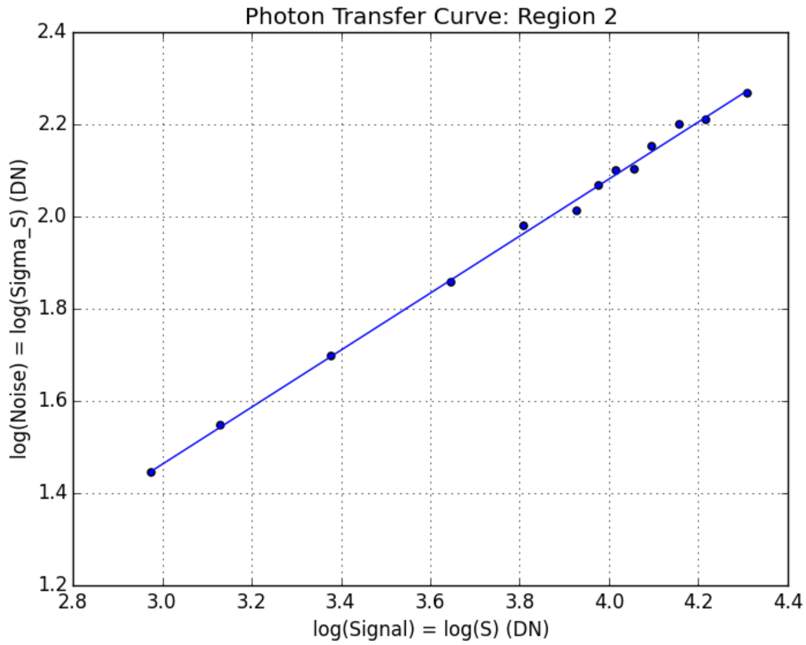

Figure 3: Photon noise dominated region of curve

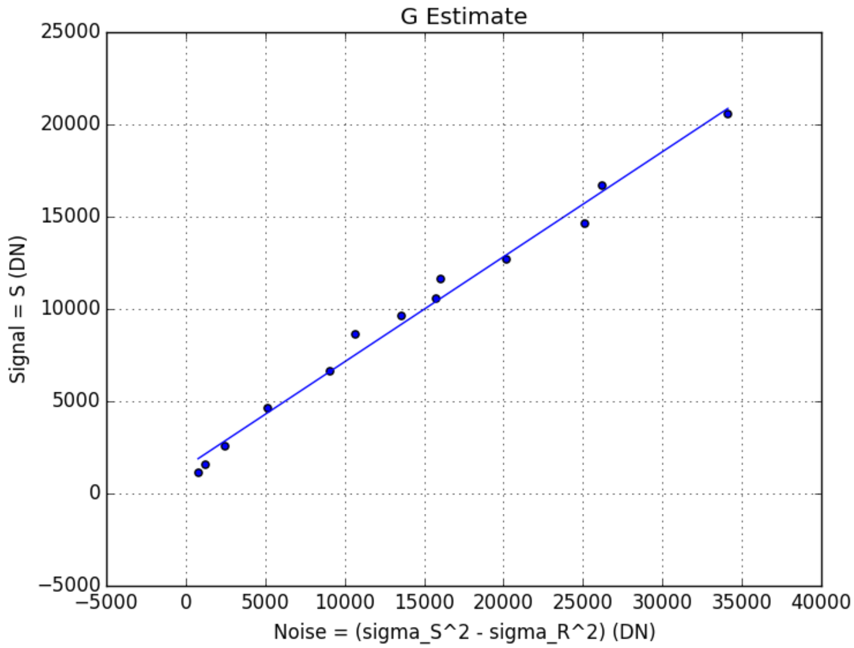

Figure 4: Estimation of G

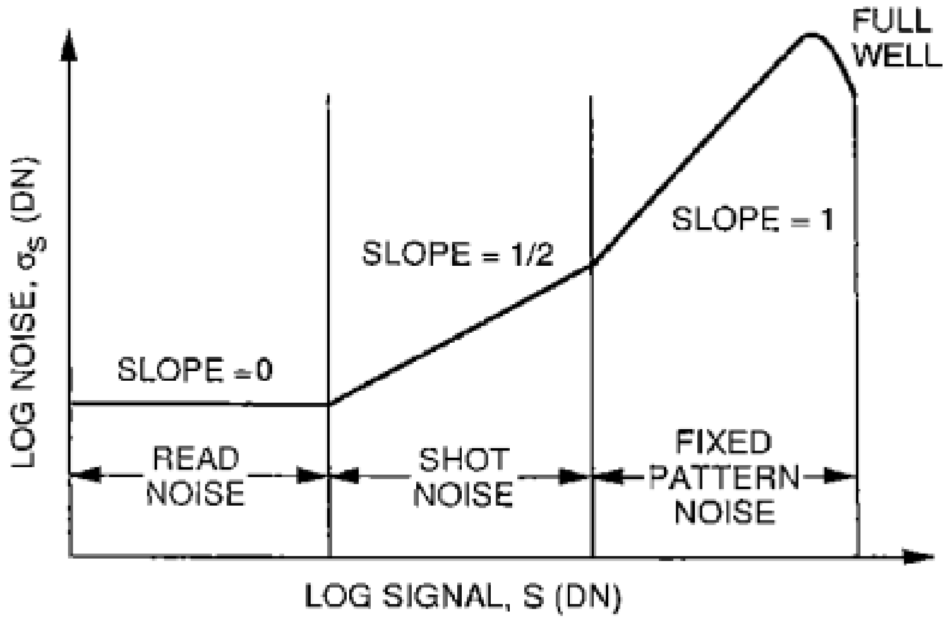

Figure 5: Ideal photon transfer curve. Source: Janesick, James R. *Scientific Charged-coupled Devices*

3.4 Linearity

The linearity of a CCD relates to the behavior of the signal it produces as a function of the exposure time of the images it captures. An ideal CCD would be perfectly linear, with its signal being directly proportional to the exposure time. The nonlinearity of the CCD can be expressed as a percentage through the following equation:

$$\gamma = \frac{Max\,positive\,deviation - Max\,negative\,deviation}{Maximum\,signal} \times 100$$

Where the maximum positive and negative deviations corresponds to the maximum distance between a series of signal values from their best fit line in a plot of signal vs exposure time, and the maximum signal is the largest signal plotted. Using the same set of data as for calculating the G factor, two 20 by 20 boxes were selected for each image, one on the upper left corner and the other on the bottom right corner. The signal vs exposure times were later plotted, and the nonlinearity of each of these lines was calculated and then averaged. Figures 6, 7 and 8 show plots for different sets of exposure times and their respective nonlinearity values. Figure 6 contains all images captured, while Figure 7 contains all images with exposure times greater or equal to 5 seconds. Finally, Figure 8 contains all images with exposure times less or equal to 20 seconds. The value of gamma was also calculated for three other sets. These are shown in Table 3.

