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DARK CURRENT OF THE STL1001 IMAGING CCD

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ABSTRACT

Dark current is thermal noise introduced to a CCD exposure due to electrons within the camera having sufficient thermal energy to jump the band gap of the internal semiconductors. This is read as counts on the image despite not being caused by an incident photon from a target source, which can lead to inaccurate measurements of the target's flux derived from the image count values and therefore must be measured and accounted for. Using the STL1001 CCD, we took a series of bias frames and dark frames with the camera at $T_{CCD} = 0°C$ and $-13°C$. For each camera temperature setting, the bias frames were subtracted from the dark frames to isolate counts due to dark current. The series of dark frames were taken with increasing exposure time, so we fit the mean count per pixel due to dark current to the frame's exposure time to obtain an estimate of the dark current at that temperature setting. At $T_{CCD} = 0°C$, we measure a dark current of (1.635 ± 0.006) e^-/pixel/s. At $T_{CCD} = -13°C$, we measure a dark current of 0.322 e^-/pixel/s.

1. INTRODUCTION

When taking images with a CCD, the image is defined by the number of counts recorded by each pixel on the camera. Two sources of noise can contribute false counts to the image: read noise and dark current. Read noise is an artifact of the electron read-out process within the CCD. The camera's internal electronics, such as the amplifiers and electrodes, or overscan regions on the camera produce a level of noise to contribute extra electrons to the read-out. Generally, this read noise is independent of exposure time but is proportional to the speed of the read-out process; a slower read-out will have a lower read noise value. Dark current is a result of thermal noise within the camera. The CCD records counts using internal semi-conductors; incident photons from the source strike the semi-conductor, causing electrons to jump from the valence band to the conduction band, from which they are read out. The energy gap between the valence and conduction band is small, so an electron can make that jump if it has sufficient thermal energy without any incident photon. The level of dark current is directly proportional to the exposure time, as a longer exposure means more thermal electrons have a chance to make the jump into the conduction band.

This report will focus solely on the dark current. The two main ways of moderating noise from the dark current have already been alluded to: reducing the exposure time and cooling the camera temperature. The first is not always a possibility. The necessary exposure time of an image depends greatly on the brightness of the target object, so dimmer objects will require a longer exposure time to obtain a decent image. As a result, long exposure times may be unavoidable, leading to a large dark current levels. The latter method, lowering the camera's temperature, is often the more practical way of mitigating dark current. Professional astronomy CCDs can achieve cooling to temperatures near $-100°C$ which is low enough to effectively eliminate any dark current. Our STL-1001, however, can only cool down to temperatures $\approx -15°C$, so there will still be a measureable level of noise. Since we can not completely eliminate noise from the dark current via reducing the exposure time or temperature of our camera, its magnitude must be measured so that it may be corrected for.

Read noise can be measured from zero-second, closed shutter exposures known as bias frames. Pixels on the CCD are set to have an intrinsic bias level: a non-zero number of counts with no incident signal. The typical count level on a bias frame gives a measure of this bias level, while deviations from it is a measure of read noise. The STL1001 CCD has no overscan region, so no correction for overscan is necessary. Dark current is measured from closed shutter exposures known as dark frames. Since the dark current is directly proportional to both the camera temperature and the exposure time, these dark frames must be taken with the same exposure time and temperature as the science images that are to be corrected. The camera shutter is closed throughout the dark frame so there are no incident photons. Any recorded counts are therefore due to electrons having sufficient thermal energy and time to jump the band gap, plus a small level of read noise. The dark current is measured in units of $[e^-/\text{pixel}/s]$. The image counts must be converted to a number of electrons based on the CCD's intrinsic gain, then the dark current can directly measured from a series of dark frames with varying exposure time.

2. DATA ACQUISITION

Our equipment included the STL1001 CCD camera and a laptop running CCDSoft, a software that controls the camera operation. Once the camera was successfully connected to CCDSoft, we cooled the camera to $0°C$. The camera was not able to remain at a completely constant temperature and fluctuated within $\pm 0.2°C$ of the setting, but we can neglect this variation. Before any data is taken, we took a bias frame to flush to camera. This gets rid of any electrons that may have built-up on the camera's internal electrodes before the start of this experiment and would introduce fallacious counts. Within CCDSoft, the image is set to use 1x1 binning and be output as a .FIT file. The equipment preparation is now complete. For dark frames, the camera need not be mounted on any telescope. To ensure that no incident light gets inside the camera, despite the internal shutter being closed, the lid is kept on the camera.

