Lecture 5

October 6, 2016

CCD’s and Data Calibration
Asteroid Eunomia
Asteroid Eunomia
Measuring the position of an individual star with RUPhAst using the aperture photometry tool.

In ImExam mouse mode, left-click on your target star to bring up the aperture photometry window.
News

• Lab 3
  – We have obtained “calibration” (part VI) data, but the weather has been cloudy.
  – Rain is forecast through at least Monday night.
    • Use the image /home/ph344/lab3/m39-30.FIT for part V of the lab. The date and time when it was taken are in the header. The weather conditions were clear.
    • Use the images in home/ph344/lab3/sep24tp for part VII. The images img.00000033.UCAC_2.0_Star.FIT and img.00000038.UCAC_2.0_Star.FIT contain the asteroid Eunomia (it is the brightest object). These unguided images were taken through light cloud.
  – Due October 8.
**CCD Imaging Detectors**

- **Charge Coupled Device:** convert photons of light to electric charges.
  - Manipulation and detection of electric charges is well advanced (electronics).
  - Signals easily digitized for analysis by computers.
- **Detector of choice in the near infrared, visible, and ultraviolet regions of the electromagnetic spectrum.**
  - Have good quantum efficiency (50 – 80%), excellent linearity, and large dynamic range (~20,000)
SBIG STL1100m CCD Camera

- Contains two CCDs
  - 4008 x 2672 pixels main imager
  - 680 x 500 pixels guide imager
CCD Analogy

RAIN (PHOTONS)

VERTICAL CONVEYOR BELTS (CCD COLUMNS)

BUCKETS (PIXELS)

HORIZONTAL CONVEYOR BELT (SERIAL REGISTER)

MEASURING CYLINDER (OUTPUT AMPLIFIER)

Slides from Simon Tulloch
CCD’s: Creation of Charge

- A brief review of electron states in solids

Energy of electrons

- Conduction Band
- Valence Band
  - Fermi level in gap.

The large energy gap between the valence and conduction bands in an insulator says that at ordinary temperatures, no electrons can reach the conduction band.

In semiconductors, the band gap is small enough that thermal energy can bridge the gap for a small fraction of the electrons. In conductors, there is no band gap since the valence band overlaps the conduction band.
CCD’s: Creation of Charge

• Photoelectric effect
  • Silicon bandgap is $E_g = 1.11$ eV. Corresponds to
    • $\lambda = \frac{hc}{E_g} = 1.12 \, \mu m$
    • $T = \frac{E_g}{k} = 1.29 \times 10^4 \, K$
  • The rate of thermal creation of hole/electron pairs is
    $\mu \exp(-\frac{E_g}{kT})$
  • The exponential is small at room temperature, but there are many electrons in a solid. So cooling is usually needed to suppress the thermal creation (“dark current”).
  • Without an electric field to separate the electron-hole pairs, they recombine in $\sim 100$ microseconds.
Photoelectric effect in silicon

- Probability that a photon is absorbed when traversing an interval $dx$ of Si is $dx/a(\lambda)$, where $a(\lambda)$ is the absorption length.

\[
\text{dFlux} = -\text{Flux} \frac{dx}{a(\lambda)}
\]

\[
\frac{dF}{F} = -\frac{dx}{a(\lambda)}
\]

\[
F(x) = F_0 \exp\left(-\frac{x}{a(\lambda)}\right)
\]

- Prob a photon absorbed in $x$ is $(1-R)(1-\exp(-x/a(\lambda)))$

where $R$ is the reflection coeff

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CCD's: Creation of Charge

![Graph showing absorption length in silicon as a function of wavelength in nanometers. From Reicke (1994).](image)
The quantum efficiency of the CCD is varying significantly across the V and B bands.
CCD’s: Charge Storage (pixel)

- The basic CCD element (pixel) is the metal-oxide-semiconductor (MOS) capacitor.
  - Applying positive voltage to the metal electrode (gate) repels holes, producing a depletion region with an E field in it.
  - Photoelectrons collect in the depletion region.