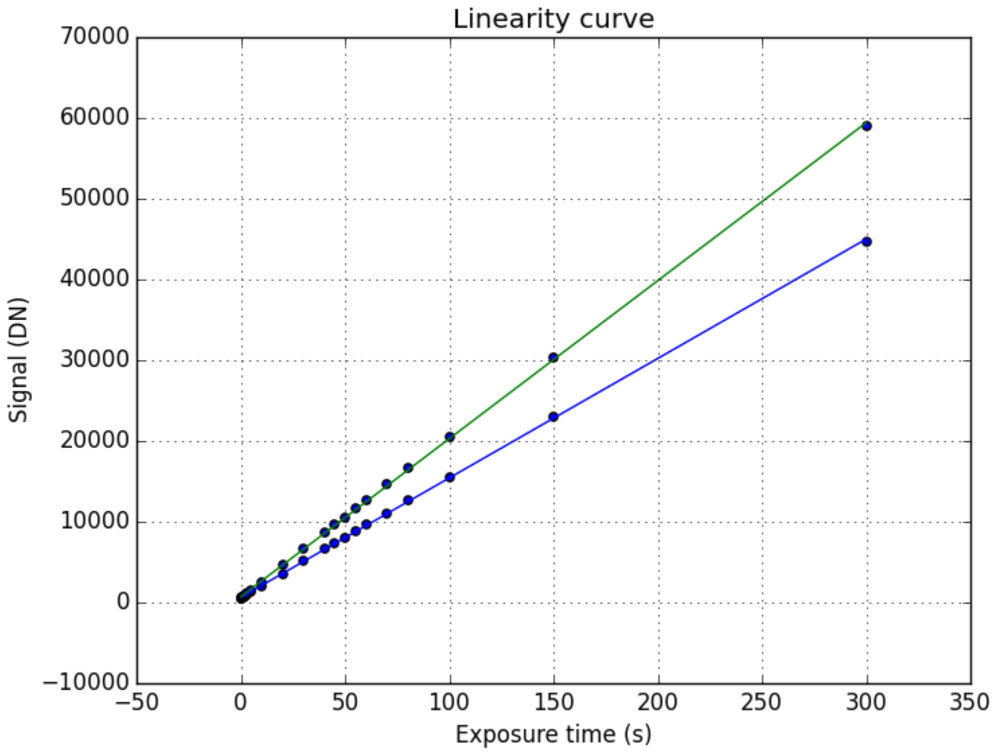

Figure 6: Linearity curve for all measurements. $\gamma = 1.115\%$

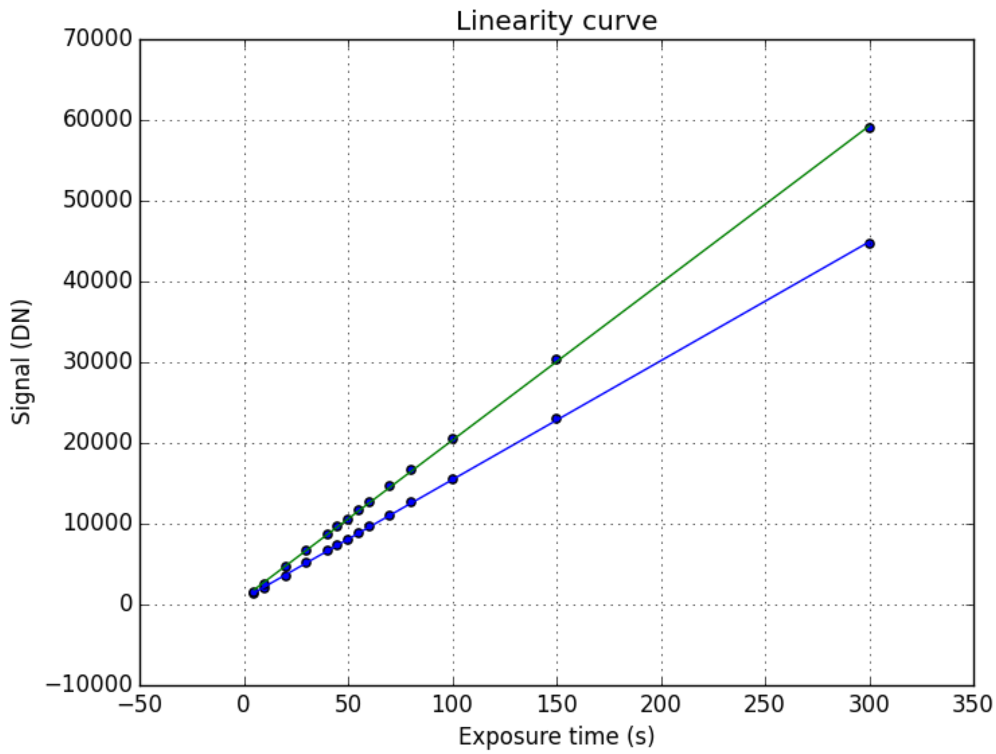

Figure 7: Linearity curve for all measurements with t_E 5. $\gamma = 1.000\%$

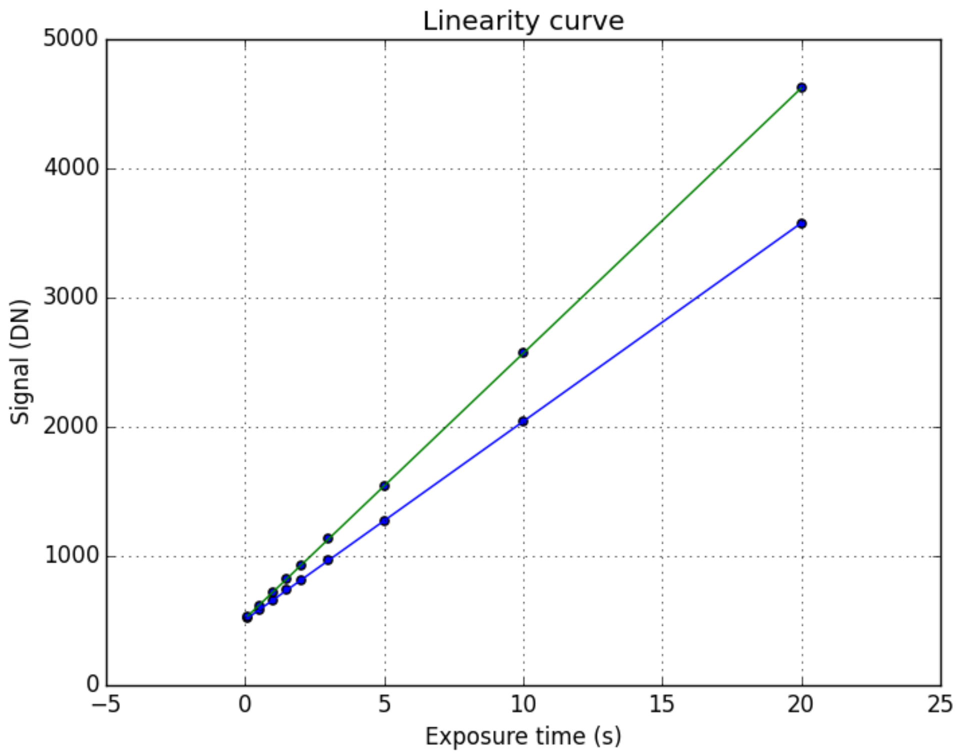

Figure 8: Linearity curve for all measurements with t_E 20. $\gamma = 0.176\%$

Table 3: Nonlinearity

Exposure time (s)	γ (%)
20	0.176
50	1.149
70	0.816
100	0.842
300	1.115

There does not appear to be a clear relationship between the nonlinearity of the data sets and their exposure times. One conclusion that can be drawn is that the data is almost perfectly linear for the first few points, and then it increases to a value close to 1%. Another conclusion that this data appears to point towards is that distortions due to the opening and closing of the shutter are not noticeable. Measurements with exposure times of less than 0.1 second might have produced different results, but these were not made.

3.5 Blooming

Blooming is the name given to a particular phenomenon that affects images produced by a CCD that has been exposed to a photon field that contains a high concentration of photons in a small area. After a long enough exposure, these photons overwhelm the electron wells that map that particular area of the field, and they start overflowing with electrons that proceed to fall into adjacent wells, producing the illusion of a signal in places where photons are not actually arriving at.

