CCD - Laboratory Evaluation

In this lab you will explore the systematics of the CCD detectors and take the sorts of data necessary to calibrate astronomical observations.

The “nosepiece” is not strictly needed for this lab, but especially if you have bright overhead lights on, it will probably be necessary.

Be careful not to rest the CCD on its fan! It needs to have access to plenty of air to cool down.

1. MEASURING THE READ NOISE

CCD operation:

1. Obtain 10 exposures of the shortest available time on the CCD with the shutter closed.

   Cover the front of the CCD also to prevent light leaks. These are dark exposures with minimal, near-zero, dark current.

   Label these appropriately: include “dark” and the exposure time in the filename. For these minimal-exposure frames, you can also call them “bias” frames

2. Obtain exposures at progressively longer times, going in intervals of 5x until you reach ~125s. For each exposure time, obtain at least 3 exposures. Between these groups of exposures, obtain a new exposure at the shortest exposure time. Keep the CCD covered to prevent light leaks.

   Label these appropriately: include “dark” and the exposure time in the filename.

   Take notes about anything that went wrong – if you bumped the CCD, turned the lights on, etc.

LINEARITY

The goal here is to make a series of exposures that result in a wide range of DN values ranging from 10 to 60,000, and to do this at two different light levels. Be careful that the light level remains constant throughout the exposures. We are testing to see if the CCD's response to faint and bright lights are the same. (Note: light from the monitor screen can significantly change the light level in the lab area!)

It is critical for both this part of the lab and the next part that the light getting into the detector does not change! Make sure you don't turn on or off the lights or make shadows across the detector – changes in the ambient lighting conditions will invalidate the experiment.

LAB WORK

1. First find a light level/lens opening combination that gives about 2,000-3,000 DN's for a 10 second exposure. You want to make sure that a 100s exposure will not saturate, so we're aiming to have 100s be no more than about 30,000 counts. Recall that because of *bias*, the counts start at 1000.

   In the lab, you will probably need to turn off the lights and/or cover the aperture. You can use sheets of paper (e.g., sticky notes) on the nosepiece to block out progressively more light.

2. Next take a set of 3x exposures of 0.04, 0.1, 0.3, 1, 3, 10, 30, and 100 seconds. **Label these appropriately: include "bright" and the exposure time in the filename.** In your lab notes, keep track of the mean value of the images of different exposure time as you take them. You can use the *histogram* tool to check these values approximately.

3. Next reduce the light level by 10-100x or so and repeat the sequence. You will have no way to accurately reduce the light level, but this is OK because in the analysis you can shift the resulting curves up and down until they overlap or just present two curves, one for high and one for low light levels. If the curves have the same shape, and are just vertically offset from one another, then the CCD has consistent response under different light conditions. **Label these appropriately: include "faint" and the exposure time in the filename**

DETERMINING THE CONVERSION FROM DN's TO NUMBERS OF ELECTRONS: The CCD Gain

If the average number of electrons in a pixel following an integration is Ne then the standard deviation uncertainty in that number is $(N_e)^{1/2}$ because the number of events happening in a given interval, assuming a constant rate, is governed by the Poisson distribution. In terms of Data Number (DN), or "counts", or ADU:

Signal = G N_e
Noise =GN_e.$^{1/2}$

Where G is the conversion factor from N_e to DN (in ADU per electron).

Therefore, if we subtract the bias level from the output signal and plot log(signal) vs. log(noise) then we should get a straight line with slope 1/2. However, at very low signal levels the system will be dominated by read noise, not $\sqrt{N_e}$ counting noise. So the plot will flatten out at low signal levels at a value close to the read noise measured above. At high levels, saturation becomes an issue and the curve flattens again (there is no "noise" in a constant saturated value of 65535!). All together there are two noise terms we consider here:

Read noise = R_n = constant
Photon noise = G $N_e^{1/2}$
Remember, N_e is the number of signal electrons in a well. Note that these terms are proportional to N_e to the 0 and 1/2 power of N_e. That provides the leverage needed to separate them from one another.

