CCD Report

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1 Introduction

In this paper we aim to test various properties of the SBIG ST-7ME guide camera and compare with manufacturer specifications. Specifically, we find values for the gain, read noise, and linearity range of one CCD, and the dark current of a separate CCD. The camera was mounted to a box that allowed for easy adjustment of light source and intensity. All our data for ST-7 was taken with the box lid held open by a pencil.

2 Read Noise and Gain

In order to find the read noise and gain of our CCD camera, we first take 2 flats of equal exposure time (6 seconds) and 2 bias frames. Then using the formula for gain:

$$Gain = \frac{(\bar{F_1} + \bar{F_2}) - (\bar{B_1} + \bar{B_2})}{\sigma^2_{(F_1 - F_2)} - \sigma^2_{(B_1 - B_2)}} \tag{1}$$

where $\bar{F_1}$, $\bar{F_2}$, $\bar{B_1}$, and $\bar{B_2}$ are the average counts for the flats and biases, respectively, and $\sigma_{(F_1 - F_2)}$ and $\sigma_{(B_1 - B_2)}$ are the standard deviations of the differences of the flats and of the biases, respectively. Using the data given in Table 1, we obtain a gain of 0.45 e$^-$ / ADU.

The read noise can be express as

$$Read\ Noise = \frac{Gain \times \sigma_{(B_1 - B_2)}}{\sqrt{2}} \ \ (Electrons). \tag{2}$$

From our previous calculation of gain (0.45) and Table 1, the read noise is 16.57 electrons. Dividing by the gain to get our read noise in ADU we see a read noise of 36.87 ADUs.

	Mean Counts (ADU)	Standard Dev of Difference
Flat 1	17697.96	
Flat 2	17692.18	284.60
Bias 1	107.69	
Bias 2	108.64	52.14

Table 1: This table shows the mean counts for each image and the standard deviation of the difference of the two images in each type.

3 Linearity

To determine the linearity of our CCD we begin by taking a series of flat field images with 1x1 binning at varying exposure times (Table 2). The scheme for choosing exposure times is as follows: 1.00t, 0.9t, 0.8t, 0.7t, 0.6t, 0.5t, 0.4t, 0.3t, 0.2t, 0.1t, 0.05t, 0.025t, 0.0125t, 0.00625t, 0.003125t, and 0.0015625t where t is an exposure time where ADU saturation occurs. In our case t=105 seconds. This allows us to have linearly spaced exposure intervals.

Figure 1 shows us that the ADU saturation point for 1x1 binning is at 28000. This is well below the theoretical limit for a 16-bit CCD camera (65536 ADU). Multiplying by the gain (0.45) to obtain counts of electrons we get 12320 electrons. This value is also substantially below the theoretical value for full-well limit of 30000 (gain$\times$max ADU).

From Figure 1, we can see that the linearity range of our CCD is from 12000 to 28000 ADUs.

3.1 Discussion of CCDs

Staying within the linearity range of the CCD is key in taking astronomical observations. Not saturating the pixels, in either ADUs or electrons, allows us to have the most accurate representation of the light from our object, since number of electrons is proportional to number of photons.

Observing different objects might require different binning, or reading out different amounts of pixels at once. Doing this requires knowledge of the linearity range of our CCD in the distinct binning modes. For example, the SBIG ST9-XE CDD has 1x1 and 2x2 binning. The ST9 is 16-bit, which means the ADU saturation should be at 65536, has a gain of 1.6 e^-, and has a full-well limit of 150,000 electron in 1x1 and 75000 in 2x2. We can dividing each full-well limit by the gain to get the number of ADUs at each limit. In 1x1 this means the saturation point we care about is in ADUs, since the full-well limit would translate into 93750 ADU, well beyond saturation. In 2x2 the opposite is true. The full-well limit in this case translates to 46875 ADUs which is below the ADU saturation point.

Exposure Time (Seconds)	Mean Counts (ADUs)
0.16	185.59
0.31	260.66
0.63	402.87
1.25	698.58
2.5	1255.83
5	1912.06
15	6514.27
25	11222.69
35	15383.94
45	19442.49
55	23804.44
65	27911.69
75	31235.74
85	33109.37
90	32542.03
95	32454.10
105	34076.27

Table 2: This table shows the exposure time (seconds) and mean counts (ADUs) for the flat field images taken.

By putting a UV or IR filter on the CCD we effectively just lower the total counts for each exposure time. The saturation points should stay at the same number of ADUs (or electrons), but the exposure times when those values occur will change. The full-well limit/ADU saturation is only dependent on the camera.

4 Dark Current

Dark current is caused by thermal excitation of electrons within the CCD itself. This requires cooling of the CCD camera to well below room temperature. Dark current can be express as

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

where A is the area of the pixels (cm^2), I_d is the dark current measured at 300K (nA/cm^2), E_g is the band gap energy, and T is the temperature in Kelvin.

Measurements were previously taken for the temperature and mean ADUs for the difference between Dark (2 min exposures) and Bias frames (Table 3). The output from scipy.curvefit() of that data determined that $E_g = 1.22$ eV, which is in close agreement with the experimental value of 1.1 eV. The model fit starts by letting $K = 2.5 \times 10^{15} A I_d T^{1.5}$, and b = E_g/2k, then D = $Ke^{-b/T}$.

