IV. Basics of CCD Image Processing [v1.2.6]

A. Overview

- The raw data acquired at the telescope is rarely of immediate use for scientific analysis
  - ◇ Need to remove unwanted/unrelated signatures
  - ◇ Need to assess uncertainties
- A significant and careful effort is made to perform these activities
  - ◇ Ideally without any loss of signal
  - ◇ And without introducing significant systematic error
- References
  - ◇ Howell, “Astronomical CCD Observing and Reduction Techniques”

B. Removing the Bias Level

- As discussed in the *CCD Basics* lecture, the readout electronics are designed to convert a signal of 0 electrons into a non-zero count value
  - ◇ This non-zero value is always much greater than 0
  - ◇ It is referred to as the bias level
- This bias level is additive
  - ◇ Rigid shift of the zero count level
  - ◇ Therefore, it is corrected for via <u>subtraction</u>
  - ◇ Note: the scatter in this bias level is the Read Noise (RN)
- Frequently, the bias level varies across the detector
  - ◇ Electronics vary a little during readout
  - ◇ Therefore, it is insufficient (or at least inaccurate) to subtract a single value
  - ◇ Instead, one generates a bias image
- Generating the Bias Image [Straightforward]
  - (a) Take a series of bias images (0s exposures)
  - (b) Combine (average/median; clip cosmic rays)
  - (c) Write to disk for future use
  - (d) This image may be subtracted from other exposures to remove the bias level
- Generating the Bias Image [Overscan]
  - ◇ CCD electronics are not 100% stable
    - ▲ A series of bias images taken at some other time may not exactly give the same bias level of your science frames
    - ▲ Would prefer to assess the bias in ‘real time’
  - ◇ Approach:

        - ▲ Read 'fake' pixels beyond the CCD device
        - ▲ There is no charge in these fake pixels
        - ▲ Therefore, the values recorded give the bias level
        - ▲ These values are written as the "overscan region"
    - ◇ Analysis:
        - ▲ Average the values in the overscan region (along the row)
        - ▲ Fit the average values along the column
        - ▲ Generate a 2D image from this overscan fit
        - ▲ Subtract from each image
        - ▲ Write the new (bias subtracted) image to disk [as desired]

C. Dark Current

- Thermal motions of electrons in the CCD accumulates a spurious charge
    - ◇ The *rate* of this charge accumulation is referred to as the dark current
    - ◇ In many modern devices, its value is negligible
- The signal from the dark current is also additive
    - ◇ But, unlike the bias, it is proportional to exposure time $t_{\rm exp}$
    - ◇ Probably linear with $t_{\rm exp}$, but no guarantee
- Removing the dark current
    - (a) Take a series of dark exposures at each $t_{\rm exp}$ of interest
    - (b) Remove the bias [optional]
    - (c) Combine (clipping cosmic rays)
    - (d) Write to disk for future use
    - (e) Subtract the dark images from the science frames
- Should you measure (and subtract) the bias level separately?
    - ◇ In general, your dark images contain both bias and dark current
    - ◇ Primarily depends on whether you perform the overscan analysis

D. Flat Fielding

- Telescope, instrument, and detector imprint unwanted signatures
    - ◇ Telescope:
        - ▲ Vignetting by the secondary, dome, etc.
        - ▲ Contributes to the so-called "illumination pattern"
    - ◇ Instrument (optics, gratings)
        - ▲ Vignetting of optics
        - ▲ Variation in throughput
        - ▲ Variations in angular magnification

        - ▲ Ghosts from internal reflections
    - ◇ Detector
        - ▲ Pixel-to-pixel variations in Q.E.
        - ▲ Variations in the sub-strate of the semi-conductor

- All of these effects are multiplicative
    - ◇ Not additive
    - ◇ All of the effects are relative
    - ◇ The absolute value is somewhat arbitrary (typically normalized to unity)
- Approach (combined)
    - ◇ Take a series of uniformly illuminated exposures
        - ▲ Twilight sky (wrong color)
        - ▲ Night sky (faint and not so uniform [e.g. stars])
    - ◇ Subtract detector signatures (bias, dark current)
    - ◇ Combine (remove stars, cosmic rays, etc.)
    - ◇ Normalize to a unit value
    - ◇ Divide into each science frame
- Approach: Two step
    (a) Correct for pixel-to-pixel variations
    - ◇ Use an artificial uniform source
        - ▲ Dome screen
        - ▲ Internal mechanism
    - ◇ Normalize to unit value on large (>100 pixel) scales
    - ◇ Divide this into each science frame

    (b) Correct for the illumination pattern
    - ◇ On-sky illumination (night sky is optimal)
    - ◇ Observe a series of exposures
    - ◇ Subtract the detector signatures
    - ◇ Smooth over pixel-to-pixel variations
    - ◇ Normalize to a unit value
    - ◇ Divide this into each science frame

E. Variance (σ^2) Image

- For many (all?) calculations, we require an estimate of the uncertainty in our measurements
    - ◇ Simplest approach is standard propagation of error
    - ◇ i.e. simple summation of the variances
- Converting to electrons (Gain)

- For a CCD, the charge accumulated is (ideally) proportional to the photons collected
  - The photons follow Poisson statistics
  - So, too, shall the charge
- The electronics output counts which are proportional to the charge
  - Gain (g) = electrons per count
- Simple conversion:
  - Multiply the *true* counts by the gain
  - True counts are those from photons (not the detector!)
  - $N = DN * g$ (DN are counts or 'digital numbers')

- Detector Variance
  - Read Noise (RN)
    - Scatter associated with counting the charge
    - Typical variance is $10 - 100$ electrons
    - Easily assessed from a series (or single) bias frames

$$\sigma_{\rm RN} = (RMS_{\rm counts})\ g \tag{1}$$

  - Dark Current (DC)
    - Poisson noise
    - Assume the average counts accumulated is $DN_{\rm DC}$
    - Variance, in electrons:

$$\sigma^2_{\rm DC} = DN_{\rm DC}\ g \tag{2}$$

  - Together, the detector variance is:

$$\sigma^2_{\rm Detector} = \sigma^2_{\rm RN} + \sigma^2_{\rm DC} \tag{3}$$

- Source Variance
  - Electrons associated with photons received: $N_{\rm source}$
    - Poisson process
    - $\sigma^2_{\rm source} = N_{\rm source}$
- Altogether

$$\sigma^2_{\rm TOT} = \sigma^2_{\rm source} + \sigma^2_{\rm detector} \tag{4}$$

F. Other (Unwanted) Issues

- Cross-talk (detector)
- Ghosts (instrument)
- Satellite trails
- Cosmic rays