KANISHKA ARORA
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CCD Lab Report

Introduction

The aim of this experiment is to study certain important features of the IIST CCD. The CCD, which stands for Charge-Coupled Device, is a type of semiconductor device made from metal oxide. It works by changing light that hits its surface into electrical signals. These signals are stored in MOS wells inside the device. A CCD is made up of many of these MOS wells, called pixels, arranged like a checkerboard. After the device is exposed to light, the stored electrical signals move efficiently between pixels, like on a conveyor belt. Finally, they are converted into a digital signal with the help of an Analog to Digital Converter (ADC).

For this lab we made use of the CCDops software, ehich was installed on the lab computer

Our operating temperature = 5°

Our plan is to do the following in this lab session,

1) Understanding the working of a CCD
2) Characterization of the IIST KAF0401E CCD in the SBIG ST-7XE Camera
    a. Read Noise
    b. Dark Current
    c. Linearity
    d. Gain
    e. Charge Transfer Efficiency
3) Analyzing data using IRAF (This part can be done after the sessions on IRAF Tutorials)

Let us look at some basic terminologies that need to be understood for this lab.

1. **Read Noise**: Read noise comes from the electronics used to 'read' the CCD. Two factors contribute to this noise - (1) The charge collected within each pixel is measured as a voltage which is converted into an output Digital Number (DN). Each pixel's charge is sensed and amplified by an output low noise amplifier which is directly built into the CCD chip and hence termed as 'on-chip' amplifier (2) passage of the signal through the amplifier and the analog-to-digital convertor. The electronics itself introduces spurious electrons generating unwanted fluctuations in the output signal. Hence, read-out noise is defined as the mean error contributed to the pixel by the amplifier and the A-D convertor. The read noise is the ultimate noise floor for the CCD.

2. **Dark Current**: Random motions of atoms at normal room temperature within the silicon lattice will give rise to continuous stream of electron-hole pair in the absence of incident light. These electrons get trapped in the potential wells and hence masquerade as signal when the CCD is readout.This contribution is called dark current, and it is a strong function of temperature. At room temperature, the dark current can saturate the detector in a few seconds and thus limits the

CCD’s utility severely. CCDs used to detect faint signals must be cooled to reduce the dark current to acceptable levels. Although the mean dark current can be measured and subtracted, the noise simply adds to the total noise and usually dominates at room temperature. Dark current is usually given as the number of thermal electron generated per pixel per second.

The dark current is proportional to the exposure time. The typical dark current seen in CCDs is 2 electons per pixel per second. This looks to be a small value but the scenario changes when the exposure time increases. For instance, a 15 min exposure will give rise to an additional 1800 thermal electrons per pixel. The contribution of these additional electrons cannot be uniquely removed from the astronomical signal after read-out. The dark current sets an inherent noise floor for a CCD. The dark current signal can be removed from the science frames. However, the dark noise follows a Possion distribution - if the number of electrons from dark current is Nd then the uncertainty is $\sqrt{N_d}$. The fluctuation in the dark current is a noise term that cannot be corrected for.

3. **Linearity**: An useful feature of the CCDs are that if operated properly, they are linear detectors over a large dynamic range – the output voltage signal is proportional to the incident number of photons falling on the CCD to very high accuracy, often better than 0.1% of the signal. This property makes it possible to calibrate observations of very faint objects by using shorter exposures on much brighter photoelectric standard stars. This feature distinguishes the CCD from earlier astronomical detectors such as the photographic plate. However, at large signal levels, the linearity breaks down. If the ADC covers the full well of the CCD, this non-linearity is often measurable.

4. **Gain**: The gain of a CCD is set by the output electronics and determines how the amount of charge collected in each pixel will be assigned to a digital number in the output image. The output voltage from a given pixel is converted to a digital number during readout. The amount of voltage needed (which translates into the number of collected electrons orreceived photons) to produce 1 count (also called an analog-to-digital unit, ADU) is called the gain of the CCD. A typical gain might be 10 electrons/count, which means that for every 10 electrons collected within a photosite, that pixel will produce, on average, 1 count.

   After further calculation, we assess that Thus a plot of the variance in ADU vs. the mean pixel value in ADU gives a straight line with slope 1/g.

