Photometric Data Reduction

Topics: CCD imaging data reduction

Sources: Chromey Ch 9, Howell Ch 4, Brightspace links

The observed intensity in any pixel can be expressed:

$$I_{obs} = (I_{real} + S)F + D + B$$

I_{real}: real source intensity that you want to measure

S: sky brightness (e.g. skyglow, zodiacal light, moonlight, light pollution, dome lights from silly astronomers who forget to turn them off, etc.)

F: a flatfield factor that describes the multiplicative pixel-to-pixel variation in efficiency

D: a dark current intensity, usually small in cryogenically cooled CCDs

B: bias, or zero level of the image

The process of image reduction involves inverting the above equation to recover the source intensity, I_{real}. This requires good knowledge of F, S, B, and D. The contribution from B, D, and F are measured using calibration images called biases, darks, and flats.

Calibration Images

Biases (or zero level images):

This is an image with a zero second exposure time, the shutter stays closed and you simply read the detector out.

Method 1 (ok): Take at least 20 bias exposures with shutter closed and zero second exposure. This will sample variations in bias along rows and columns better than one frame. Combine these to create a master bias frame. Subtract the master bias from all your other science frames.

Use daylight to take these images so you don't waste science time at night! Telescope time is valued at $1500 (WIRO) to $50,000 (Keck) per night. Be a rabid photon beast! (D. Dale, 2008)

Method 2 (better): Use the overscan region in each exposure to fit a low-order polynomial and subtract that from each column in your image. This is better because it samples the instantaneous zero level of the image; this level might drift by a few ADU over the night.

Method 3 (best): Follow method 2, then combine the overscan-subtracted bias images to produce a master bias with a level near zero ADU. This master bias still contains any pattern signal in the bias. Subtract this master bias from each overscan-subtracted image of all other types (dark, flat, science).

Darks:

These are images taken with the shutter closed, but for some exposure time, usually that equal to a science frame. They measure the thermal noise of the CCD, which is usually negligible for cryogenically cooled CCDs (i.e. you don't need them).

Method: take at least 7 dark (shutter closed, lights off, dome closed) exposures using the exposure time you are planning to use for your science frames, or longer. Combine these bias-subtracted dark exposures, using appropriate rejection algorithms, to create a master dark. Dark current is usually linear with time. For example, you can usually create a 10s dark by dividing a 100s dark by 10.

Flats:

Identical signals do not produce identical responses in the CCD. Flat fields are used to correct for pixel-to-pixel variations in the response of the CCD to light. These are produced by exposing the CCD to uniform light from the twilight sky or an illuminated dome screen. Flats are needed for each instrumental setup, color, or wavelength region to be used. Good flats are constant to ~1%.

Method 1 (sometimes okay for imaging, usually ok for spectra): Point telescope at dome screen and take 5-10 where you collect 20-30k ADU.

Method (best for imaging): Do as dome flats, but point at twilight sky. Dither ~20" or more to allow removal of stars. Pick region with relatively few stars.

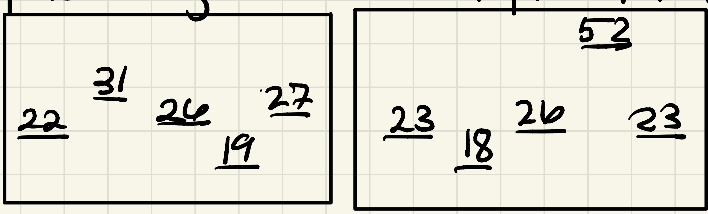
Beware shutter timing effects. Most shutters take 0.05–0.1s to open or close. This means the center of the chip (for iris-type shutters) is exposed slightly longer than the edges, leading to systematic differences between locations on the CCD. Minimize shutter effects by taking all types of exposures longer than 5–10s, whenever possible.

Also note: the ADU you see in your images are not the numbers to use in SN calculations! You must convert back to photons/electrons for Poisson statistics to apply!

Image Combination:

Case: 2 images

Suppose you have two images, where a small number of pixels along one row are represented by:



Combine these two images with an average. What problems result?

