CCD Laboratory Evaluation
Observational Techniques for Astronomy (AST 6725)

Alyssa Bulatek, Michael Estrada, Rachel Losacco, Sheila Sagear

October 15, 2020

1 General Objectives

Though it is generally not true that a carpenter is only as good as the tools they have at their disposal, it is important for craftspeople to know the characteristics of their tools well before they begin to use them in earnest. The same adage rings true for the astronomer. In order to understand our data, we must understand the tools we use to take our data. In particular, we would like to know how our CCD translates light we see from an object we are observing into electronic signals that we can read. There are four particular characteristics that we focus on in this lab: read noise, dark current, gain, and linearity. All of these characteristics affect the way that the CCD records data, and so the particulars of each effect are important to understand. Each characteristic is discussed in more detail in the sections that follow.

2 Experimental Setup

Sarik ran the lab for us from his office. The CCD was housed within a cardboard box for most of the lab. The box had oval-shaped holes as handles, but they were obscured by a computer case and the wall for most of the lab. When the CCD needed to be illuminated, the box was removed and one (or two) computer monitors were placed the CCD to allow light into the shutter. Sheila ssh'ed into the computer to do the actual data acquisition while the rest of us joined in on the Zoom call.

3 Read Noise

Objective: Our first objective was to estimate the read noise of the CCD, or the statistical noise generated by the output circuitry in the detector while it is not being illuminated.

Methods: In order to estimate the read noise of the detector, we took nine consecutive dark exposures, each 0.1 seconds long. In Python, we stacked these exposures in an array and calculated the RMS of each pixel value across the nine images. The mean (and median) values of this RMS array should represent the average read noise of the detector in DNs, and the RMS value of the RMS array should represent the statistical spread in that average read noise value. When we divide the RMS by the square root of the number of pixels on the detector, we get the uncertainty on the average read noise value. In the data processing process, I called this the "array averaging" method for measuring the read noise.

A more statistically robust way of estimating the read noise and the spread in the read noise is to assume that the read noise values as measured per pixel lie in a Gaussian distribution about some mean value and with some statistical spread around that value. So, we can fit a Gaussian curve to a histogram of the values in our RMS array to get another estimate of the read noise and a value which represents the spread of values around our average estimate. The uncertainty in the average read noise for the Gaussian fit method can also be computed in a similar way to the "array averaging" method, by dividing the RMS value by the square root of the number of pixels.

We also took six more dark exposures with longer exposure times (three at 1 second and three at 10 seconds, which are 10 times and 100 times our original exposure time respectively) to determine if there was a measurable difference in read noise with exposure time. We estimated the read noise via the "array averaging" method, comparing our average read noise value, RMS, and uncertainty to the 0.1 second exposure values.

We could attempt to determine is a light leak in the CCD housing by taking several dark exposures of equal exposure time, with half of them taken under normal conditions and the other half taken when a bright light was being shined onto the detector (the room lights or a desk lamp could work). If the median pixel value of the median-combined "bright" frames is significantly higher than the median pixel value of the median-combined "dark" frames, then there may be a light leak. We did not test this due to time constraints.

Results: Our initial estimates for the average read noise of the detector as well as the statistical spread and uncertainty on that value are presented in Table 1, denoted with "array averaging" in the method column. The mean value of the RMS array that we calculated was 25.376 DNs and the median value was 25.078 DNs; averaging these two values together, we get an average read noise of 25.227 DNs. The RMS of the RMS array, which represents the statistical spread in the average read noise value, is 6.538 DNs. The uncertainty in the average read noise, or the RMS value divided by the square root of the number of pixels (8,487,264), is 0.002 DNs (rounded to one significant figure).