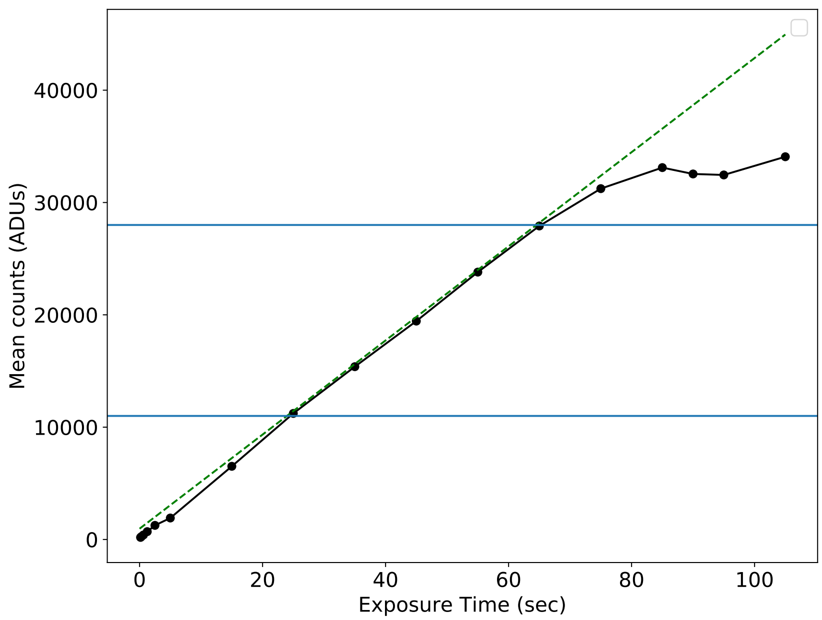

Figure 1: This figure shows the mean counts in ADUs vs the exposure time in seconds for each flat field image taken. The blues line represent the upper (ADU saturation) and lower bounds of the linearity range. We can see the pixels saturate at well below the theoretical limit for a 16-bit CCD (65536 counts).

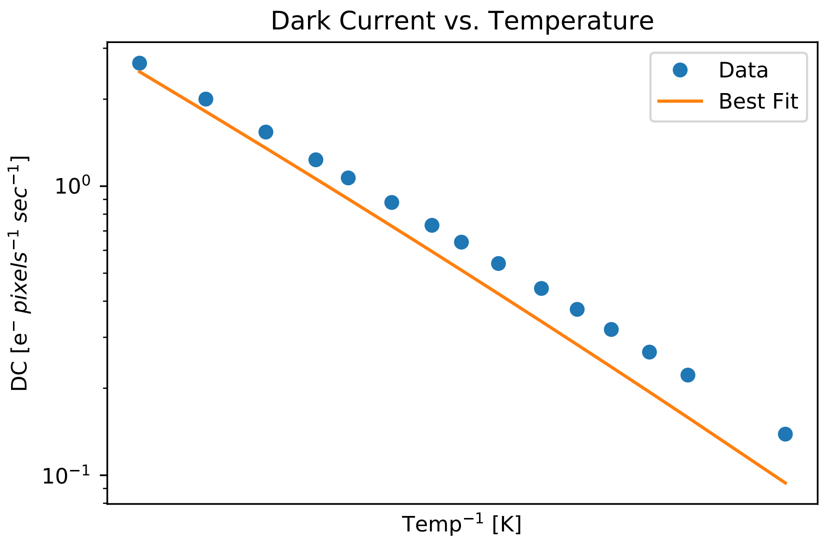

Figure 2: This plot shows the dark current (electrons per pixel per second) vs Inverse temperature in log scale. The data roughly follows a power law.

In the limit that T becomes large, D converges to K. This upper limit is going to be set by the area of the CCD. In the limit that T goes to 0, D converges to 0.

At small values of T, our approximation lowers the values of dark current, effectively decreasing the slope. At larger values of T, dark current for the model and the data converge.

The manufacturer's specs. give the dark current to be 1 $e^{-}/pixel/sec$, the value from our data and model give a value of 0.4. A reason for this discrepancy could be from measurement error in both the manufacturer specs. and in the fact that we only have 1 measurement for each temperature. Redoing the experiment using multiple points for each temperature might lower the discrepancy. Also, the CCD could just have manufacturing defects. A test could be to try another "identical" camera.

5 Summary and Comparison

The spec sheet for the ST-7ME guide camera is given here: http://www.astrosurf.com/re/st7.html. Table 4 summarizes the comparison of our experimental data to the manufacturer specs. The read noise agrees fairly closely with the spec. The gain is not given in the spec sheet, so we cannot compare that. Dark current is roughly

Temperature (C) +/- 0.3C	Dark - Bias (Mean ADUs)
-15	13
-10	15
-8	16
-6	17
-4.2	19
-2.3	22
0	24
2	28
3.6	32
5.8	37
8.2	43
10	50
12.8	62
16.2	89
20	139

Table 3: This table shows the temperature of the CCD in Celsius and the Dark (2 minute exposures) - Bias frames

half of the spec value. This could be due to measurement error. The most glaring discrepancy is in the ADU saturation values. The manufacturer ADU saturation is derived from the experimental gain (since that's all we had, 0.45) and the given full-well limit (85,000 e- un-binned). This also assumes a quantum efficiency of 100%. We can see that these values disagree by an order of magnitude. We can see that the practical values of these properties of the CCD may vary substantially from the manufacturer's specifications.

	Experiment	Manufacturer
ADU Saturation	~33000 ADU	180,000 ADU
Read Noise	16.57 e-	15 e-
Dark Current	~0.4 e-/pixel/sec	1 e-/pixel/sec
Gain	0.45	No Spec.

Table 4: This table shows the values obtained from our experiment and the values given by the manufacturer. A notable discrepancy is the ADU saturation points. The experimental value is much lower than expected from a 16-bit A/D converter. Also, the manufacturer value is derived using the experimental gain and the given full-well capacity (85,000 e- un-binned).