Lecture 4

September 27, 2018
CCD’s and Observing
News

• I still want everyone to complete Lab 2, since that is where you learn how to operate the telescope.
  – Visual observing will continue this week for most groups – weather forecast more promising.
  – Lab periods: 7:00 – 9:00 and 9:00 – 11:00 PM
  – Lab 2 is now due October 11.

• Lab 3 handed out today. Due: October 11.
  – “Cloudy lab” data is part of this lab. Start working on these data, if you have them.
  – Most groups will get existing CCD data to analyze rather than taking their own.
**News**

• Observing & analysis plans for the coming week:
  
  – Friday:  clear – visual observing (lab 2); cloudy – analyze lab 3 data
  – Sunday: clear – finish visual observing (lab 2) & do some lab 3 observing if there is time; cloudy – analyze lab 3 data
  – Monday:  clear – visual observing (lab 2); cloudy – analyze lab 3 data
  – Tuesday:  clear – lab 3 observing; cloudy – write up lab 2 and analyze lab 3 data
  – Wednesday:  clear – visual observing (lab 2); cloudy – analyze lab 3 data
RAIN (PHOTONS)

BUCKETS (PIXELS)

VERTICAL CONVEYOR BELTS (CCD COLUMNS)

HORIZONTAL CONVEYOR BELT (SERIAL REGISTER)

MEASURING CYLINDER (OUTPUT AMPLIFIER)

CCD Analogy

Slides from Simon Tulloch
A 300 s exposure of M31. How do we convert this array of numbers into quantitative measurements of the brightnesses of stars and the galaxy?
CCD (+camera + telescope) Calibration

• Additive corrections: ensure that zero CCD signal corresponds to zero detected light.
  – Measure and remove electronic bias signal.
  – Measure and remove “dark current” signal from thermally-generated electrons.

• Multiplicative corrections: What is the proportionality constant between corrected CCD signal and photons/cm²/sec (also per wavelength interval) coming from a star or piece of a galaxy.

• Sources of noise.
CCD (+camera + telescope) Calibration

• Bias frame: a zero-length exposure with the shutter closed.
  – Contains only electronic bias (and noise from the electronics).
  – Subtract from science image.

• Dark frame: a non-zero-length exposure with the shutter closed.
  – Contains only thermal emission ("dark current") and the bias. Typically same length exposure as science image.
  – Subtract from science image (our CCDSOFT system has an auto-dark subtraction mode).
A 300 s dark exposure.
CCD (+camera + telescope) Calibration

• Additive corrections: ensure that zero CCD signal corresponds to zero detected light.

• Multiplicative corrections:
  – Proportionality constant (gain) relating corrected CCD signal to # of electrons (# of detected photons).
  – Proportionality constant relating # of detected photons to the # of arriving photons.
  
• Correcting variations in the constant across the image (pixel-to-pixel sensitivity variations; vignetting) – a “flat-field correction”.

• Correcting the average sensitivity of the CCD + telescope (CCD quantum efficiency; absorption in filters, windows, and atmosphere; reflectivity of mirrors) – absolute calibration.
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%.
If there is significant dark current present:

- **Science Frame**
- **Dark Frame**
- **Bias Image**
- **Flat Field Image**

**Output Image**
A flatfield image produced by the median of dome exposures (auto-dark subtracted).
Raw image (autodark subtracted); can see the flatfield pattern in the sky level.
Flattened image = (science − dark)/flat
Good, though not perfect correction.
CCD Calibration

• Gain: the number of electrons per A-to-D digital unit (ADU 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.

Note “hot” pixels with high dark current. “Speckling” around the constant bias level is due to read noise.
Zoomed flat-field (uniform illumination) image

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.

IDL> b2=readfits('biasquarterh1.00000006.BIAS.FIT',h) * 1.0
% READFITS: Now reading 1002 by 668 array
IDL> b1=readfits('biasquarterh1.00000005.BIAS.FIT',h) * 1.0
% READFITS: Now reading 1002 by 668 array
IDL> f2=readfits('flatquarterh1.00000008.FIT',h) * 1.0
% READFITS: Now reading 1002 by 668 array
IDL> db=b1-b2
IDL> df=f1-f2
IDL> phast, b1
IDL> phast, b2
IDL> phast, b1
IDL> phast, db
IDL>
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, \( \sigma_{s_1} = \sigma_{s_2} = rn \) and \( rn = \sigma_\Delta/\sqrt{2} \).
  
  • 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).
  
  \[ \Delta = s_2 - s_1 \quad \text{and} \quad s = (s_2 + s_1)/2 \]

- \[ \sigma_\Delta^2 = \sigma_{s_1}^2 + \sigma_{s_2}^2 = 2\sigma_s^2 \quad \text{(since} \quad s_1 \approx s_2) \]

- Now \( N_e = g \times s \rightarrow \sigma_{N_e} = g \times \sigma_s \) from prop. of errors and \( \sigma_{N_e} = \sqrt{N_e} = \sqrt{g \times s} \).