5. **Charge Transfer Efficiency:** The Charge Transfer Efficiency (CTE) is a measure of the fraction of charge which is successfully transfered for each pixel transfer.The transfer of charge from one pixel to the next is never perfect. Modern CCDs are remarkably good. In shifting the charge one pixel to the next, good CCDs transfer 99.999% of the original charge.

Steps to be followed:

1) **Bias Level**: For all the bias frames taken for the CCD do the following (1) Examine each bias frame. Draw boxes of different sizes and determine the mean value. For this you need to avoid cosmic ray hits. The best way to do that is to use the task 'cosmicrays' in noao - imred - crutil. The default parameter values will suffice. Make a table listing the bias level in different frames. (2) If you have taken bias frames at different operating temperatures then include this information in the table. Does the bias level change with temperature.
Bias frames are used to compensate for the CCD's positive voltage offset that would otherwise result in an artificially high count rate in all images. Since this rate can vary by location on the CCD, we need to correct each pixel independently, rather than using a constant offset value across the CCD. Make an average bias frame (using 'imcombine') and subtract this from all images taken at this particular operating temperature.

2) **Read Noise**: Determine the read noise of the CCD by examining the bias subtracted read noise frames. Determine the average read noise (with rms) in the CCD. Repeat this exercise for the different exposure times used by you. How does the read noise vary with exposure time? Make a table to show individual measurements.

3) **Dark Current (a)**: Use 'bias-subtracted' dark frames to obtain average signal as a function of time. Make a table showing the exposure time and the average signal for it. Plot the same and determine the dark current. Dark frames were obtained using two methods. Is there any difference in the values? Interpret your result.
Use large statistics box (ncstat and nlstat around 50 or more) in 'imexamine'.

4) **Dark Current (b)**: Make a table and a plot to show the behaviour of dark current with temperature.

5) **Gain**: Refer to the 'CCD Characterization' manual and obtain the gain of the CCD. Show the plot.

6) **Linearity**: Make a table and show the plot for linearity.

7) **Charge Transfer Efficiency**: Refer to the manual and determine the CTE of the CCD.
The expression for (DN)p / (DN)p+1 in terms of the CTE can be written as

$$\frac{(DN)_p}{(DN)_{p+1}} = \frac{N\alpha^p}{pN\alpha^{p-1}(1-\alpha)} = \frac{\alpha}{p(1-\alpha)}$$

Invert the above equation to get an expression for the CTE, α. Use the data from any dark frame that has cosmic ray hits, and measure the signal at the cosmic ray hit pixel and the next adjacent pixel. Use the equation derived above to determine the charge transfer efficiency. Repeat this exercise for several cosmic ray hits. Show your analysis below:

Evaluation and Results:

1) Bias Level

At our operational temperature, three zero-exposure frames were captured, while at other temperatures, single zero-exposure frames were obtained using the dark-only option in the CCD software in the lab PC. The mean output level was assessed across various regions of the frames, and the average value for each frame was documented. The below table provided will display all these recorded values.

File Name	Temperature(°C)	Bias Level(DN)
Temperature_5_Bias_1.fits	5	106.3
Temperature_5_Bias_2.fits	5	107.6
Temperature_5_Bias_3.fits	5	107.6
Temperature_5_Mbias.fits	5	107.2
Temperature_Minus_0.23_Bias.fits	-0.23	105.3
Temperature_10.7_Bias.fits	10.27	105.7
Temperature_15.45_Bias.fits	15.45	107.3
Temperature_Minus_4.82_Bias.fits	-4.82	106
Temperature_5.33_Bias.fits	5.33	105.3
Temperature_Minus_8.13_Bias.fits	-8.13	105.9

Below is the table containing the file names, temperature (in degrees Celsius), and corresponding mean output levels with revised, more descriptive filenames:

There exists a frame named **m_bias.fits** which results from averaging the outputs of the three bias files obtained at our operational temperature. Observing these values reveals that the bias level exhibits minimal variation with temperature. Consequently, after determining the bias level, we subtracted this bias from all other files recorded at their respective temperatures.