Fig. 6.7. A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD.
Charge collection in a CCD

Photons entering the CCD create electron-hole pairs. The electrons are then attracted towards the most positive potential in the device where they create ‘charge packets’. Each packet corresponds to one pixel.
Charge Collection: Full Well

- As charge packets become larger, the electrons repel each other and the charge leaks into adjacent pixels.
  - Usually along a column; channel stops prevent diffusion between columns.
  - Bigger pixels (area and depth) have larger full wells.
  - Values: 30,000 – 500,000 electrons. Our camera has a full well of ~60,000 electrons.
In the following few slides, the implementation of the ‘conveyor belts’ as actual electronic structures is explained.

The charge is moved along these conveyor belts by modulating the voltages on the electrodes positioned on the surface of the CCD. In the following illustrations, electrodes color coded red are held at a positive potential, those colored black are held at a negative potential.

Slides from Simon Tulloch
Charge Transfer in a CCD 2.
Charge Transfer in a CCD 3.
Charge Transfer in a CCD 4.
Charge Transfer in a CCD 5.
Charge Transfer in a CCD 6.
Charge Transfer in a CCD.

Charge packet from subsequent pixel enters from left as first pixel exits to the right.
Charge transfer efficiency needs to be very high (~0.99999) because the charge is transferred 1000’s of times.
Structure of a CCD

Below the image area (the area containing the horizontal electrodes) is the ‘Serial register’. This also consists of a group of small surface electrodes. There are three electrodes for every column of the image area.

Once again every third electrode is in the serial register are connected together.
Interline-Transfer CCD (ours)

Photosites have low dark current, while transfer sites have a much higher one. But transfer sites are scrubbed during exposure.
CCD’s: Charge Detection

• The crucial step is the on-chip amplifier – it must add as little noise as possible to the small measured signals.
  – Serial register dumps the charge on a capacitor and the resulting voltage is amplified.
  – There is usually more amplification off of the chip.

• Voltage is then digitized (with 12 to 16 bits).
  – Must add an offset voltage (“the bias”)
    • The bias ensures that the input voltage to the analog-to-digital (A-to-D) converter never goes below the zero level.
The serial register is bent double to move the output amplifier away from the edge of the chip. This useful if the CCD is to be used as part of a mosaic. The arrows indicate how charge is transferred through the device.
The on-chip amplifier measures each charge packet as it pops out the end of the serial register.

The measurement process begins with a reset of the ‘output node’. This removes the charge remaining from the previous pixel. The output node is in fact a tiny capacitor (< 0.1pF).
The charge is then transferred onto the Summing Well. $V_{out}$ is now at the ‘Reference level’.

There is now a wait of up to a few tens of microseconds while external circuitry measures this ‘reference’ level.
The charge is then transferred onto the output node. $V_{out}$ now steps down to the ‘Signal level’.

This action is known as the ‘charge dump’. The voltage step in $V_{out}$ is as much as several $\mu$V for each electron contained in the charge packet.
V\textsubscript{out} is now sampled by external circuitry for up to a few tens of microseconds.

The value of (sample level - reference level) will be proportional to the size of the input charge packet.

Low-noise readout is SLOW. A full-frame readout of our CCD takes about 26 seconds.
Photomicrograph of the on-chip amplifier of a Tektronix CCD and its circuit diagram.
Charge Detection Variants

• On-chip binning (e.g., 2×2):
  – Combine two or more pixels from each column in the serial register.
  – Combine two or more pixels from the serial register in the summing well.
  – Combination occurs before measurement, so no noise is added. Increases signal relative to noise and reduces readout time.