Our estimates for the average read noise using the Gaussian fitting method are also presented in Table 1, denoted with "Gaussian fit" in the method column. An graphical representation of the Gaussian fit to the histogram of the values in our RMS array is shown in Figure 1. After performing the Gaussian fit, we got a mean value of 24.426 DNs for the average read noise and a value of 6.443 DNs for the statistical spread in the histogram. We also computed the uncertainty in the average read noise by dividing the RMS value by $\sqrt{8487264}$, which gives us 0.002 DNs. The read noise value we estimated using the Gaussian fitting method is slightly lower than the read noise from the array averaging method, but they are within 1σ of each other. The two average read noise estimates do not fall within the measurement uncertainties calculated for each value, though. The uncertainties we calculate via the two different methods are quite close (rounded to one significant digit, they are identical).

The estimated average read noise, statistical spread, and uncertainty for our longer exposure times (1 second and 10 seconds) are also noted in Table 1, with their exposure times noted in the final column. We note that the average read noise estimates are lower for these longer exposure times, but the statistical spread on those estimates are also higher ($\sim$10 DNs), so the values are within the statistical spread of each other. The higher statistical spread and uncertainty are likely due to the fact that we are only averaging three frames together for the longer exposure times.

Summary: We estimated the read noise of the detector as well as the statistical spread in the read noise and its uncertainty using two different methods, one slightly more statistically robust than the other. Using the "array averaging" method, where we calculate statistics from an RMS array of nine 0.1 second dark exposures, we estimate an average read noise of 25.227 DNs with a statistical spread of 6.538 DNs and an uncertainty of 0.002 DNs. Using the "Gaussian fit" method,

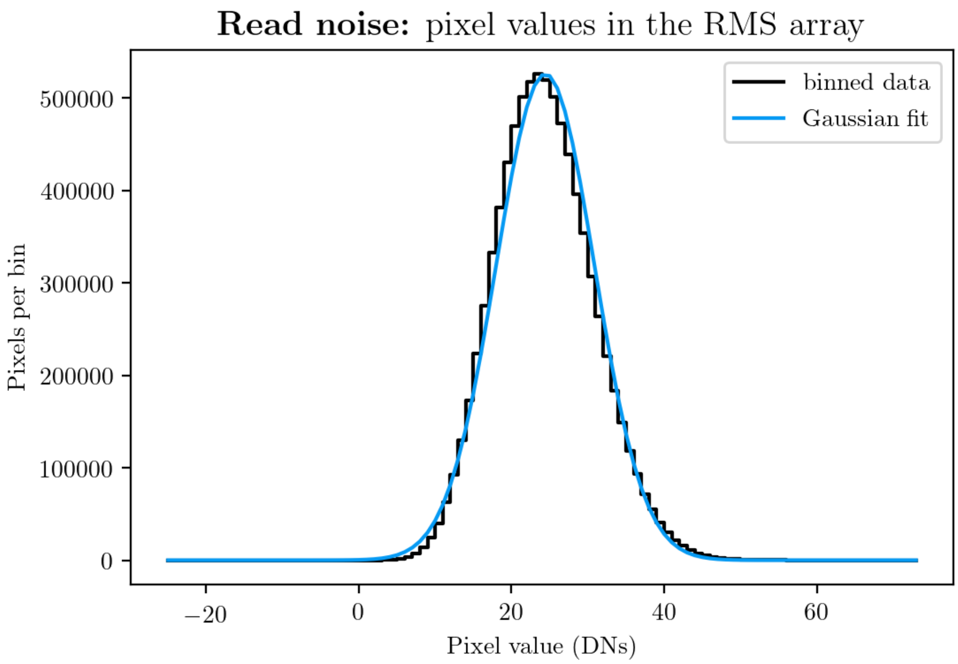

Figure 1: A histogram of the read noise measurements with a smooth Gaussian fit to that histogram overlaid. We used the best-fit μ (mean) and σ (statistical spread) values from the Gaussian fit to measure the read noise and uncertainty via this method.