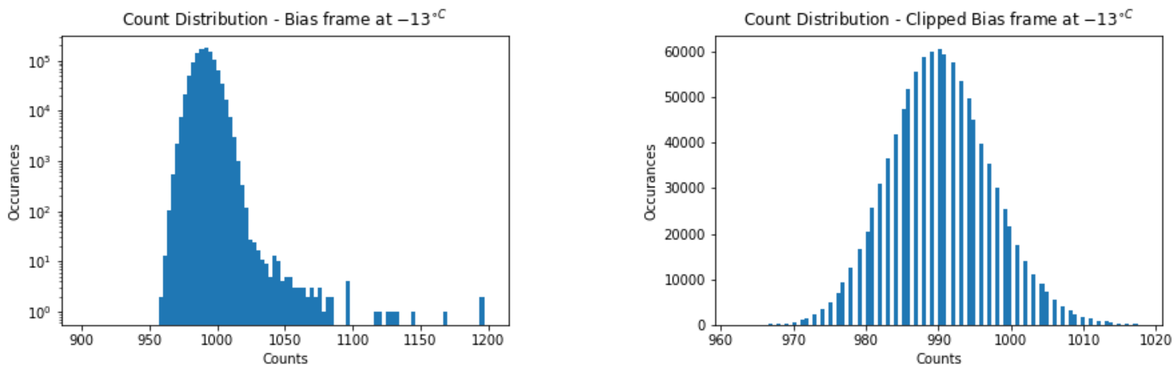
First, ten bias frames were taken with $T_{CCD} = 0°C$. Next, a series of nine dark frames were taken with increasing exposure time. These exposure times were [10, 20, 30, 60, 90, 120, 180, 240, and 300] seconds. After these images were taken, the camera was set to cool down further to a temperature of $-13°C$. This temperature was chosen so that it would be at least $10°C$ away from the previous setting but not at the minimum possible temperature of the camera. At $-13°C$, another bias frame was taken and another dark frame was taken with an exposure time of 300 seconds. This was the longest exposure time taken at the higher temperature and will allow us to calculate the dark current at two different camera temperatures for comparison. No automatic reduction was performed on any image.

3. ANALYSIS

3.1. *Creating master bias frames*

The dark current of our camera at these two different temperature settings will be calculated directly from the sets of dark frames. However, the dark frames must first be corrected for the intrinsic bias level of the pixels. To correct for the pixel bias, separate master bias frames must be constructed for camera temperatures of $0°C$ and $-13°C$. At the latter temperature setting, only one bias frame was taken so the single frame will serve as the master frame. The distribution of counts across the pixels of this bias frame is plotted in figure 1a. The distribution looks Gaussian with a number of outliers toward the high count range. These outliers are likely due to read noise or random fluctuations, but may also just be faulty pixels. Either way, we will reject these pixels by clipping the distribution using the standard deviation, a process known as σ-clipping. The mean and standard deviation of the distribution in 1a are calculated to be 990.28 and 9.47 counts, respectively, then all pixels with counts outside ± 3 standard deviations of the mean are rejected. The new distribution is our master bias frame for $-13°C$, shown in figure 1b. Only 0.03% of the total number of pixels were rejected as a result of this σ clipping, so the vast majority of the frame is unaltered and is therefore still valid to use in our analysis.

