**Astrophysics 250—CCD Lab**

**Objective:**

In this laboratory exercise, we will examine the functional characteristics of the Charge Coupled Device in its primary application as a photon detector and amplifier in astronomic instrumentation. We will collect data using a CCD and examine the images, and use Python to examine and quantify sources of noise in the collected images.

**Introduction:**

Astrophysics relies on the collection of EMS which allows us to determine intrinsic properties of celestial objects including their luminosity, mass, temperature, and chemical composition. A charge-coupled device is a light-sensitive integrated circuit designed to convert the incoming flux of photons into electrons which can then be input into a computer and displayed in picture elements [2]. The flux of photons can be interpreted on the display as the difference in wavelengths and the intrinsic brightness of stars. The modernly efficient method of collecting EMS data utilizes CCDS, or more recently, CMOS devices, which moves electric charge between capacitive bins [2]. The device was initially invented by Willard Boyle and George E. Smith at AT&T Bell Labs in 1969 [1], with the main purpose of the device being the transfer of charges along the surface of a semiconductor from on to the next storage capacitor. The first variation of the device was made with integrated circuit technology, presented by a simple 8-bit shift register. The photoactive region is an epitaxial layer of p-doped silicon with a transmission region. The image is projected through a lens onto a capacitor array, on which the electric charge is accumulated is proportional to the intensity of the light. As the photons penetrate the layer of silicon of the photon diode, electrons are released. Silicon requires 1.2eV to release an electron from its atomic lattice structure. As visible light ranges between 1.6 and 3.4 eV, it is sensitive even to the faintest exposures (least energetic photons). The sensors located on the array have a PN diode and a storage cell that stores the electrons released after the photon exposure—together they constitute for a pixel unit. As light floods the aperture, the electrons are stored in a potential well, determined by the electric field that is being generated by a positive charge. In the case that the number of electrons exceeds the storage capacity of the potential well, the pixels become photon saturated and may result in bright blots on the final image. [6] Once the array of capacitors has been exposed, the transfer of electrons through the silicon begins as they are dumped from the potential well into the storage locations by the applied positive voltage on the vertical shift register. The control circuit in each capacitor transfers its photons quantity to the neighbouring bin, down the rows. As the rows get shuffled down, the last capacitor row in the array dumps the charge into a charge amplifier, which converts the charge into a potential difference that can be digitized in an amplifying device, which translates the total sum of electrons into the number of photons collected.[2][4][6]

Of course, the conversion of photons into their equivalent charges is not perfect. Modern devices have a quantum efficiency (conversion success of photons into electrons) from 70 and up to 95%. The detector being imperfect results in there being certain sources of ‘noise’ in the data, the types which will be examined including: Poisson noise, noise due to cosmic rays, bias, pixel-to-pixel variations, dark current or thermal noise, and read noise. When incoming photons hit the detector, the probability of the arrival of a photon is known as the Poisson distribution, and it can be approximated by taking the square root of the number of electrons. Taking cosmic images means exposing the CCD to cosmic rays, which may cause bright spots to appear on the image and impact its quality; this noise can be compensated by averaging multiple images. The bias frame is taken at zero seconds without any light to account for the slight variation in the zero points on the pixels. An extra charge from thermally ionized electrons must also be accounted for as it introduces thermal noise, which can be reduced by cooling the CCD. It can be calculated by taking the rate at which photons hit the detector per second, rate S, times the exposure time, t, and adding it with the dark current, D, times t and all square-rooted. Finally, the read noise is caused when the charge is amplified, quantified, and transposed into analog-to-digital units. We can calculate the noise using equation 4.5 in the manual.[3][5][7]

**Procedure:**

This lab exercise combines the collection of data from the CCD itself and processing the images via Python, using the programming language to efficiently download, process, and conduct a statistical analysis of the images. Firstly, we must gather our data; a bias shot taken with an exposure time of 0s will allow us to account for the bias, otherwise known as the bias frame, since the pixels do not have the same zero points. The next shot is the long exposure shot, set for 100 seconds, in which the CCD is blocked off with an aluminium plate. This will allow us to account for the thermal noise from the CCD. The remainder of the shots will be flat fields, in which we take a series of shots using increments of n2, i.e. shot one is 0.1 second, shot two is 0.2 seconds, shot three is 0.4 seconds, and so on. Setting the filter to CC, the dome is to be illuminated with a lamp, and frames up until 51.2 seconds will be taken for the flat images.

