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CCD Lab Assingment

Michael Higgins[1]

[1] *Astronomy*

Submitted to Sarah Tuttle

INTRODUCTION

Charged Coupled Devices(CCDs) are a thirty year old device that is used in the field of Observational Astronomy. They convert incident photons into electrons that can be read into a computer to compose a digital photo. The goal of this project is to take a series of biases and flats to determine the read noise, gain, and linearity of the CCD. My data was taken from a ST-8XME CCD and I will be comparing the results of my data with the factory specifications.

1. READ NOISE AND GAIN

There are a few equations that can be used to estimate the gain(1) and read noise(2) of a CCD. These equations are functions that depend on the mean and standard deviations of flat frames and bias frames that have the same conditions and duration of exposure. The gain is the number of electrons per pixel divided by the number of counts per pixel. So our gain estimation is looking at the change in mean counts divided by the change in variance and that will give a very close approximation of the gain. Our Read Noise is just our gain multiplied by the standard deviation of our bias difference image all over the square root of 2. In order to get our read noise in terms of electrons we need to multiply by the gain again since gain is in units of e^{-}/ADU.

$$\mathrm{Gain} = \frac{(\overline{\mathrm{F}}_1 + \overline{\mathrm{F}}_2) - (\overline{\mathrm{B}}_1 + \overline{\mathrm{B}}_2)}{\sigma^2_{(\mathrm{F}_1 - \mathrm{F}_2)} - \sigma^2_{(\mathrm{B}_1 - \mathrm{B}_2)}} \tag{1}$$

$$\mathrm{Read\ Noise} = \frac{\mathrm{Gain} \times \sigma_{(\mathrm{B}_1 - \mathrm{B}_2)}}{\sqrt{2}} \tag{2}$$

Using the data from two 5 second flats and two biases I can find the values above.

$$\overline{F}_1 = 1736.86$$

$$\overline{F}_2 = 2202.33$$

$$\overline{B}_1 = 1061.02$$

$$\overline{B}_2 = 1060.81$$

$$\sigma_{(B_1 - B_2)} = 14.38$$

$$\sigma_{(F_1 - F_2)} = 41.59$$

With these values I find the gain and read noise to be

$$\mathrm{Gain} = 1.19 \frac{\mathrm{e}^{-}}{\mathrm{ADUs}}$$

$$\mathrm{Read\ Noise} = 12.13 \text{ in ADU}$$

$$\mathrm{Read\ Noise} = 14.47 \text{ in electrons}$$

The manufacturers listed gain is $2.5\frac{e^{-}}{ADUs}$ which is a bit off from our measured value, but we get a similar read noise compared to the manufacturer's 15 in electrons.

2. LINEARITY OF THE CCD

Using a series of flats from 1.5 seconds to 80 seconds I can find the mean value of each flat and

Corresponding author: Michael Higgins
higgins0@uw.edu

get an idea of the linearity of the ST-8XME CCD.

Exposure Time(Sec)	Mean Counts
1.5	3174.873510
3.0	5353.182539
6.0	9578.537012
12.0	18178.722682
15.0	23983.323802
18.0	28975.716336
24.0	36629.318385
30.0	45259.308315
36.0	52164.646178
42.0	56429.005788
48.0	57330.156085
54.0	57626.195524
60.0	57723.531514
80.0	57786.300762

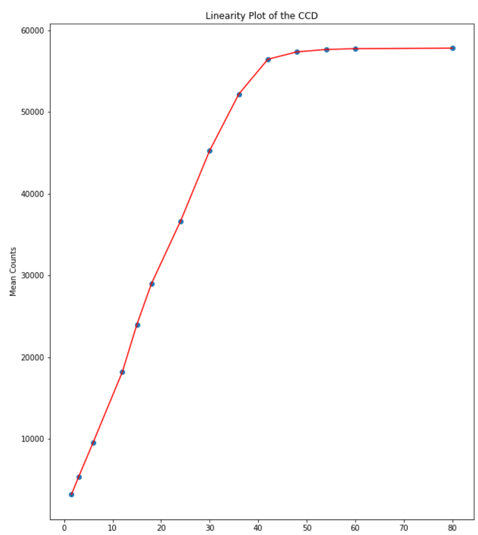

Figure 1. Plotting the data from above.

In 1x1 binning our CCD reaches full-well capacity before ADU saturation. We can see that after an exposure of 40 seconds the counts plateau at about 57,000 counts meaning that the wells have filled with electrons, but the 16 bit converter can still process them instead of being saturated at 2^{16} ADU.

I can conclude from my data that the ST-8XME CCD will be linear from about 3,000-57,000 counts. This is just from visual inspection of my linearity plot.

From a observational or scientific standpoint it is important to stay within a linear range on the CCD because that provides the information about how many photons are incident on the detector. Keeping within the linear range of the detector allows one to compare the number of photons received between pixels since the number of counts corresponds linearly to the number of photons received.