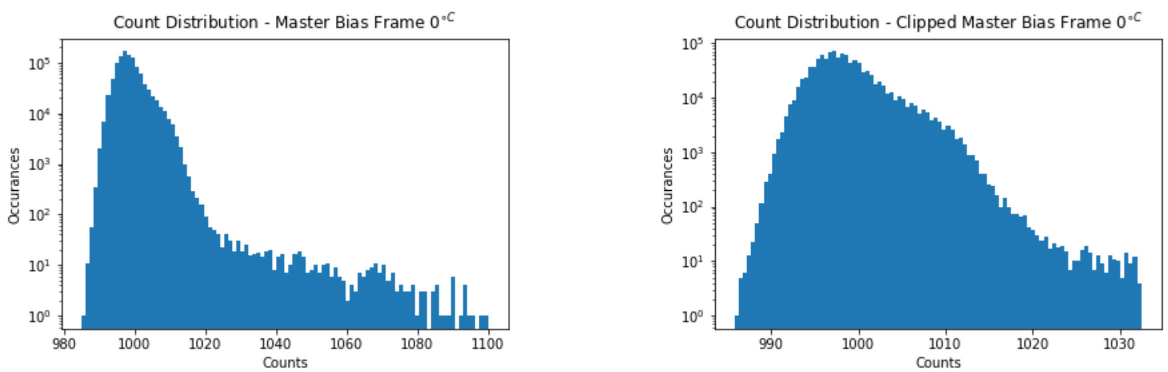
The process is the same to create a master bias frame from the set of bias frames taken at $T_{CCD} = 0°C$. The ten bias frames taken at this temperature must first be combined into a single frame. Each individual frame's count distribution is Gaussian-like so each distribution is well characterized by its mean. The ten frames are therefore average combined; the count on each pixel is averaged across its value on each frame. We then calculate the mean and standard deviation of the resulting distribution to be 998.69 and 11.25 counts, respectively, then reject pixels with counts outside ± 3 standard deviations, as before. The result is our master bias frame for $0°C$. We note how both the mean count and standard deviation were lower for the bias frame at a lower camera temperature.



(a) Unclipped Bias Frame

(b) σ Clipped Bias Frame

Figure 1: 1a shows the single bias frame taken at $T_{CCD} = -13°C$ and 1b is the same distribution after rejecting counts outside 3σ from the unclipped distribution mean. The frame was a 0 second exposure with the shutter closed and no dark reduction. The clipping decreased the distribution mean by 0.002% to 990.26 counts and decreased the standard deviation by 25% to 7.07 counts.



(a) Unclipped Bias Frame

(b) σ Clipped Bias Frame

Figure 2: 2a shows the master bias frame averaged from a series of ten individual bias frames, while 2b is the same distribution with all counts outside 3σ from the mean rejected. All constituent frames were 0 second exposures; closed shutter with no reduction done. The clip acted to decrease the mean count by 0.006% to 998.63 counts and decrease the standard deviation by 66% to 3.88 counts from the corresponding unclipped distribution values.

Again, this master bias frame looks Gaussian, though not as strongly so as the master bias frame taken at $-13°C$. This is likely due to the camera's temperature; when the camera is warmer there will be larger random thermal fluctuations that contribute to outliers and non-Gaussian behavior.

3.2. *Dark Current at* $T_{CCD} = 0°C$

The master bias frame constructed for $T_{CCD} = 0°C$ is subtracted from each dark frame taken at that temperature. This corrects for the bias level of each pixel so now the counts in each dark frame is a measure of only the dark current.

The distribution of each exposure is not fully Gaussian and we wish to cut out outliers. The cut is defined to reject pixels with counts outside ± 3 standard deviations of the mean, for each frame. The pixels being rejected by the upper limit of the clip are likely 'hot' pixels; these are faulty pixels that produce abnormally high noise. After the clipping is done, the mean and standard deviation of each frame distribution is recalculated. Prior to the clip, each frame's distribution was skewed toward high count values with very few pixels having counts lower than the frame's mode. The clipping mostly cuts these high count outliers, causing the mean count to decrease and become closer to the mode. This has the effect of making the mean count a better descriptor of the typical level of counts due to dark current.

The dark frames were corrected using the master bias frame so that the counts in each dark frame measure only the dark current. Therefore, the mean of each frame is a measure of the typical level of dark current on each pixel in the image. Dark current is directly proportional to the exposure time, so we expect that the relationship between the mean count and the corresponding frame's exposure time will provide a measure of the dark current. Indeed, figure 3 shows a strong linear relationship between exposure time and the mean.

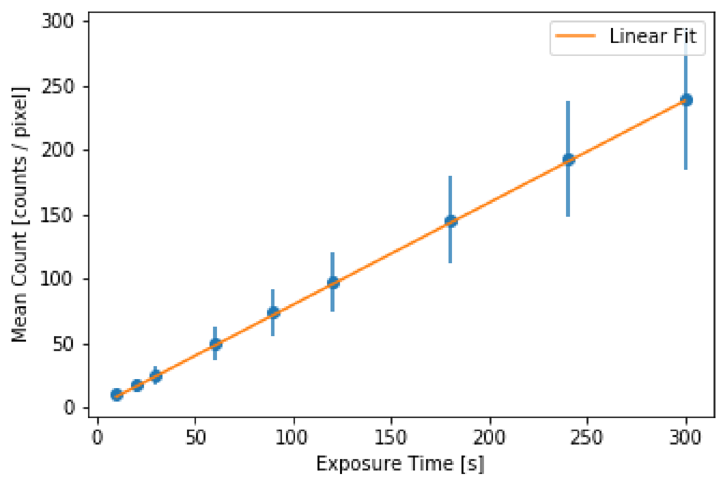


Figure 3: Plotting the mean count per pixel of the nine dark frames vesus their exposure time. Here, the errorbars represent the uncertainty on the mean given by $\sigma_{frame}/\sqrt{N_{frames}}$, where $N_{frames} = 9$. The linear fit was performed using the numpy polyfit function, returning a slope of 0.794 ± 0.003 counts/pixel/s.