• Partial readout (half frame, quarter frame):
  – Only measure some of the pixels. Reduces readout time.
CCD Calibration

• Because of the strange features of the bias images in our camera, we usually just take one or more dark images with an exposure time equal to the science image.
  – Subtract the dark from the science image to remove both the bias level and the dark signal.
  – The CCDSOFT system has a mode that automatically takes a dark image after the science image and subtracts it.
CCD Calibration

• Sensitivity variation: pixel-to-pixel variation in the quantum efficiency.
  – Correct for this by taking a uniformly-illuminated “flat-field” image (the inside of dome or the twilight sky). Divide the science images by a normalized flat-field image.
  – Our camera also does not completely illuminate the corners of the CCD (vignetting). This is also corrected with the flat.
The “doughnuts” are the out-of-focus shadows of dust on the filter or CCD window. The corners are darker because of incomplete illumination (vignetting).
Contours of a flat-field image divided by maximum.

So only in the right-hand corners is the illumination less than 90% of maximum.
Horizontal and vertical cuts through a normalized flat.

Note that pixel-to-pixel sensitivity variations are less than 1.5%.
CCD Calibration

• Gain: the number of electrons per A-to-D digital unit (or data number).
  – Really an inverse gain (is small if the amplifier gain is large).

• Read noise: the noise added by the amplification and measurement (usually given in electrons).
Zoomed bias frame from our camera.

Again note hot pixels. “Speckling” around the constant bias level is due to read noise.
The “speckling” is a combination of pixel-to-pixel sensitivity variations and the Poisson noise of the photon arrivals.
Differencing two images reduces the effect of signal variations (due to variations in brightness or pixel-to-pixel sensitivity variations) on the measured variance around the mean.

Use IDL to do image arithmetic and display the result with PhAst.
Standard deviation of the pixel values in the difference of two biases.
Standard deviation of the pixel values in the difference of two flats.
 CCD Calibration

• Read noise: the noise in electrons added by the amplification.
  – Difference two bias images:
    • $\Delta = s_2 - s_1$
    • $\sigma_\Delta^2 = ((d\Delta/ds_1)\sigma_{s_1})^2 + ((d\Delta/ds_2)\sigma_{s_2})^2 = \sigma_{s_1}^2 + \sigma_{s_2}^2$ from propagation of errors
    • Since the noise in each pixel of a bias frame is the same read noise, $\sigma_{s_1} = \sigma_{s_2} = \text{rn}$ and $\text{rn} = \sigma_\Delta/\sqrt{2}$.
    • So just need to find the variance of $\Delta$ around mean for patches of the difference between two bias frames.
  – Produces the read noise in digital units (du or adu).
CCD Calibration

- Read noise: the noise in electrons added by the amplification.
- Gain: the number of electrons per A-to-D digital unit (or data number).
  - Determined by the noise in an image with high signal: is dominated by Poisson noise (shot noise), $\sigma_{Ne} = \sqrt{N_e}$.
  - Again difference two flat field images to remove variations due to illumination and sensitivity variations.
CCD Calibration

• Gain: the number of electrons per A-to-D digital unit (or data number).
  - \( \Delta = s_2 - s_1 \) and \( s = (s_2 + s_1)/2 \)
  - \( \sigma_{\Delta}^2 = \sigma_{s_1}^2 + \sigma_{s_2}^2 = 2\sigma_s^2 \) (since \( s_1 \approx s_2 \))
  - Now \( N_e = g \times s \) \( \sigma_{N_e} = g \times \sigma_s \) from prop. of errors and \( \sigma_{N_e} = \sqrt{N_e} = \sqrt{g \times s} \).
  - So \( \sqrt{g \times s} = g \times \sigma_s \) \( g \times s = g^2 \times \sigma_s^2 = g^2 \times \sigma_{\Delta}^2/2 \)

  - Solving for \( g \): \( g = 2s/\sigma_{\Delta}^2 = (s_1 + s_2)/\sigma_{\Delta}^2 \)
CCD calibration

If there is significant dark current present:
The flatfield produced by the median of dome exposures.
Raw image (autodark subtracted)
Flattened image = (science − dark)/flat