Characteristic	Value	Method (exposure time)
Average read noise	25.227 DNs	array averaging (0.1 s)
Statistical spread in average read noise (σ)	6.538 DNs	array averaging (0.1 s)
Uncertainty on average read noise	0.002 DNs	array averaging (0.1 s)
Average read noise	24.426 DNs	Gaussian fit (0.1 s)
Statistical spread in average read noise (σ)	6.443 DNs	Gaussian fit (0.1 s)
Uncertainty on average read noise	0.002 DNs	Gaussian fit (0.1 s)
Average read noise	19.449 DNs	array averaging (1 s)
Statistical spread in average read noise (σ)	10.543 DNs	array averaging (1 s)
Uncertainty on average read noise	0.004 DNs	array averaging (1 s)
Average read noise	19.556 DNs	array averaging (10 s)
Statistical spread in average read noise (σ)	10.635 DNs	array averaging (10 s)
Uncertainty on average read noise	0.004 DNs	array averaging (10 s)

Table 1: A summary of our estimated read noise for the detector along with measures of statistical spread and uncertainty. Our measurements for the read noise and related uncertainties for different exposure times (0.1, 1, and 10 seconds) are shown along with the results we got from using a Gaussian fit to measure the average read noise value more robustly.

where we fit a Gaussian curve to the distribution of pixel values in the RMS array, we estimate an average read noise of 24.426 DNs with a statistical spread of 6.443 DNs and an uncertainty of 0.002 DNs. These values are very close to each other within their respective statistical spreads, as are our estimates of the average read noise as taken from longer exposure times.

4 Dark Current

Objective: Our next objective was to measure the dark current in the CCD, or the rate at which the detector builds up signal while unilluminated due to the thermal properties of the detector.

Methods: To measure the dark current in the CCD, we need several exposures at progressively longer and longer exposure times. We used five exposure times: 1, 5, 25, 125, and 500 seconds. Between each of these exposures, we took short (0.2 second) bias frames, but we did not end up incorporating those images into our analysis.

By taking images at increasingly larger exposure times, we can measure dDN/dt, or the slope that governs the (hopefully) close to linear relationship between the number of counts we get at each exposure time and the exposure time itself. This slope will be our value for the dark current.

For this calculation, we also used both an "array averaging" and a "Gaussian fit" method to measure the mean pixel value in each image. In the "array averaging" method, we calculated the mean and standard deviation of each frame at each exposure time. We can then perform a linear fit on the data and use the value of the slope as our measured dark current.

We can be more statistically robust by using a "Gaussian fit" method to calculate the mean and statistical spread of the pixel distributions at each exposure time. We repeated this analysis with the Gaussian fit method, fitting a line to the data and using its slope as the measured dark current value.

Results: Our measured values for the dark current using both measurement methods are reported in Table 2. I did not manually perform error propagation to determine the uncertainty on the dark current measurement, but I do report the uncertainty on the linear fit, which takes into account the uncertainties on each of the data points. Those uncertainties are also reported in the table. For the "array averaging" method, we measured a dark current of 0.27 DN/s with an uncertainty of 0.05 DN/s. For the "Gaussian fit" method, we measured a dark current of 0.25 DN/s with an uncertainty of 0.01 DN/s.

We plotted the pixel values as a function of exposure time in Figures 2 and 3 for the array averaging and Gaussian fit methods respectively. The data values are shown as black dots in both figures, and the dashed line represents the linear fit to the data, the slope of which is our estimate for the dark current.

Characteristic	**Value**	**Method**
Average dark current	0.27 DNs/s	array averaging
Statistical spread in average dark current (σ)	0.05 DNs/s	array averaging
Average dark current	0.25 DNs/s	Gaussian fit
Statistical spread in average dark current (σ)	0.01 DNs/s	Gaussian fit

Table 2: A summary of our estimated dark current for the detector along with a measure of statistical spread. We show the measurements we made using both the "array averaging" method as well as the more robust "Gaussian fit" method.

Summary: We estimated the dark current in the detector as well as a measure of uncertainty on our estimated value using the same two methods we used to estimate the dark noise. In the first method, we calculated the average signal level in dark exposures of progressively longer exposure time, and calculated a linear fit on those signal values versus exposure time. The slope we measured (0.27 DN/s) represents our dark current measurement (with $\pm$ 0.01 DN/s as our uncertainty). For the second method, we created a histogram of the pixel values for each exposure time, fit a Gaussian to the histograms, and plotted the mean and sigma values of each Gaussian versus their exposure time. We then fit a line to the mean values versus exposure time, and that slope (0.25 $\pm$ 0.01 DN/s) served as another measure of the dark current.