Once the data is collected, we will use python notebook to download the images and obtain the x and y dimensions of each image and the exposure times. We can then subtract the bias frames from each image in order to account for the bias. Once the images have been processed, we may conduct a statistical analysis. We can find the mean and standard deviation in order to examine whether or not we have Poissonian distribution. Using the number of counts and the exposure time, we can also observe the linearity trend of the CCD, in addition to the gain value, and examination of the relative noise.

Equipment required for this lab includes the CCD camera system STAR I on the Climenhaga 0.5 m telescope located in the observatory atop the Elliott Building. The CCD chip is a Thompson CCF TH7883CDA, 512x512 pixel chip with each pixel measuring 23 microns2. The system has a 12-bit analog-to-digital converter, implying the largest possible intensity in ADUs being 212. Count above this value will saturate the pixels. The quantum efficiency of this CCD is approximately 40%. The CCD is cooled to -50º C to reduce the thermal noise. Data obtained from the Thompson CCF TH7883CDA will be processed using Python notebooks, with the option of viewing the images in the DS9 application.

**Discussion:**

In this lab exercise, we studied the characteristics of the Thompson CCF TH7883CDA CCD camera system STAR I located on the Climenhaga 0.5m telescope at UVic by taking multiple images and processing them via Python. In processing the images taken, including two bias images, one dark shot, and ten flat field images from 0.1s to 51.2s exposure times, we were able to predict the gain of the CCD, and examine the effects of various sources of noise on the CCD.

The gain of the CCD refers to the average ratio of the analog charge measurement and the assigned data number and is given the units of electrons/ADU [8]. The gain was determined using a linear relation between the variance (ADU) and the mean counts (ADU). It can be noted that the relation appears linear at longer exposures, but the linearity appears to degrade at shorter exposure times. Using the fitted parameters, we obtained a gain value of 12.57 e-/ADU. We can compare this to the theoretical value, which is around 8.3 e-/ADU, giving us a deviation by 4.27. The exceeded gain value indicates a larger than expected amount of electrons over the count number.

Next we examined the various sources of noise. Firstly we observed whether or not our values agreed with what we would expect of a Poissonian distribution. Poisson noise or shot noise is an inherent characteristic of the particle nature of light; as photons arrive on the surface of the device from a distance source, they arrive in a random manner, making it virtually impossible to predict when specific photons will arrive at exact times. The function which describes the *probability* of a photon’s arrival on the surface of the device and the fluctuations of the flux of photons is considered the Poisson distribution. It can be quantified by the Signal-to-noise ratio, as it is equal to the square root of the average number of electrons; SNR= . By observing that the standard deviation is *not* the square root of the mean value, we observed no Poissonian distribution. That is likely due to the reason that the number of events, N, which in this case is the income of photons or their analogous electrons (analogous in terms of being converted into charges, not in the nature of subatomic particles), is very large, and so the signal to noise ratio is also large.

The dark current has been largely omitted from our calculations as it was deemed negligibly small. During the 100s exposure, the dark current was accounted for, similarly to the bias. Dark current is defined as the relatively small electric current which flows through photosensitive devices even when there is no exposure. [9] This is a characteristic of the device itself which can only be reduced by cooling the device. Alternatively, dark current can also be defined as the thermal noise or Johnson noise caused by the thermal motion of electrons through resistance. The RMS voltage contribution of Johnson noise can be quantified as Vj=2, in which kb is Boltzmann’s constant, T is the temperature, delta f is the bandwidth, and R is the resistance. Although we do not utilize this equation in this lab, we can see the obvious relation which states that the noise will increase as the temperature increases, and therefore can be reduced by decreasing the temperature.