We observe a direct linear relationship between the mean count on each pixel, due to dark current, and the exposure time of the dark frame. The slope of this fitted first-order polynomial is 0.79 counts/pixel/s, this is the dark current as counts per pixel per second. Dark current, however, is measured in units of electrons read out per pixel per second of exposure. Luckily, the CCD's intrinsic gain provides a way of directly converting the number of counts per pixel to the corresponding number of electrons read per pixel. The STL1001 has a specified gain of 2.06, so one count corresponds to approximately two electrons being read out. Since we have the slope value in units of counts per pixel per second, the dark current is simply this slope multiplied by the gain. We determine that the dark current for the STL1001 at a temperature of $0°C$ is (1.635 ± 0.006) e^{-}/pixel/s.

3.3. *Dark Current at $T_{CCD} = -13°C$*

One dark frame was taken with the camera at $T_{CCD} = -13^{\circ C}$ with an exposure time of 300 seconds. The bias frame at this camera temperature was subtracted from this dark frame to isolate the counts due to dark current. The fact that only one frame was taken prevents a linear fit being done on the data directly, so we must be clever in determining the dark current at this camera temperature.

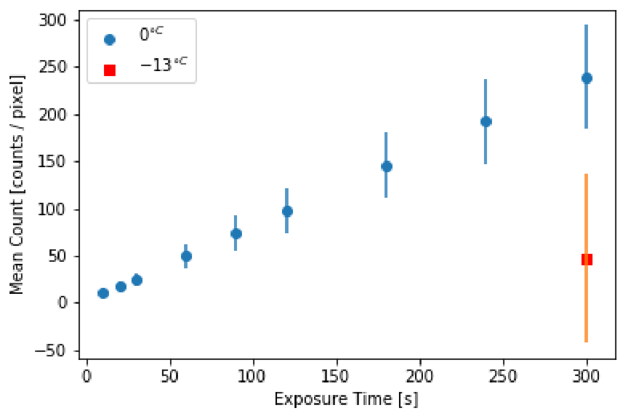


Figure 4: Here we overlay the mean count of the dark frame taken at $T_{CCD} = -13°C$ with the $0°C$ data from figure 3.

Dark current is caused by thermal noise within the camera. When the exposure is being taken, electrons with large thermal energy can jump the band gap and be read by the camera as a fallacious signal. The key aspect is that this requires exposure time; if there is no exposure time then there is no time for thermally energetic electrons to jump the band gap. A bias corrected dark frame with zero exposure time, essentially a bias frame but with the pixel bias subtracted out, will therefore have a mean count of zero. We can then place a point at the origin of figure 4. We now have two points: the origin and the data point from the one dark frame at $T_{CCD} = -13°C$ plotted on figure 4, so we can fit a line between them. The slope of this line multiplied by the CCD's gain gives the dark current at $T_{CCD} = -13°C$, which we determine to be 0.322 e^-/pixel/s.

4. CONCLUSION

When the STL1001 CCD was at a temperature of $0°C$, we measured a dark current of (1.635 ± 0.006) e^-/pixel/s. The manufacturer specifications of the STL1001 [1] report a dark current of 9 e^-/pixel/s at $T_{CCD} = 0°C$. Our measured value is considerably lower: over a hundred σ difference.

Lowering the CCD to a temperature of $-13°C$ caused the measured dark current to decrease to 0.322 e^-/pixel/s, an 80% decrease. This serves as a confirmation that dark current counts are due to thermally energetic electrons. Lowering the CCD temperature means that electrons within the camera have less thermal energy, on average. The band gap energy does not significantly change under this change in temperature, so fewer electrons had enough thermal energy to make the jump.

[1] https://github.com/anjavdl/PHY517_AST443/blob/master/documents/STL1001E_specs_7.11.11.pdf