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CCD Characterization
Lab Report

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1. INTRODUCTION

Pictures and digital images are integrated in todays world, but most do not know how complicated the electronics actually are. Light detectors, commonly charge coupled devices (CCDs) or CMOS sensors, are the magic behind cameras. CCDs have come a long way in the last thirty years, with more precise construction, design, and treatment. A CCDs characteristics can affect and limit our analysis of the incoming photons from distant stars and galaxies. In this lab we analyze the gain, read noise, linearity, dark current, and band-gap energy of CCD Kodak KAF-0402E/ME + TC-237.

2. PROCEDURE

When characterizing a CCD, there are certain types of images that tell us information. Bias images, for example, are taken with zero exposure time, and the standard deviation of the bias pixel read out is the read noise in electrons. When the detector is exposed to a uniform source (perhaps pointing at a dome or a twilight sky), this is a flatfield image. The variation in the flats comes from both read noise as well as a random Poisson noise of the incoming light (the square root of the signal).

My group used the SBIG ST-7/7E/7XE camera (attached to the small spectrograph Kia) in the Imaging Lab space. The camera is pointed into a closed box, and to let a small amount of light in, we used a pencil to prop the lid open. The software used is CCDsoft, on an old Windows XP computer. We made sure to use the autoguider instrument to take images rather than spectra. In this lab, all images were in 1x1 binning for consistency and simplicity. The Take Image tab has a Frame drop down menu to select the type of image, as well as an Exposure area to set exposure time.

1. To get set up, we switched on the camera and connected it to the computer. We set the temperature control to -5°C and waited for it to cool down.

2. We selected bias in the Frame menu and took three bias frames. This took no time since the exposure time is 0 sec.

3. After selecting flats from the Frame menu, we took three flats at 29.5 seconds exposure time. We chose this time since it had ample exposure but was certainly not at saturation point. These flats were later used in gain calculation.

4. To get a range of data for plotting linearity, we followed a pattern of seconds: 0.14, 0.28, 0.56, 1.13, 2.25, 4.5, 9.00, 12.5, 27, 36, 45, 54, 63, 72, 81, 90, 99, 108, 117, 126, 135, 144, 153, and 180 to ensure we passed saturation point.

5. Once saving all of these images, we turned off temperature control and allowed the camera to warm closer to room temp, disconnected, and powered off.

6. After collecting data, I used the python packages astropy, numpy, matplotlib.pyplot, glob, and scipy.optimize. The full code is uploaded to my github. Astropy.fits can access and read fits files' headers and data, and ax.imshow plots them. I used glob to read in all flat files for creating the photon transfer curve for looking at linearity. Numpy has the math functions for calculating means, standard deviations for the various values found.

3. GAIN AND READ NOISE

Fundamentally, CCDs pixels collect incoming photons and convert them to electrons. To measure these electrons, CCDs amplify the data, which adds an electronic read noise (the average error contributed from the amplifier to each pixel, voltage uncertainty). There is also an Analog-to-Digital Converter (conversions in ADUs, digital numbers) that digitizes the data. Gain describes the number of electrons per data in these conversions (e/ADUs); a smaller gain would have a high number of electrons per conversion, and a higher gain might leave the image extra grainy. Multiplying an ADU value by the gain will give the value in e^-, and vice versa, since gain is defined to be the e^- per AD unit.

$$Gain = \frac{(\overline{F}_1 + \overline{F}_2) - (\overline{B}_1 + \overline{B}_2)}{\sigma^2_{(F_1 - F_2)} - \sigma^2_{(B_1 - B_2)}} \qquad Read\ Noise = \frac{Gain \times \sigma_{(B_1 - B_2)}}{\sqrt{2}}$$

I defined functions of these equations to calculate gain and read noise with two flats and two biases. I used astropy.fits to find the mean counts of two 29.5 second flats and two bias frames.

For these images, the mean counts were 6739.779, 6457.847, 115.257, and 117.790. The gain is 0.3115 e^-/ADUs and the read noise is 36.3178 ADUs, or 11.3146 e^-. I use this value of gain in converting between ADUs and electrons in the linearity analysis below. If I were to use a different combo of the three 29.5 second flat images taken, the gain drops down to 0.09 and 0.1678 e^-/ADUs, read noise down to 3 and 6 electrons. This is bothersome, as I thought flats were supposed to be very similar.