The ST9-XE has a 16-bit converter so that means it will reach ADU saturation at 2^{16} or 65,536 ADUs. Since it has a full-well capacity of 150,000 electrons so dividing that by the gain will yield a full-well capacity of 93,750 ADUs. This means ST9-XE will reach saturation before full-well capacity in 1x1 binning. If it is 2x2 binning we will have the same problem since we are just increasing the full-well capacity while the A/D saturation remains the same.

If we were to use a UV or IR filter our detector should still reach full well capacity before A/D saturation. This is because the different wavelengths would just have different quantum efficiencies - typically lower than the QE in visible light regime. This would mean that a lower percentage of the incident photons are turned into electrons, but this does not change anything about what form of saturation we achieve first. The linearity would be better with a filter on though. This is because with a filter we would only be letting a small band of wavelengths into the detector and they should all have a similar QE with the detector so they will be linear with themselves. This is opposed to letting all forms of light into the detector and having some wavelengths of photons better converted into electrons and read by the computer, thus making some wavelengths have different slopes for counts vs exposure time.

3. DARK CURRENT AND BAND GAP ENERGY

We can model Dark Current as a function of temperature using equation 3.

$$D = 2.5 \times 10^{15} A I_d T^{1.5} e^{-\frac{E_g}{2kT}} \quad (3)$$

By taking 2 minute darks at various temperatures we can plot what the dark current looks like as a function of inverse temperature. In the graph below the red curve is my data and the blue curve is a fitted model based off equation 3.

In order to solve for the band gap energy E_g I fit a model of the form $D = \alpha e^{-\frac{E_g}{2kT}}$. I told the model to assume that $E_g = 1.1\ eV$ since that is what the expected energy band gap is for silicon. After establishing a fit for the data I printed the fitted value for E_g and found that is was Fitted $\mathrm{E_g} = 1.22$ eV. This value is very

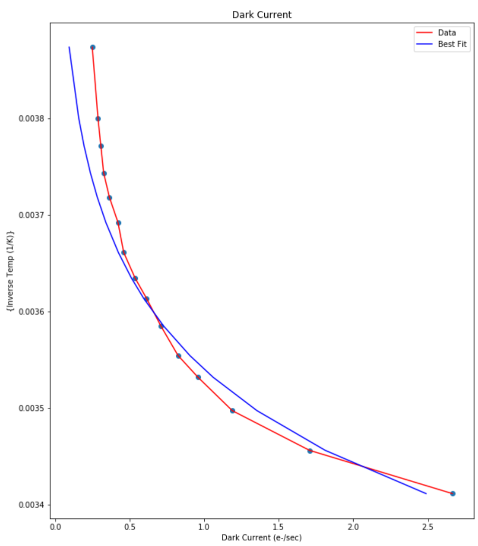

Figure 2. Plotting Dark Current Data.

reasonable considering it is only about 10% away from the band gap energy of silicon.

At high temperatures D will converge to infinity and the only thing that will determine the upper temperature limit is how hot the CCD can get before melting or malfunctioning. At low temperatures D will converge to 0.

By assuming that D is a function of the form $D = \alpha e^{-\frac{E_g}{2kT}}$ we disregard the $T^{1.5}$ term by assuming it is close to constant across our measurements. This means that the estimate of the slope term uses the average of the temperatures we measured so it will cause us to underestimate the dark current at higher temperatures and over estimate it at lower temperatures. This effect can be clearly seen on the Dark Current graphs above.

Our value for the dark current at 273 K is $D(273) = 77098901498.76e^{-\frac{1.22}{2k(273)}} \approx .42\ e^{-}/pixel/sec$. My value is about half what the expected value is. This may have happened because we did not take enough data points over a wider range of temperatures. If we took more measurements at different temperatures I would expect our fit to become more similar to the data given by the manufacturer and this would be how I would test that hypothesis. It is also possible this happened because I assumed the slope of the exponential to be constant with temperature and I assumed the energy band gap to be constant with temperature. Both of these could have contributed to why my estimated value for the dark current at 273 K is different from the manufacturer.

4. SUMMARY

Comparing my values to the manufacturer values shows that there may have been some issues with the way I gathered data or moreover that I just did not gather enough data. For the ST-8XME the read noise should be 15 electrons, and I found that it was 14.47. This number is very close the the manufacturers so I must have done decently well there. My only worry is that my bias frames were not short enough and that if I could have taken shorter biases I would have gotten a better value. I was relatively far off on what the gain should be. I found that the gain was $1.19\frac{e^{-}}{ADUs}$, but the actual gain should be $2.3\frac{e^{-}}{ADUs}$. I was about a factor of 2 off from the actual value, but still managed to get a similar read noise. My dark current value was about half of what the manufacture listed value was. I believe this occurred because I did not have a wide enough spread of darks at various temperatures and that more data points would have led me to a value closer to the manufacturers. Moreover, I learned that with some basic software and careful data acquisition I could determine a lot about the CCD I operate.