2) Read Noise:

Three frames were captured for exposure times of 0.5 seconds, 1 second, and 3 seconds, respectively, while keeping the lens cap on the CCD. Subsequently, cosmic ray removal and bias subtraction were performed on these frames.

File Name	Read Noise(DN)
0.5s_Frame_1.fits	6.468
0.5s_Frame_2.fits	6.459
.5s_Frame_3.fits	6.465
RMS at 0.5s	6.464
1.0s_Frame_1.fits	6.465
1.0s_Frame_2.fits	6.467
1.0s_Frame_3.fits	6.468
RMS at 1.0s	6.467
3.0s_Frame_1.fits	6.499
3.0s_Frame_2.fits	6.495
3.0s_Frame_3.fits	6.499
RMS at 3.0s	6.498

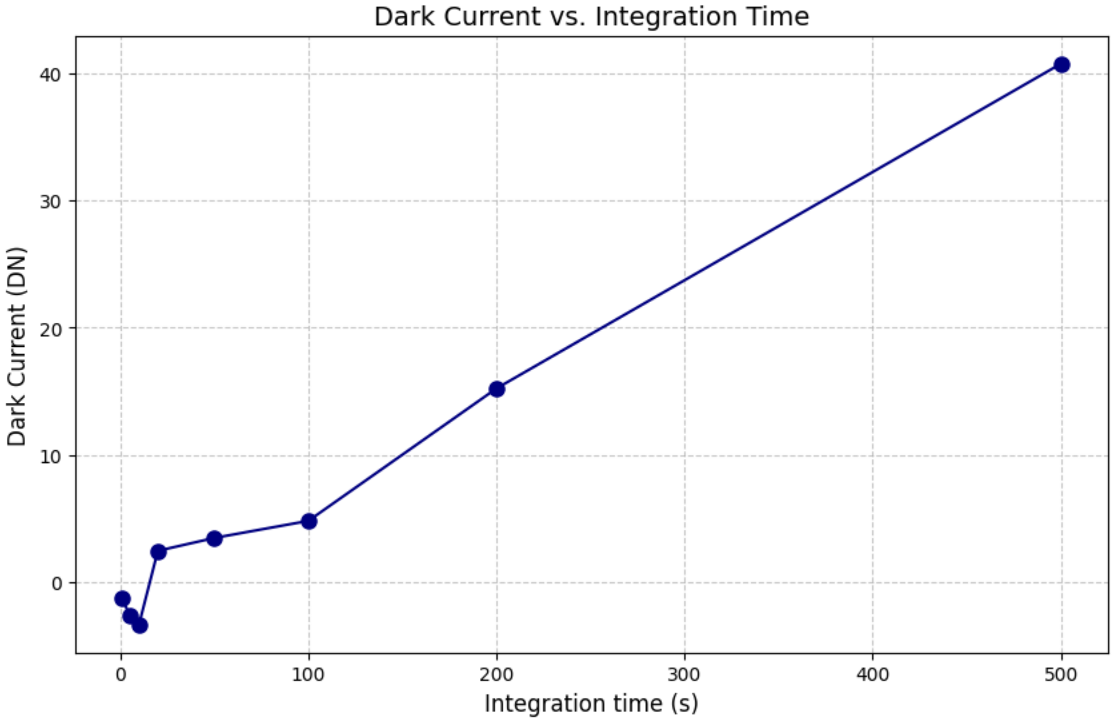
As it says with the filenames, the first 3 are 0.5 second exposure and then the RMS value computed for those 3. The same is done for the other as well. We observe that the read noise value is independent of time and exposure.

Read noise of the CCD is found out as **6.476 DN**.

3) Dark Current:
   a. Variation with Integration Time:
      Here, we captured frames with varying integration times at the operational temperature while keeping the shutter closed. We recorded the average signal from these frames, and the table below presents these values.

Integration time(s)	Dark Current(DN)
1	-1.292
5	-2.585
10	-3.339
20	2.455
50	3.467
100	4.811
200	15.23
500	40.77

I have plotted this data in python, and that can be viewed below.



