Physics 344 Lab 4 CCD Characterization

Take Data: October 9 – 16
Report Due: Thursday, October 20
Text Reference: Chapters 8 & 9

Purpose: Charge Coupled Devices (CCDs) are solid-state imaging detectors that are the detector of choice for almost all astronomical applications. They are very sensitive, able to record 85% to 90% of the photons that illuminate them. They are photometrically stable, giving highly accurate and reproducible measures of the intensity of the light that falls on them. Their geometry is very stable, so that they can produce highly accurate measurements of the positions of features in the images. They produce data that is easily digitized and recorded in computers for later analysis. The only significant limitations to CCDs are the need to cool them to low temperatures to eliminate dark current signals, and their limited sizes, although mosaics of multiple CCDs are now becoming common to produce larger effective sizes.

In this lab we will learn how to operate the direct CCD system on the 0.5 m telescope, and take the auxiliary images needed to calibrate CCD data. We will use these data to measure some of the properties of the CCD system.

Data Acquisition:

1. Turn on the dome white lights, but leave the dome shutter closed. Slide the fold mirror in the instrument adapter box to the "CCD" position. Make sure that the eyepiece tube is covered. Remove the telescope cover, and point the telescope to the southwestern part of the dome. Turn on the CCD system with the power strip in the telescope mount base.
2. Start the *CCDSoft* program on Hipparchus. You may find it useful to also start *IDL* and run *RUATV* to view the saved images.
3. In *CCDSoft*, click on *Camera/Setup* to bring up the Camera Control tool. You will use this tool for running the CCD. On the *Setup* tab, click *Connect*, and observe that the Imager and Autoguider become "linked" with Status "ready". Click on the *Temperature* button, and on the pop-up menu enter a setpoint temperature that is 35 to 40 °C cooler than the ambient, select the "On" radio button, and then click "Ok". Observe that the cooler power goes to 100%, and the CCD temperature begins dropping. It will take a few minutes for the CCD to stabilize at the selected temperature. Note the % power used – it will be near 100% while cooling, but should drop to a lower value when the setpoint is reached. If it takes more than about 90% power to maintain the setpoint, raise the setpoint temperature a bit.
4. Select the *AutoSave* tab, and make sure that the *Image* radio button is selected. Click on "*Choose Folder…*" and navigate to *G:/Ph344/lab4/* Create a new folder here,

named with the date and your initials (e.g. Oct01TP), and then select this folder. Set the *starting number* to 1. Select a *prefix* image name – you may want to use different names for each group of files created in Steps 5, 6, 7 and 8 below. Make sure that *Save As FITS* is selected, and *AutoSave* is on.

5. **High Gain Calibration:** Select the *Take Image* tab. Set the *Exposure Time* to 30 seconds, the *Bin* to 1x1, *Series of* to 2, *Subframe* on, *Size* to Quarter, *Filter* to V, *Frame* to Light and *Reduction* to None. Click the *Take Series* button to take two sequential images. During these exposures, no one should move in the dome, since this can change the illumination pattern on the dome. Use the cursor on the displayed image to verify that the exposure has produced an intensity of roughly 20,000 ADU per pixel. Then change the *Frame* to Bias, and take another series of two images.
6. **Low Gain Calibration:** Change the *Bin* to 2x2, *subframe* to off, and the *Exposure Time* to 15 seconds. Repeat the two Light and Bias series as in the previous step.
7. **Dark Signal/Temperature:** Start at the coldest temperature that you can achieve (about 40 °C cooler than ambient). Set the *Bin* to 2x2, *Exposure Time* to 60 seconds, *Series of* to 1, *Subframe* on, and *Size* to Quarter. Set *Frame* to Dark and take an exposure. Raise the temperature setpoint by 5 °C and wait for the CCD to stabilize at the new temperature. Then take another Dark image. Continue this process to obtain dark images every 5 °C up to the ambient temperature (cooler off).
8. **Dark Signal/Time:** Set the temperature setpoint to +5 °C and wait for the temperature to stabilize. Using the same setup as Step 7 above, take a series of dark frames of exposure times 5, 10, 30, 60, 120, 240, 400, and 600 seconds.
9. When you are finished, cover the telescope and point it to the zenith. End the *CCDSoft* program, and turn off the power to the CCD at the plug strip in the telescope base.

Data Analysis (in IDL):

Data analysis can be done at any time, using the server computer (astrolab). Using VNC, you can connect to astrolab from anywhere and analyze your data.

1. **IMPORTANT!** Copy all your Lab 4 CCD images from the folder /home/ph344/lab4/… to a folder in your home area. Make sure that you always work on these copies, not the original images! Use the file manager tool to copy the images (or Linux commands if you are a Linux wizard).
2. Setting up IDL. You should have already set the software path in IDL for Lab 3 – if you haven't done this, do it now. In IDLDE, click on *window/preferences*, then select *IDL* and *Paths*; click on *Insert*, and then in the Places window navigate to *File System* and double click. Then navigate to */usr/local/src/idl* (make sure *idl* is highlighted) and click *OK*. This path will be added to the path window. Check the box preceding this item to include the subdirectories. Then click *Apply* and *OK*. You only need to

do this once, and then the IDL astronomy libraries will be automatically added to your path every time you run IDL.