When looking at a few different sub-regions, I didn't expect the values to change that much. Indeed, the gain are 0.4290 and 0.4521 e^-/ADUs– these are slightly larger (which is good, getting closer to 2.3). The read noise is also better, being 15.5 and 16.4 electrons, respectively. Since this slight increase in gain intrigued me, I plotted a gain map of a flat, shown below. It is weird to me that the average gain is less than each of the regions. The distribution of gain (lower on edges, higher in middle) makes sense, since this is visibly not a perfect flat image, with vignetting and uneven brightness.

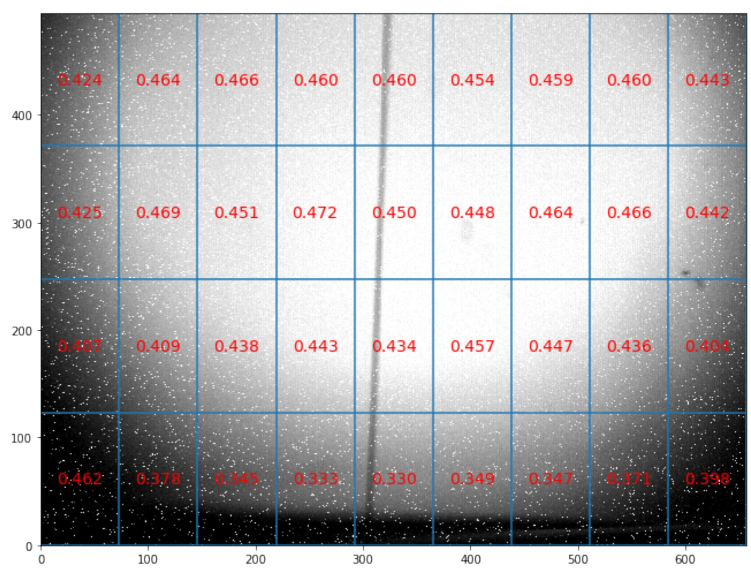

Figure 1. Gain map for one of the flats used in the calculations.

4. LINEARITY

Linearity is another important characteristic of a CCD. This is the degree to which output signal is proportional to the incoming photons received by the detector (i.e. 1 photon to 1 electron, 2:1, etc). Interestingly, the human eye behaves with more of a logarithmic than linear response. But, to have accurate quantitative photometric analysis, staying in the linear regime of a CCD is ideal. We want absolute measurements with little dependence on gain (the

CCD itself) and intensity (the type of light). Ideally, the photon signal is just the electron signal times some constant (amplification). In short, linearity can allow us to do less processing with the data.

Most CCDs behave linearly and then flatten out when the CCD is saturated. There are two types of saturation: full well, and ADU. Full well saturation occurs when the pixel wells reach capacity and cannot accept any more photons, and might even spill over. The point of this type of saturation can be decreased when binning 2x2, since four times the amount are accepted into what is treated as one pixel. The A-D converter also has a certain number of bits (how many conversions) that also have a maximum output signal, causing another saturation point.

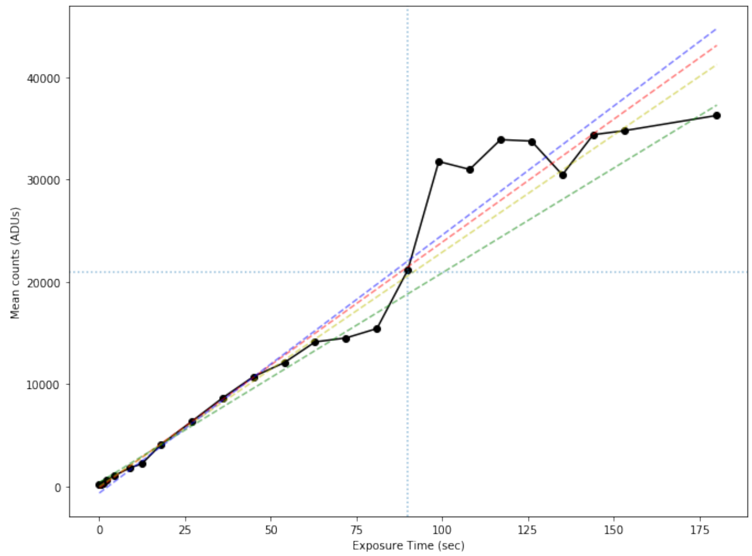

Figure 2. Mean ADUs plotted as a function of exposure time. Full well saturation points plotted in blue.