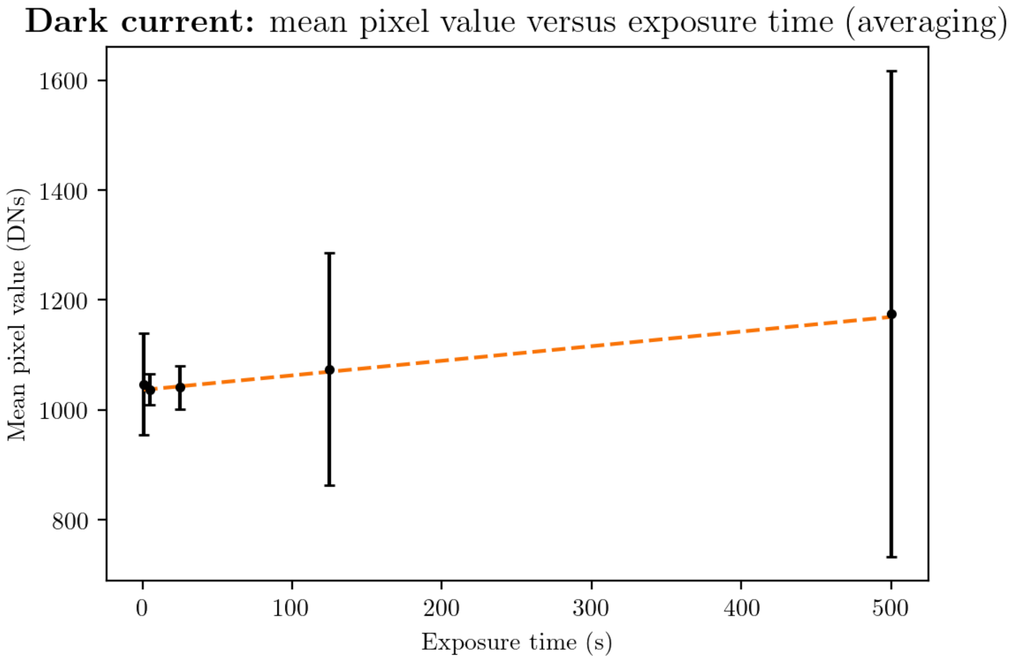

Figure 2: Mean pixel values (measured using the "array averaging" method) for the dark current measurements with progressively longer and longer integration times. The mean values are shown in black dots with error bars representing the uncertainties on the mean values. The orange dashed line is the linear fit to our data, taking into account the uncertainties. The slope of the dashed line is our dark current value.

5 Gain

Objective: Next, we wished to determine the relationship between the number of counts (DNs) measured by the detector in a given pixel and the number of electrons liberated in that pixel, also known as the gain (in units of DNs per electron). To do this, we needed a measure of the variance in each pixel as well as the signal, giving us over eight million distinct estimates of the gain.

Methods: As suggested by Sarik, we used Group 4's data for this section since our data were not satisfactory. For this section, they attempted to uniformly illuminate the detector such that the average pixel value at an exposure time of 100 seconds was about 50,000 DN. Group 4 took a series of exposures at increasing exposure times (0.1, 1, 5, 15, 25, 50, 75, and 100 seconds) so they could probe a variety of signal strengths. They took three exposures at each exposure time (though for certain exposure times, they actually took four exposures—I selected the latter three in case something had happened to the first exposure, though I did not consult with the other group on this).