The plot showcases important findings:

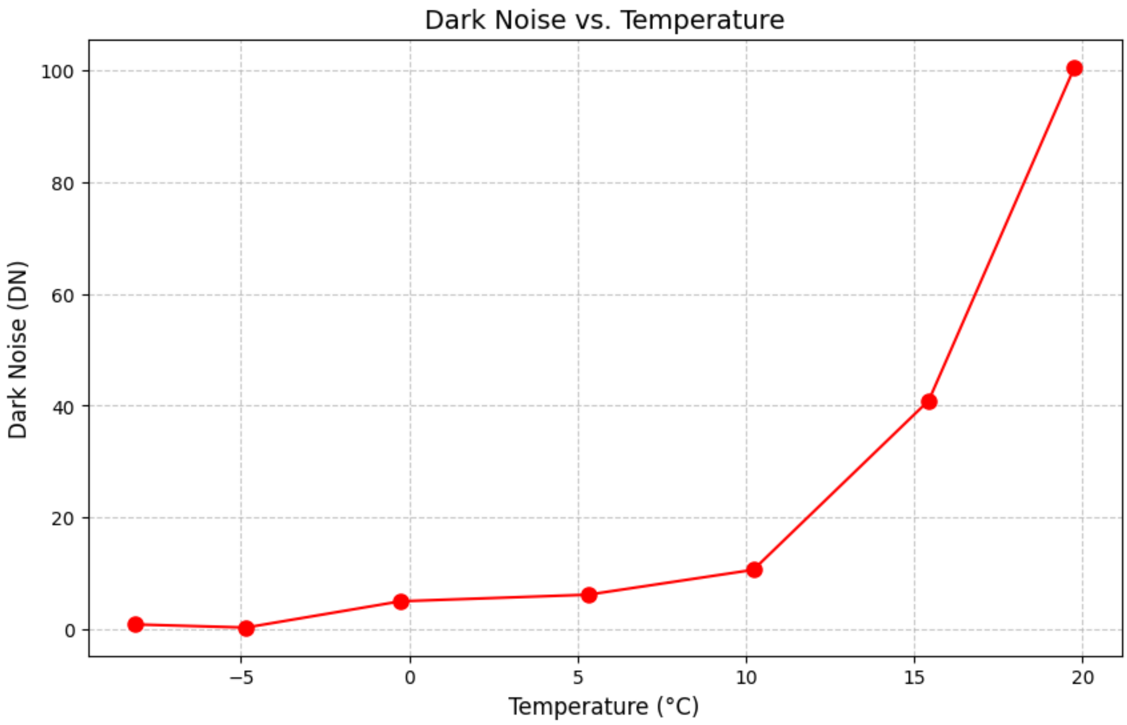
- Integration times of 10 seconds and below yield negative dark current values, indicating the prevalence of read noise over dark current.
- Beyond the initial observations, a clear linear trend emerges in the relationship between dark current and integration time.

   b. Variation with Temperature:

The different exposure times were captured at an operating temperature of 5°C to plot the variation of the mean value with exposure times. Additionally, single frames with the shutter closed and a 100-second integration time were obtained at temperatures ranging from -10°C to 20°C to examine the variation of mean values of dark frames with temperature. In the table below, we list the dark current level, which is evaluated by taking the mean of various regions in the frame.

Temperature(°C)	**Dark Noise(DN)**
-8.15	0.9147
-4.85	0.3506
-0.26	5.045
5.31	6.222
10.22	10.67
15.43	40.92
19.76	100.48

Below is the plot that graphically explains the above data.