Above is a plot of mean counts in ADUs versus exposure time, with a few best fit lines plotted. The shape is the same when plotting against counts in electrons, just with a scaled value. You can tell there is definitely a linear trend in the first 90 or so seconds. Since the latter half of the data had ever so slightly more light exposure, I have approximated the linearity to occur not at the first sudden jump, but closer to 90 seconds. This implies the full well saturation occurred at about 21000 ADUs, or 6542.42 e^-. If I had said the linearity had stopped closer to 75 seconds, the full well point would be closer to 18000 ADUs.

For this CCD, the ADU sat occurs at 2ˆ16=65536 ADUs, or 5963.78 e^-. This detector reaches full-well capacity first since the count for saturation is lower. If the binning were 2x2, the full well saturation would occur at around 42000 ADUs, but the ADU sat point does not change and is less than this. Thus, higher binning results in ADU saturation occurring before full well saturation, and being more limiting when taking data.

Gain, and the points of saturation, would not change if using a filter, as they are both a property of the electronics of the detector. The saturation points also might decrease when exposed to a high intensity light. Filters would decrease total photons entering, thus decreasing the ADU response as well. Another factor to a CCD response is its quantum efficiency (QE), which describes the actual efficiency of detecting photons (number electrons/number photons) and is usually very close to (but not exactly) 1. QE is dependent on wavelength, adding another factor that can decrease the number of electrons produced in response. A standard CCD has low QE at very high or very low frequencies, but filters or coatings can increase the overall QE to improve on a CCD's performance. Thus, with filters, the linearity may indeed change.

5. BETTER DATASET

In lab we were offered a better data set. After running my code with these files, the determined values seem more reasonable. Below is a plot of Mean counts in ADUS versus exposure time, similar to above. For these files, the calculated gain is 0.7447 electrons/ADUs and the read noise is 10.2106 ADUs, or 7.6039 electrons.

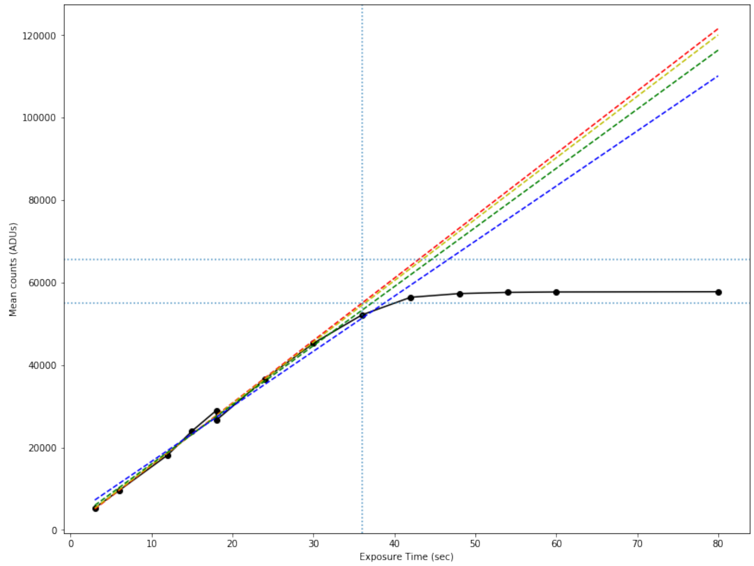

Figure 3. Mean ADUs plotted as a function of exposure time. Full well saturation point and time, as well as ADU saturation line, plotted in blue.

The lines of full well and ADU saturation are in light blue. Full well saturation occurs before ADU sat, just as above, however the two are much more similar. The graph's clean, visibly linear-then-nonlinear trend implies my previous dataset is unreliable, even though the gain and read noise values were closer to the manufacturer's value.

6. DARK CURRENT AND BAND GAP

CCDs rely on the movement of electrical charge, and nearly all of them utilize the conductivity of silicon in their design. There are electrons within the silicon that are boosted into conduction by thermal excitation, causing Dark Current (electrons/pixel/sec). Cooling the CCD decreases the dark current, but also decreases the quantum efficiency. Dark current is related to pixel area in cm^2 (A), Temperature in K (T), band gap energy (E_g), and constant dark current measured at 300 K in nA/cm^2 (I_d). Band gap is the energy difference between the Fermi level and the conduction band of the CCD. The dark current approaches zero as T approaches zero, and approaches ∞ as T approaches ∞.

$$D = 2.5 \times 10^{15} A I_d T^{1.5} e^{\frac{-E_g}{2kT}} \tag{1}$$

When analyzing dark current and band gap energy, we were given measurement data of varying Temperature and mean ADUs (see below). Each frame has an exposure time of 2 minutes (120 sec) with a bias level of 1000 ADUs. The mean ADU counts come from the difference of the dark and bias readouts to reduce noise. This data is from the ST-8XME Class 2 Camera, with properties listed here: CCD Sensor KAF-1603ME, Pixel Array (640X480) 1530 x 1020 pixels, Pixel Dimensions 13.8 x 9.2 mm, Total Pixels 1,500,000, Pixel Size 9 x 9 microns, Full Well Capacity 100,000 e-, Dark Current 1e/pixel/sec at 0°C,and Gain: 2.3 e-/ADU.