We imported each of the three images at each exposure time and calculated the pixel-wise mean and standard deviation of each pixel across the three images, leaving us with a mean array and a standard deviation array for each exposure time. We then squared the standard deviation arrays to get the variance arrays. Next, we calculated the median of each of the mean arrays to get a measure of the "signal" at each exposure time, and we calculated the median of the variance arrays

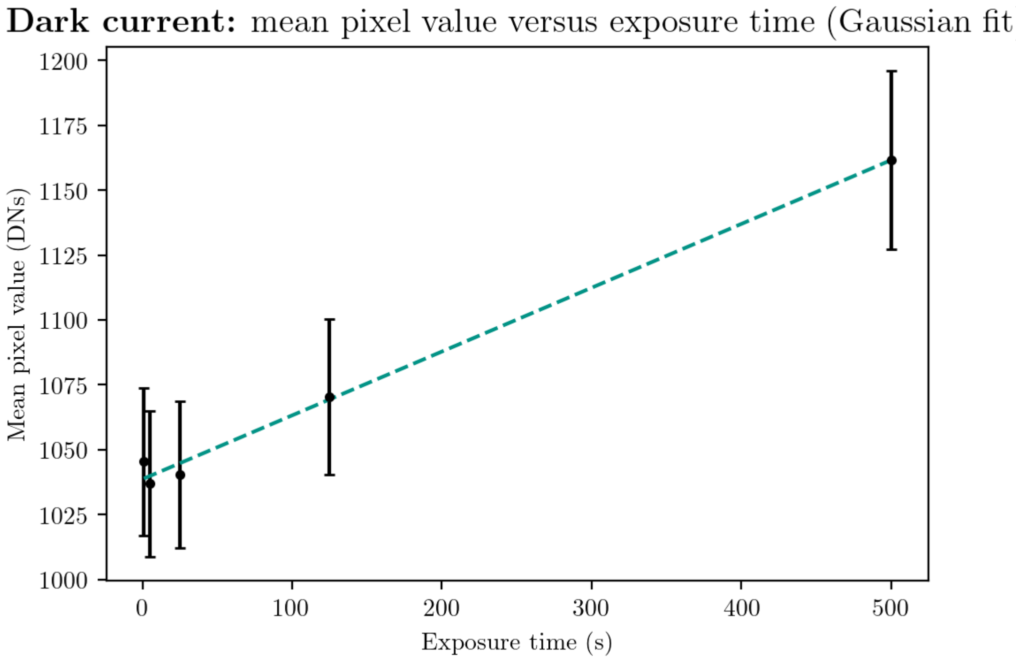

Figure 3: Mean pixel values (measured using the "Gaussian fit" method) for the dark current measurements with progressively longer and longer integration times. The mean values are shown in black dots with error bars representing the uncertainties on the mean values. The teal dashed line is the linear fit to our data, taking into account the uncertainties. The slope of the dashed line is our dark current value.

to get the variance at each exposure time. We plotted these variance values versus signal, and performed a linear fit on those data points. The slope represents our gain in DNs per electron. We also calculated the uncertainty on this fit based on the covariance matrix output from `curve_fit`.

Results: The results for our gain measurement as well as the uncertainty on the measurement are given in Table 3. Our average gain value from the linear fit was 1.8 DN/electron with an uncertainty of 0.4 DN/electron. Nazar found a reported value from the manufacturer of 2.78 DN/electron, which is within 3σ of our estimated value. A systematic effect that could have affected our measurement is the fact that it is unlikely that the CCD was fully illuminated given the laboratory environment it was in. This would cause there to be many dark areas of the CCD, which would draw the average pixel value down artificially. This could result in an underestimate of the gain. We plot the variance versus the signal in Figure 4. The slope of the dashed line is is the gain value.

Summary: We (or, really, Group 4) estimated the gain value of the detector by taking a variety of exposures of different signal strengths with the detector illuminated. We then calculated the mean and variance in each pixel at each exposure time, and took the median of each of those values for a given exposure time. Plotting variance versus signal, we fit a line to our eight data points and measured the slope, which gives us an estimate of the gain. We calculated a gain value of 1.8 $\pm$ 0.4 DN/electron, which is within 3σ of the value reported by the manufacturer of 2.78 DN/electron.