CCD OPERATION

Obtain exposures with times 0.04, 0.1, 0.3, 1, 3, 10, 30, 60, 100 seconds under conditions that will fill the wells (have data number ~50,000) at 100 seconds. Aim for uniform illumination. Take 3 images at each exposure time. *If your bright exposures from the previous section got to >30,000 counts, you can re-use the "bright" exposures.* **Label these appropriately: include "light" and the exposure time in the filename**

CCD Exposure Checklist:

You will have the following

● Darks

10x short-exposure dark frames (also called “bias” frames)

12-18x progressively longer dark exposure frames (total integration time ~40m)

● Linearity

24 progressively longer bright light exposure frames (8m total)

24 progressively longer faint light exposure frames (8m total)

● Gain

24 progressively longer light exposure frames (can reuse the linearity exposures if they were bright enough)

THE REPORT:

For the lab report, please submit the following in a write-up:

1. Background of the lab. Why are we doing this lab (Bad weather is *a* reason but not the *only* reason)? What purpose does each of the things we measure serve (Bias, Dark, Flat, linearity, etc.)
2. Methodology: What did you do during the lab. What went wrong, what went right, etc. Include a table describing the observations (just as you would if these were astronomical observations) including things like exposure time, etc.
3. Show your results and analysis. This includes plots showing the linearity or lack thereof of the detector. At what count level does nonlinearity become significant (and therefore needs to be calibrated)? Show how you quantitatively get to this conclusion. IE – “If we care about photometry at the 1% level, then nonlinearity becomes significant at X counts”. State the gain and read noise of the detector that you measured. Does this seem like a normal amount? How does this compare to a professional-grade CCD at an observatory of your choice (observatory instrument webpages will tell you their CCD characteristics).
4. Conclusion: Summarize your results and what went correct and incorrect during the lab. What would you do different or what would you change if you were to do it again?

A Bonus Way to Get the Gain of the Detector

We need to measure the gain of the CCD to understand how many actual photons we are detecting.

The number of photons from an object:
$N = t * \text{Rate}$

Because we are observing in the lab, this "object" is a FLAT frame. So, the number of photons from a FLAT frame of counts F and Bias frame of B counts is:

$N = g * (F - B)$ photons, where g is the gain.

From poisson statistics, we also know that $\sigma (N) = \sqrt{(N)}$. So, if we have 2 flat frames (F1 and F2) and 2 BIAS frames (B1 and B2) we know that the uncertainty (σ) of F1-F2. We can also rearrange the above equation to get the counts in the flat field: $F = N/g + B$

Then, the standard deviation σ (F) would be
$\sigma (F) = \sigma (N/g + B)$

and the standard deviation of the difference frame between two flats (F1-F2), using the definition of F from above and the propagation of errors for variables that are being added/subtracted we get:

$$\sigma (F1-F2) = [\, (\sigma (N1-N2)/g)^2 + (\sigma (B1-B2)^2 \,]^{1/2}$$

Rearranging:
$$\sigma (N1-N2)/g = [\, (\sigma (F1-F2))^2 - (\sigma (B1-B2))^2 \,]^{1/2}$$

$$\sigma (N1-N2) = g\, [\, (\sigma (F1-F2))^2 - (\sigma (B1-B2))^2 \,]^{1/2}$$

Now, let's manipulate the left hand side of this equation a little bit. With propogation of errors:

$$\sigma\,(N1-N2) = [(\sigma N1)^2 + (\sigma N2)^2]^{1/2}$$

But because N1 and N2 are governed by Poisson statistics and $\sigma(N) = N^{1/2}$:

$$\sigma\,(N1-N2) = [N1 + N2]^{1/2}$$

since $N1 = g*(F1-B1)$ and $N2= g*(F2-B2)$ we can rewrite the above as:

$$\sigma\,(N1-N2) = g^{1/2}*[F1-B1 + F2-B2]^{1/2}$$

hence

$$\sigma\,(N1-N2) = g^{1/2} * [(F1+F2) - (B1+B2)]^{1/2}$$

Now we can plug that in to the left hand side of the equation above and solve for the gain:

$$g = [\ (F1+F2) - (B1+B2)\ ]\ /\ [(\sigma\,(F1-F2))^2 - (\sigma\,(B1-B2))^2]\quad \text{electrons/ADU}$$

And this is how you can measure the gain of a detector from the measuring pairs of flat fields and biases and their standard deviations!