Temperature (°C)	Dark - Bias (Mean ADUs)	Temperature (°C)	Dark - Bias (Mean ADUs)
-15	13	+2	28
-10	15	+5.8	37
-8	16	+8.2	43
-6	17	+10	50
-4.2	19	+12.8	62
-2.3	22	+16.2	89
0	24	+20	139

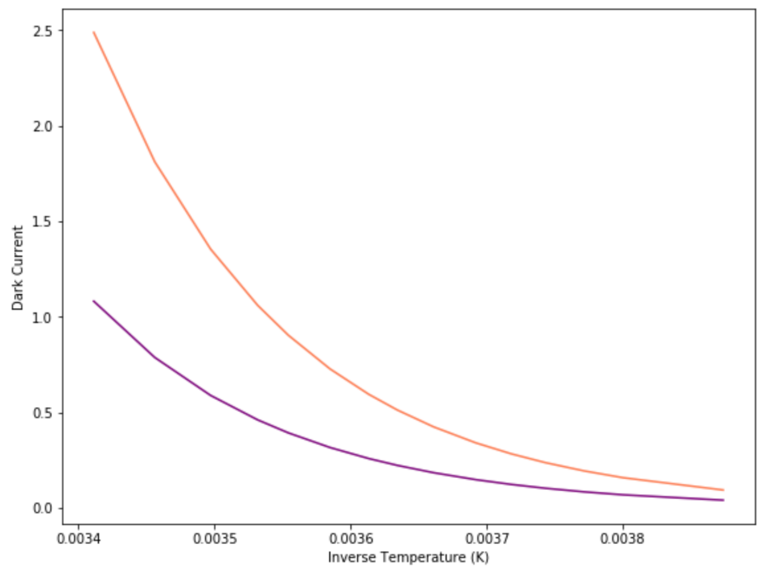

Figure 4. Dark Current versus inverse temperature. Orange is in electrons/pix/sec, purple is in ADU/pixel/sec.

I defined a function for dark current and wrote arrays of the data to analyze and plot easily. Above is a plot of dark current versus inverse temperature. The Dark Current does increase as temperature increases. When plotting the dark current in ADUs versus electrons, the graph moves down and the slope decreases, as shown in purple. At 0 °C, the dark current for this data equals 0.4242 electrons per pixel per second, or 0.18 ADUs per pixel per second (using 2.3 as gain). From the function and data, I used curve fit to find the values of the parameters in the exponential function. In this function, we can use the exponential form to have just a constant (alpha) times an exponential of slope energy/(2*Boltzmann constant, in eV/K). The best fit alpha (the first four terms of the equation) is 77098910165.43, and the best fit Band Gap Energy is 1.22 eV. This is close to the true energy gap of silicon, 1.1 eV, only off by about 9 %.

7. CONCLUSION

The manufacturer values of the camera in linearity and gain analysis are: CCD: Kodak KAF-0402E/ME + TC-237, CCD Array: 765 x 510 pixels, Pixel size: 9x9 microns, Full Well Capacity (NABG) 100,000 e^-, Dark Current 1e^-/pixel/sec at 0°C, 16 bits AD converter, A/D Gain: 2.3e^-/ADU, Read Noise: 15e^- RMS.

My derived values are: Gain: 0.3115 e^-/ADU, Read Noise: 11.3146 e^-

This gain is 86% less than the correct value, and the read noise is just 27% less. The higher error in gain might imply the simpler equations are not completely accurate. I took more data to make sure I reached saturation and had to use a different pencil to prop open the box. This slight difference in light may have introduced error into these results.

After this lab, I have seen that CCD Characterization is more precise than I first imagined. Further, CCD properties of gain, noise, dark current, and others, are very significant in data reduction and photometric analysis. Knowing more about the electronics behind collecting images will benefit me as I continue to learn about data reduction and take more images.