Characteristic	Value	Method
Average gain	1.8 DN/electron	array averaging
Statistical spread in average gain (σ)	0.4 DN/electron	array averaging

Table 3: A summary of our estimated gain for the detector along with a measure of statistical spread.

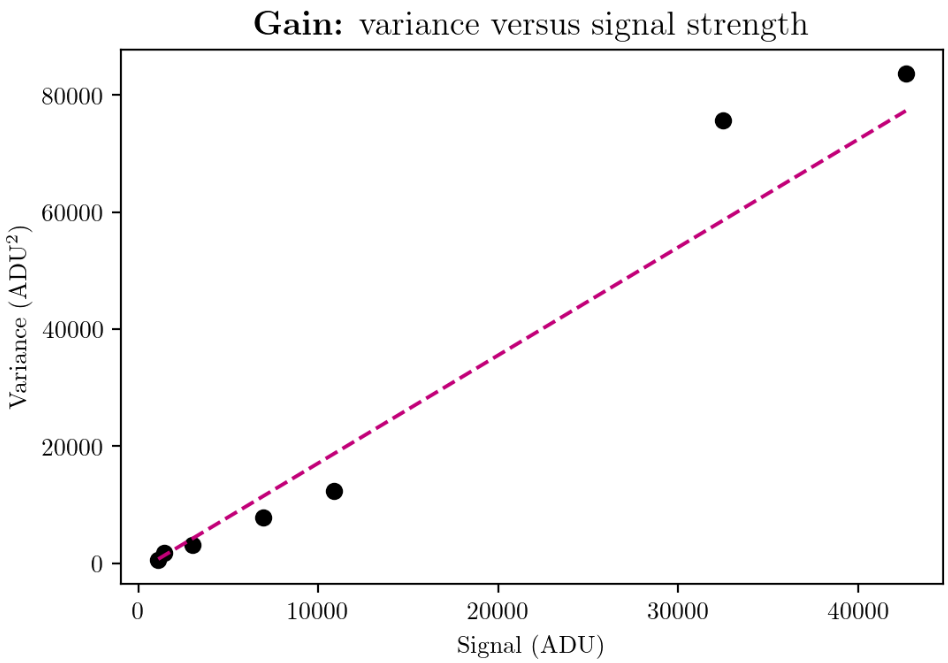

Figure 4: Variance versus signal for a variety of exposure times. The pink dashed line is a linear fit to the data. The slope of the dashed line represents our estimate of the gain for the detector.

6 Linearity

Objective: Finally, we wanted to measure the linearity of the response of the detector as a function of light level. Ideally, the number of counts reported by the detector would be proportional to the number of photons striking the detector. We can see if this is true if we take images of different exposure times that give us a wide range of pixel values while keeping the illumination constant, allowing us to measure the linearity of the detector response as a function of exposure time.

Methods: We also used Group 4's data for this section due to time constraints on the day we took our data. Group 4 used two different illumination setups: the "ambient" setup, in which two computer monitors were used to illuminate the detector, and the "dim" setup, where only one monitor was used. This was used to measure the difference in linear behavior in different light levels. Group 4 took a series of exposures in the ambient light (at 1, 3, 10, 30, 60, 120, and 180 seconds) and in the dim light (at 3, 10, 30, 60, 120, 180, 240, and 300 seconds). We took the median pixel value at each exposure time for each light level. Then, we simply plotted each pixel value as a function of exposure time, fitting a line to the data and qualitatively assessing how linear the data looked.

Results: We plotted the median pixel value for each exposure time for each light level in Figure 5. We can see that for the dim lighting conditions, the relationship between median pixel value and exposure time is described well by a line. For ambient lighting conditions, however, a linear fit does not describe the data well—at longer exposure times, we see a drop in the median value.