Observation of blooming in this experiment was done by exposing the CCD to a point light source and then taking a total of four exposures, each two times longer than the previous one, starting with a 1 second exposure. Blooming was observed for both the 4 and 8 second exposures. For each of the images captured, the pixel that contained the maximum counts was located and its value measured. Table 4 shows the results of these measurements and Figure 9 contains a plot of the maximum counts vs the exposure time. The relationship between signal and exposure time was found to be nonlinear, which is to be expected since some of the electron wells in charge of measuring the signal coming from the direction of the point source were overwhelmed. Thus, they were unable to measure the total signal coming from the source, instead redistributing electrons into adjacent wells, essentially sharing data counts with them. This means that the expected shape of the plot would be one were the difference between the maximum data count for each of the exposures would decrease as the exposure time increased, which corresponds to the actual shape observed. This is made more explicit in Table 4.

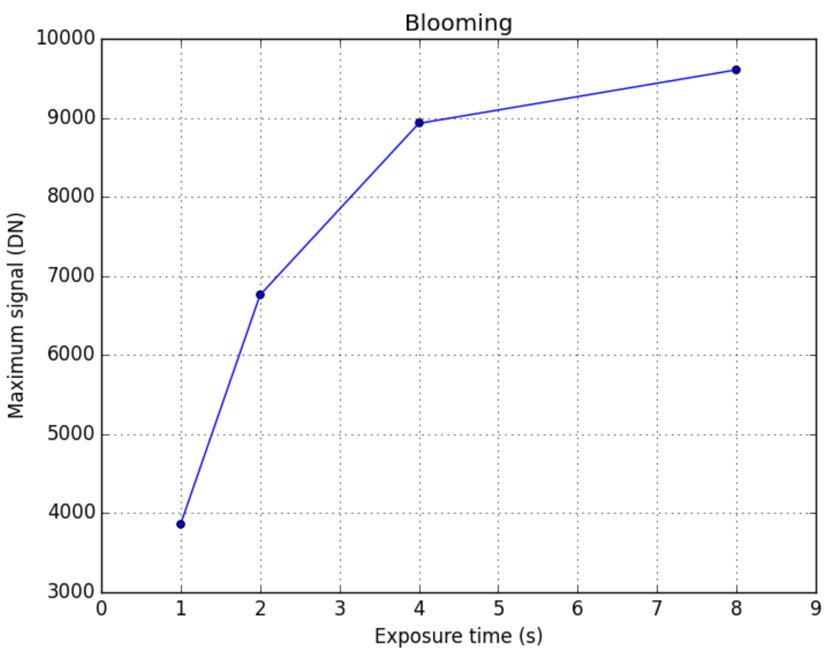

Figure 9: Maximum signal as a function of exposure time

Table 4: Exposure time and maximum signal

Exposure time (s)	Maximum signal	Signal gain
1	3862	
2	6759	2897
4	8929	2170
8	9606	677

References

Janesick, James R. "CCD Transfer Curves and Optimization." *Scientific Charge-coupled Devices.* Bellingham, WA: SPIE, 2001. 95-119. Print.