- So \( \sqrt{g \times s} = g \times \sigma_s \rightarrow g \times s = g^2 \times \sigma_s^2 = g^2 \times \sigma_\Delta^2 / 2 \)

- Solving for \( g \): \( g = 2s/\sigma_\Delta^2 = (s_1 + s_2)/\sigma_\Delta^2 \)
CCD’s: Creation of Charge

• A brief review of electronic 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.

a. Insulator
b. Semiconductor
c. Conductor
CCD’s: Creation of Charge

• Photoelectric effect
  – Silicon bandgap is $E_g = 1.11$ eV. Corresponds to
    • $\lambda = \frac{hc}{E_g} = 1.12$ µm
    • $T = \frac{E_g}{k} = 1.29 \times 10^4$ K
  – The rate of thermal creation of hole/electron pairs is
    $\propto \exp\left(-\frac{E_g}{kT}\right)$
    • 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.
CCD’s: Creation of Charge

• 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.
  
  \[
  d\text{Flux} = -\text{Flux} \, dx/a(\lambda) \quad \Rightarrow \quad \frac{dF}{F} = -\frac{dx}{a(\lambda)} \\
  \Rightarrow \quad F(x) = F_0 \exp(-x/a(\lambda))
  \]

  – Prob a photon absorbed in \( x \) is \( (1-R)(1-\exp(-x/a(\lambda))) \)
    where \( R \) is the reflection coeff

Fig. 3.1. The photon absorption length in silicon is shown as a function of wavelength in nanometers. From Reicke (1994).
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.

• Signal also limited by the 16 bits of the signal digitizer; $2^{16} - 1 = 65535$. 
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.
Charge Transfer in a CCD 2.

Time-slice shown in diagram
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.
The on-chip amplifier measures each charge packet as it pops out the end of the serial register.

RD and OD are held at constant voltages

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. $V_{\text{out}}$ 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_{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.
CCD Camera Control

Usually have the main imager selected in *Take Image* tab.
Focusing the CCD

• We focus the telescope on the CCD by moving the secondary mirror.
  – Controls are on the observing panel.
  – Mirror position is shown on the display above the panel (turn on with the green power button).
  • Don’t push the yellow “zero” button.
Focusing the CCD camera is done by moving the position of the secondary mirror with these controls. The position of the secondary is shown by this readout. Turn it on with the green button. Do NOT push the yellow button.
Focusing the CCD

- We focus the telescope on the CCD by moving the secondary mirror.
  - Controls are on the observing panel.
  - Mirror position is shown on the display above the panel (turn on with the green power button).
    - Don’t push the yellow “zero” button.
  - Be careful not to use saturated images to determine the focus.
  - Best focus will be around 0.000 mm, value increases by about 0.100 mm for every 5 °C decrease in temperature.
Sequence of 7 images spaced by 0.05 mm in mirror position.
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Focusing the CCD

• Use RUPhAst and its aperture photometry tool (p key or left-mouse-button) to measure the full-width at half-maximum (FWHM) of stellar images.
  – RUPhAst fits a gaussian to the profile of the star to determine the FWHM.
  – Smallest FWHM is the best focus.
    • But should also visually assess the quality of the fit to the profile.
    • Subsequent slides show a good and a bad focus that had similar derived FWHM’s.
CCD Camera Guiding

- Contains two CCDs
  - 4008 x 2672 pixels main imager
  - 680 x 500 pixels guide imager
CCD field of view in *The Sky*.

Rotation tool (in *Orientation* menu)
Main CCD field of view

Guide CCD field of view; When the telescope is pointing west of the meridian, the position angle of the guide CCD is 270°.
When the telescope is pointing east of the meridian, the position angle of the guide CCD is 90°.
A 10\textsuperscript{th} magnitude star that would be a good guide star.
Offsetting the telescope east and south puts the guide star in the guider.
Guider Setup

Usually have the main imager selected in *Take Image* tab.
However, can select Autoguider to choose binning (1×1) and reduction (autodark subtract).
Guider Setup

Set up guiding with the Autoguide tab. Note can guide using either the guide CCD or the main CCD.

- Choose exposure for guiding.
- Take an image with the selected guider.
- Start guiding.
- Calibrate guider (this sometimes helps if the guiding is poor).
• Select the Autoguide tab and take a test exposure of a few seconds.
• Click in the displayed image to select a guide star. White box flashes and coordinates appear in the tab.
• Start guiding with Autoguide button (will hear clicks of corrections being made).

Figure 2: An autoguide image taken for reference. Note that there is one star significantly brighter than the others; this is a good choice for a guide star.
Guider Problems

Over-correcting by the guider can cause the telescope to oscillate back and forth. These images can still be useful if use a big aperture.
Guider Problems

Really bad guiding. Waiting a few correction cycles for the guiding to settle down before starting an exposure can help. If the problem persists, try doing a guider calibration.