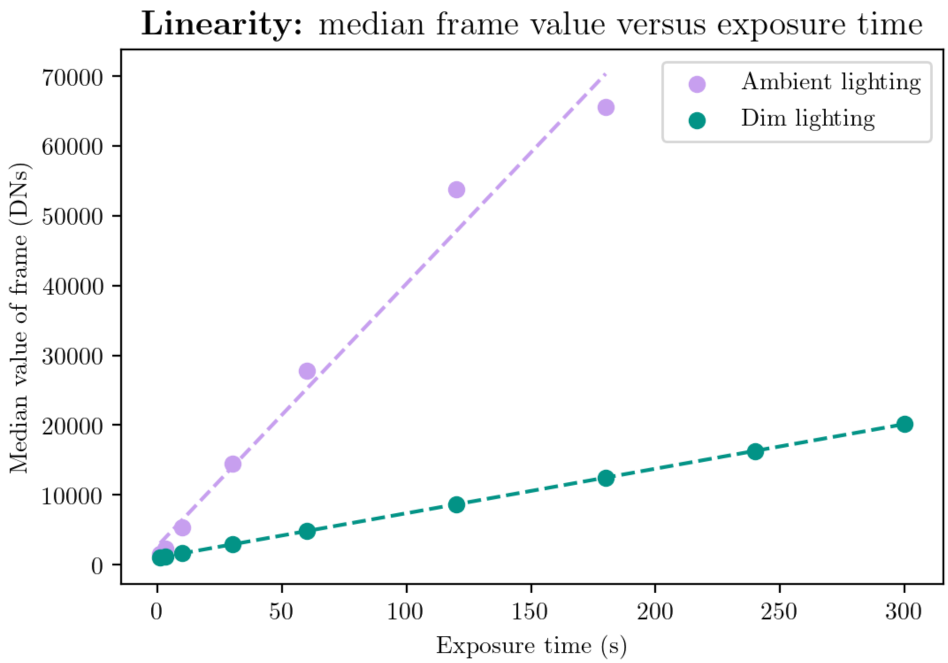

Figure 5: Median pixel value as a function of exposure time for two different light levels. "Ambient" lighting was under the illumination of two computer monitors, while "dim" lighting was under the illumination of a single computer monitor. The ambient lighting conditions show nonlinearity at higher exposure times, as can be seen by the non-ideal linear fit. Conditions are more linear for the dim lighting scenario.

Summary: We measured the linearity of the detector response by taking progressively longer exposure times under two different lighting conditions. We note that in dimmer conditions, we see generally linear behavior across all exposure times we took images at. In the brighter conditions, we see deviation from linearity at longer exposure times.

7 Additional Characteristics

We were unable to measure blooming with the CCD because we did not set up a point source in the lab. Also, we were not able to measure the charge transfer efficiency due to the high quality of the CCD.

8 Conclusion

Table 4 shows a summary of each of the characteristics we measured in this lab, as well as uncertainties on each value. Regarding strange results, we were getting strange results on the first day of lab, likely due to a faulty USB connector on the CCD. It seemed to fix itself on the second day of lab, although we ran out of time and had to use another group's data. An aspect of the lab that could improve our results would be to perform the lab in a windowless room so that changing ambient light conditions from outdoors do not affect our data significantly. Since we were doing the lab around sunset, this may have affected the lighting conditions in the lab over time.

Characteristic	**Method**	**Value**	**Spread (σ)**	**Uncertainty**
Read noise	array averaging (0.1 s)	25.227 DNs	6.538 DNs	0.002 DNs
Read noise	Gaussian fit (0.1 s)	24.426 DNs	6.443 DNs	0.002 DNs
Read noise	array averaging (1 s)	19.449 DNs	10.543 DNs	0.004 DNs
Read noise	array averaging (10s)	19.556 DNs	10.635 DNs	0.004 DNs
Dark current	array averaging	0.27 DNs/s	0.05 DNs/s	
Dark current	Gaussian fit	0.25 DNs/s	0.01 DNs/s	
Gain	array averaging	1.8 DN/electron	0.4 DN/electron	

Table 4: A summary of our estimates of the read noise, dark current, gain, and linearity of the CCD we will use for our imaging and spectroscopy projects.