The read noise is introduced in the amplification, quantization, and transformation of charge into ADUs. The theoretical value for the read noise can be obtained via equation 4.4; R= in which St = Ne and sigma is the deviation. We were able to obtain a theoretical noise value of 2.11. Using this value, we were able to print out an array of theoretical noise values and measured noise values. At lower exposure times, the deviation appeared greater between the theoretical and measured values, but with greater exposure times, the values of noise became closer to the theoretical, although still not exact. This implies a greater domination of the read noise at lower exposures. Using our Signal-to-noise ratio plot, we were able to accurately estimate for which value of electrons we could achieve an S/N of 100. Using equation 4.5, we are able to include the theoretical read noise in order to estimate a value of around 10417.7 electrons needed to attain an S/N value of 100, which is close to what we would expect from the graph using the nearest point to 100 S/N of 11294.8 e-.

Multiple methods were studied and applied in order to correct for the above-mentioned sources of noise. The first step in the procedure involved the taking of two bias images with exposure time of 0s to attain a count between 54 and 55 ADUs. The bias was then used to correct for the fact that the pixels have varying zero points. Following the correction for the bias, we address the measures and assumptions taken to reduce the dark current, which as can be observed from the calculations, was considered negligible. STAR I camera system manually minimizes the dark current by reducing the temperature of the CCD and therefore the thermal motion of the electrons by cooling the CCD chip to -50ºC. In addition to that, the dark frame was taken by placing an aluminium sheet in front of the CCD and taking a long shot (exposure time=100s). From the image we could observe a few bright spots. The counts amounted to 151 ADUs. As we did not observe evident Poisson distribution, we address the final significant source of error in the CCD, which is the read noise, caused by the CCD itself but potentially external circuits as well [10]. It is possible to reduce the read noise by increasing the read-out time.

**Conclusion**:

The gain obtained for the Thompson CCF TH7883CDA CCD was 12.57 e-/ADU. This is higher than the expected value obtained using the gain formula, which predicted a value of 8.3 e-/ADU. The theoretical read noise was found to be 2.11, and the dark current was determined to be negligible. The data did not show Poissonian distribution as the standard deviation did not appear to be the square root of the mean value, which would be the expected trend for a Poissonian distribution. The CCD’s linearity was consistent at longer exposures, and the linearity appears to degrade at shorter exposures. The greatest sources of error on the CCD came from the read noise, which was not compensated for unlike the bias (by using two bias shots), and the thermal or Johnson noise, which was compensated for manually by the system cooling the CCD down to -50ºC as well as a long shot to monitor the effects of thermal noise.

**Sources**

[1] Laboratory Manual Astronomy 250, First Edition, Sakari & Robb (2011), revised, Thanjavur & Berg (2016), Department of Physics and Astronomy, University of Victoria.

[2] <https://en.wikipedia.org/wiki/Charge-coupled_device>, Charge coupled device, Wikipedia, accessed 07-10-18

[3] <http://www.edgefxkits.com/blog/types-of-mosfet-applications/>, Edgefx Kits & Solutions, accessed 07-10-18

[4] <https://www.youtube.com/watch?v=Te5YYVZiOKs>, Transistor/MOSFET tutorial, Afrotechmods, accessed 07-10-18

[5] <https://www.youtube.com/watch?v=ebSc7xnQwtY>, Indian Institute of Technology, CCDs, accessed 07-10-18

[6] <https://www.youtube.com/watch?v=Xkput-1xNYE>, Digital Camera Sensor Technology, published 19-02-2014, Graham Houghton, accessed 15-10-18

[7] <http://www.qsimaging.com/ccd_noise.html>, QSI, Understanding CCD Read Noise, accessed 14-10-18

[8] <http://www.public.asu.edu/~rjansen/ast598/ast598_jansen2014.pdf>, ASU, Fall 2014, Basics of CCDs and Astronomical Imaging, R.A. Jansen, accessed 15-10-18

[9] <https://en.wikipedia.org/wiki/Dark_current_(physics)>, Dark Current, Wikipedia, accessed 15-10-18

[10] <http://123.physics.ucdavis.edu/week_7_files/CCD_imaging_lecture.pdf>, Davis, Imaging with CCDs, accessed 15-10-18

* The electrons are shifted into the integrator/amplifier, and depending on the efficiency of the device you will find that the voltage generated when the sum of the converted electrons is digitized is proportional to that of the photons collected
* The digital array falls within zero (no light) to 255 (highest intensity of pixel) digital value that comes out of the analogue to digital converter is stored by processor, which then shifts the rows to the right

CMOS devices use p-doped metal oxime semiconductors (MOS) capacitors, the most common element being silicon with trivalent impurities added, such as boron. This creates an intrinsic semiconductor with positive ‘holes’ and atoms with net negative charges.