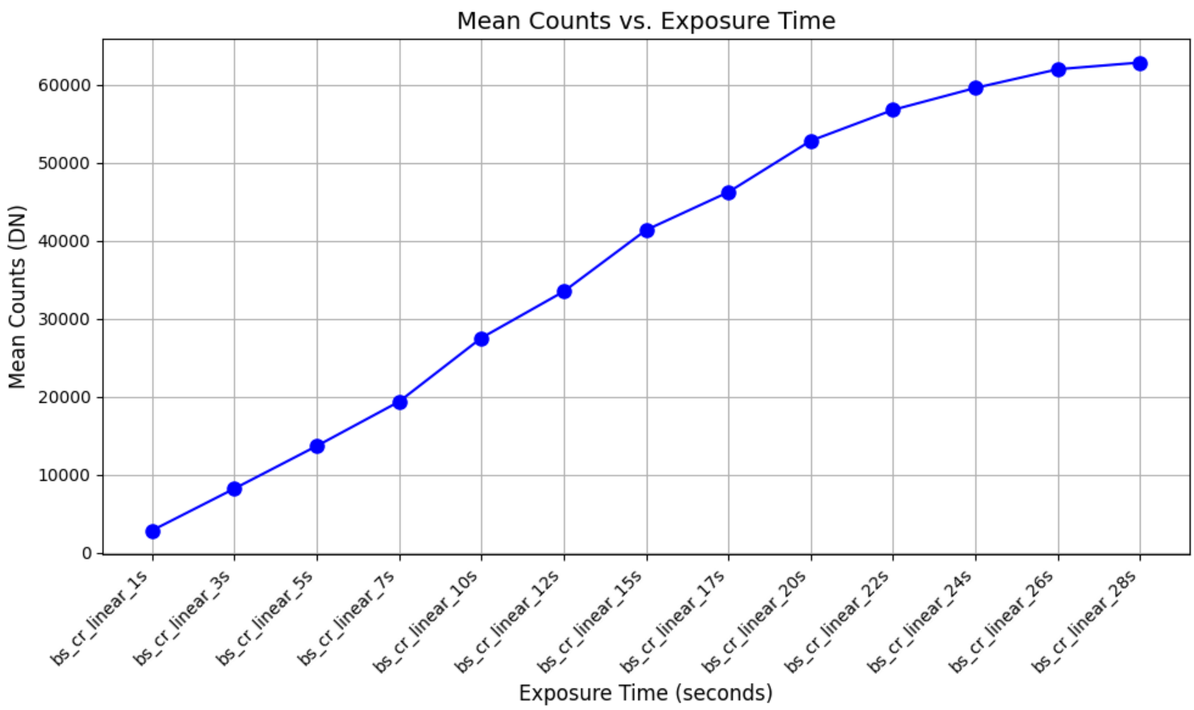
We observe that the noise starts increasing in an exponential manner with temperature.

4) Linearity and Gain:

For this experiment, we subjected our CCD to increasing integration times while exposing it to a uniformly illuminated region. We recorded the mean counts in this uniformly illuminated region of the CCD, and the table below presents these values.

Exposure Time(s)	**Mean Counts(DN)**
bs_cr_linear_1s	2835.05
bs_cr_linear_3s	8204.52
bs_cr_linear_5s	13666
bs_cr_linear_7s	19350.1
bs_cr_linear_10s	27520.3
bs_cr_linear_12s	33473.1
bs_cr_linear_15s	41348.8
bs_cr_linear_17s	46211.6
bs_cr_linear_20s	52790.3
bs_cr_linear_22s	56753.8
bs_cr_linear_24s	59566.5
bs_cr_linear_26s	61962
bs_cr_linear_28s	62822.2

We obtain the following plot for this data.



We see that the graph is linear until the exposure time crosses 17 seconds, after which non-linearity is observed.

For the gain we will only consider exposure times upto which the linearity is observed, and I will I give tabulated data as well.

We utilize the relationship between the mean and variance of the response of a Charge-Coupled Device (CCD) under uniform illumination to determine its gain. In the case of a signal, the number of electrons generated follows a Poisson distribution. Consequently, the variance of the signal remains consistent when quantified in terms of electrons. However, when this quantity is measured in counts, the ratio of variance to mean yields the reciprocal of the gain:

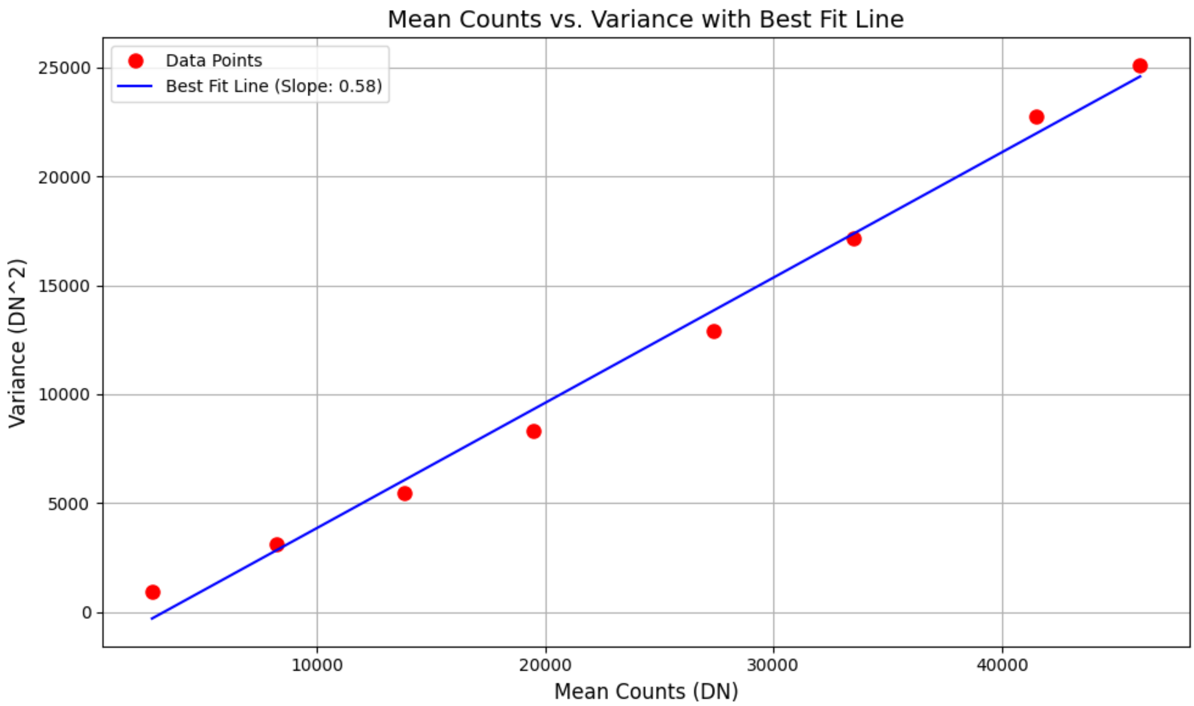
$$\frac{\sigma_A^2}{<N_A>} = \frac{1}{g}$$

We leverage the same dataset employed for linearity analysis, plotting the mean against the variance for each integration time.

Below are the mean and variance values upto the linear region.

Mean	Variance
2785.05	912.159
8254.52	3121.36
13816	5439.37
19500.1	8324.14
27370.3	12889.8
33523.1	17144.4
41498.8	22736.6
46061.6	25098.9

Below represents the plot for the same, along with the best fit line.



Hence **g = 1 / 0.58 = 1.7241**

6. Charge transfer Efficiency:
   CTE can be evaluated easily from the value of counts in two neighboring pixels in a CCD. These two pixels should be such that during readout the charge from one pixel is transferred to the second pixel. Also, one of the two pixels should be illuminated. This puts a stringent condition on the choice of pixels.

   This condition is easily satisfied by a pixel that is struck by a cosmic ray in the absence of exposure to a source. So, we use cosmic ray hits in the dark frames.

   From theory, we know that:

$$\frac{(DN)_p}{(DN)_{p+1}} = \frac{\alpha}{p(\alpha - 1)}$$

   To find CTE, we invert this equation to arrive at:

$$\alpha = \frac{p(DN)_p}{(DN)_p + 1 + p(DN)_p}$$

   For this study, the cosmic ray hits in the dark frame at 10.22 °C were used. This frame was chosen randomly. The choice of a specific frame is bound to result in no different values for CTE. We looked for five cosmic ray hits in this frame, and the counts at the location and at the adjoining location were noted. The table below lists the results found.

p	**DN_p**	**DN_{p+1}**	**CTE**
121	9480	33	99.9971%
331	5077	114	99.9932%
485	12720	51	99.9992%
582	6065	21	99.9994%
716	6963	26	99.9996%

p : pixel number in the row where the cosmic ray hit (x-value in ds9)
DN_p : value of counts in the pixel where the cosmic ray struck
DN_{p+1} : value of counts in next pixel
α : charge transfer efficiency

Conclusion

The various characteristics of CCD were studied and analyzed.