3. Depending on where you were in the filesystem when you started IDLDE, you will need to change the path so that you can find your image files. IDL does this with the *cd* command:

   ```
   cd, “/home/yourusername/thedirectorywhereyouputthedata”
   ```

   Note that the quotes are important, as is the comma. Obviously, replace “yourusername” with your user name on the system, and “thedirectorywhereyouputthedata” with the appropriate path to the place where you saved the copies of the original images.

4. Examine your Flat, Dark and Bias images with *ruatv*. Explore the headers of the images to see what information was recorded. Comment on any structure that you see in the images.

5. Read your high gain (full resolution) images into arrays for processing:

   ```
   f1=readfits(‘image.00000001.fit’,h) * 1.0
   f2=readfits(‘image.00000002.fit’,h) * 1.0
   b1=readfits(‘image.00000003.BIAS.fit’,h) * 1.0
   b2=readfits(‘image.00000004.BIAS.fit’,h) * 1.0
   ```

   Note that you can use the up arrow key to recall a previous IDL command – saves a lot of typing. Multiplying each image by 1.0 forces them to be saved as floating point numbers rather than unsigned integers. Your images may have different names – obviously, use the actual filenames of your images.

6. Form the difference of the two flats and biases:

   ```
   db = b1 – b2
   df = f1 – f2
   ```

7. Use *ruatv* to load and examine these six images, using the command:

   ```
   ruatv, b1
   ```

   (and replace b1 with the names of the other 5 images). Use the “i” command in *ruatv* to measure the image statistics in a 51 x 51 pixel box centered at x=1000, y=650 in each image, and record the mean and standard deviation for each frame. The ambitious may want to measure more than one region on the image.

8. Calculate the gain (in e^-/adu) and read noise (in e^-) for the system using the statistical data from step 5:

   $$\text{gain} = [\text{mean}(f1) + \text{mean}(f2) - \text{mean}(b1) - \text{mean}(b2)] \,/\, \{[\text{stdev}(df)]^2 - [\text{stdev}(db)]^2\}$$

read noise = gain * stdev(db) / 1.414

9. Repeat steps 5-8 to calculate the gain and read noise for the low gain (2x2 bin) data, and comment on the comparison of these results with the high gain results.

10. Analyze your dark current vs. time images (from Data Acquisition step 8 above) using the IDL program KAFDark. It will ask you for an image filename, read that image, determine the mean value for each row in the CCD (excluding outlying hot pixels), plot the signal as a function of row number (i.e. vertical position along the CCD), and fit a straight line to the plot, listing the coefficients of the fit – i.e. it fits the equation:

$$y = A + Bx$$

    and lists the values of A and B. Run this for all your dark images and record the A and B values.

    The slope of these graphs comes from the dark signal that accumulates in the Y readout transfer register during readout time. Note that this slope is about the same for all exposure times. This indicates that this signal arises only during the readout (which always has the same time), not during exposure. The intercept (A), is the dark signal that has accumulated in the photosites during exposure, and contains no contribution from the readout; this signal does increase with exposure time. Thus you can use these data to measure both the dark current in the photosites, and that in the transfer register. You will need the readout times for the device to assess the latter. The following table from the manufacturer documents the read times (in seconds) for the different modes. The lab instructed you to use quarter frame 1x1 for part 5, and quarter frame 2x2 bin for all the rest of the measurements; if you used different setups (the information is all in the image headers), the table will tell you the readout times.

Resolution Mode	Full Frame	Half Frame	Quarter Frame
High (unbinned 1x1	~29	11.5	5.6
Med (binned 2x2)	9.5	4.7	2.4
Low (binned 3x3	4.5	2.1	1.2
Ultra low (binned 9x9)	1.5	0.9	0.5

Plot the dark signal, in e^-, as a function of exposure time, for both the transfer area and for the photosites. Fit a straight line to each plot and determine its slope, which is the dark current. (You may find that the Excel spreadsheet program is a convenient way to do the plot and fit.) Include the plots and fits in your report.

11. Use KAFDark to analyze your dark current vs. temperature images (from Data Acquisition step 7 above). Use the intercept (A) as a measure of the photosite dark signal. Plot the dark current as a function of temperature, both linear and log plots. A formula for CCD dark current is given by Janesick in his book (Scientific Charge Coupled Devices):

$$I_D = \beta + 2.5 \times 10^{15} \ A_p \ R \ T^{1.5} \ \exp(-E_g/2kT)$$

Where: I_D is the dark current, in e^-/pixel/sec
β is the bias level
A_p is the area of a pixel, in cm^2 $A_p = (9 \times 10^{-4} \text{ cm})^2 = 8.1 \times 10^{-7} \text{ cm}^2$
T is the absolute temperature of the CCD, in °K
Eg is the silicon band-gap energy, in eV
$E_g = \alpha \, [1.11557 - (7.021 \times 10^{-4} \ T^2) / (1108 + T)]$
k is Boltzmann's constant (8.62×10^{-5} eV/K)
and R is the figure-of merit for the CCD
$R = 1 \text{ nA/cm}^2 = 5056 \ e^-$/pixel/s is a typical value.

I have added a scaling constant α to the standard relation for the silicon band-gap energy, to account for doping of the silicon.

Add this curve to your plot and determine the values of β, R and α for this CCD. You can vary the parameters by hand and judge the fit (“chi by eye”), or use Excel’s solver function to determine the best fit values of the two parameters. Compare this β term, scaled into consistent units, with the bias levels that you determined previously.