Much like all data collecting devices, CCDs are not immune to ‘noise’ from external sources, most of which cannot be control but can be quantified and accounted for. Factors of noise are often inseparable from the device itself, such as thermal heating noise

* Device for the movement of electrical charge, shifts signals between stages within the device. Move charge between capacitive bins in the device, shift allows transfer of charge between the bins.
* In modern CCDs represented by p-doped metal oxime semiconductors (MOS) capacitors. Biased above the threshold for inversion, allows conversion of incoming photons into electron charges at the semiconductor interface.
* Invented in 1969, at AT&T Bell Labs by Willard Boyle and George E Smith. Essence of device initially was the ability to transfer charge along the surface of a semiconductor from one storage capacitor to the next.
* First CCD made with integrated circuit technology, a simple 8-bit shift register. Device had input and output circuits, used to demonstrate its use as a shift register.
* Photoactive region (epitaxial layer of silicon), transmission region
* Image is projected through a lens onto the capacitor array, capacitor accumulates electric charge proportional to the light intensity
* Once array has been exposed to the image, control circuit causes each capacitor to transfer its photon contents to its neighbor.
* The last capacitor in the array dumps the charge into a charge amplifier, converts charge into voltage/potential difference.
* Voltages are sampled, digitized, and stored in memory
* Have quantum efficiency (conversion of photons into electrons/charges) can be 70-95%

Observe cross sectional diagram

* Large MOSFET gate, fragmented into smaller gates, gate electrodes split into smaller subsections. MOSFET is the metal-oxide semiconductor field-effect transistor, a type of field-effect transistor most commonly fabricated by controlled oxidation of silicon. MOSFET has a source, a gate, and a drain. The device is used for switching and amplifying electronic signals in devices.
* MOSFET works by varying the width of a channel along which the charge carriers flow. Charge carrier (electrons for example) enter the channel from the source and exit through the drain. Channel width is controlled by the voltage on an electrode (gate). Insulated from the channel near a thin layer of metal oxide.
* Using an n channel MOSFET, a type of transistor, we can explain each component individually: the drain pin will draw the current into itself, and the source is where the current flows out, gate turns transistor on and off.
* See clocking diagram

**exact workings thanks to** [**https://www.youtube.com/watch?v=Xkput-1xNYE**](https://www.youtube.com/watch?v=Xkput-1xNYE)

* When photons penetrate the silicon layer of the photon diode, electrons are released, directly proportional to the amount of photons which have entered the pixel
* Silicon needs 1.2 eV to release an electron from its atomic lattice (provide a calculation), visible light ranges between photons of 1.6 to 3.4 eV
* The sensors on the array have a PN diode and a storage cell, which stores the electrons released by the photons during exposure
* Pixel=photo diode + storage cell
* As electrons begin to accumulate in reaction to the photons flooding the aperture, the electrons are held in the potential well, the size of which is determined by the electric field that is being generated by a positive charge. If the amount of electrons exceeds the storage capacity of the potential well, then the pixels become saturated and results in an overly bright image
* Once the exposure time stops (ie there are no more photons being collected and converted into electrons) the movement of electrons through the silicon material can begin as they begin to shift from the potential well into the storage bin by an applied positive voltage on the vertical shift register, a process that occurs throughout each row of pixels
* First clock pulse moves all from row zero on the device into the serial shift register, which digitizes the electrons captured into an electric voltage
* The electrons are shifted into the integrator/amplifier, and depending on the efficiency of the device you will find that the voltage generated when the sum of the converted electrons is digitized is proportional to that of the photons collected
* The digital array falls within zero (no light) to 255 (highest intensity of pixel) digital value that comes out of the analogue to digital converter is stored by processor, which then shifts the rows to the right