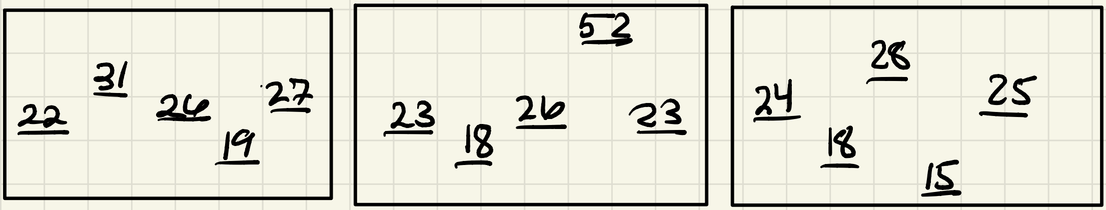
- outliers have a big impact on outcome
- can't do outlier rejection
- can't take a median

Outliers often from cosmic rays (CRs). Usually remove CRs before image combination. Identify outlier by comparing to mean of neighboring pixels, iterate so outliers don't bias the mean.

→ in a 4Mpix CCD there are $0.03 \cdot 4\text{M pix} = 12{,}000$ pix that are more than 3σ from the mean. Maybe start with 5σ rejection.

If your data are under sampled (e.g. 1 star on 1 pix), outlier rejection is messy/tricky.

Case: 3 images



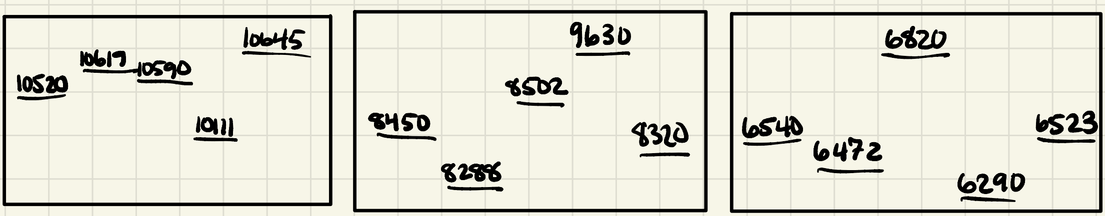
With 3 images you can do a median.
pros: simple, gets rid of outliers
cons: does not converge as quickly as mean

Mean:
pros: converges quickly toward true mean
con: subject to outliers

Mean w/ outlier rejection:
pros: converges quickly, not subject to outliers

Moral of the story: always take at least two images of any science field, and at least 3 (preferably 5 or more) of any flat, bias, dark, etc.

Case: 3 images with differing levels
(e.g. twilight flats when sky brightness is changing rapidly)



Median: will give you the middle image → includes bad 9630
mean: better, but you still have outliers → still uses bad pix
mean w/ rejection: can end up rejecting good pixels because your mean stays constant, even for frames with low levels

What can you do?

1. Scale the images to the same level before you combine them. Use the mean or median of an image segment as a scale factor.
2. Then weight the images by the original means or medians (or possibly the exposure time) so that the images with more photons end up being more influential in the final product.

There is no magical recipe for image combination. Use difference imaging or image ratios to see what is changed from a new approach (you probably won't be able to see it by eye) and assess results e.g. with final image RMS.

Gain and Readnoise Measurement (Howell Ch 4.3)

- Measure gain from bias and flat images.
- Let S_e be the signal you receive in electrons and S_a the signal in ADU. Then:

$$S_e = G \cdot S_a$$

For Poisson noise, the rms standard deviation in S_e is σ_e and $\sigma_e = \sqrt{S_e}$, or $\sigma_e^2 = S_e$. Then, $S_a = G \cdot \sigma_a^2$.

S_1, S_2, and S_3 are three flats with increasingly higher signal.

Assumes the Poisson noise of the source photons is much larger than the read noise.

In practice, the bias level adds noise to an image.
Suppose we take two flats, F_1 and F_2, and two biases, B_1 and B_2. Then $F_1 - F_2$ is the difference between the two flats and $\sigma_{F_1-F_2}$ is the RMS of this difference image.

$$\text{Gain} = \frac{(\bar{F}_1 - \bar{F}_2) - (\bar{B}_1 + \bar{B}_2)}{\sigma^2_{F_1-F_2} - \sigma^2_{B_1-B_2}}$$

If you had no read noise, every bias frame would be identical. Thus, read noise can be measured from the noise in a difference between two bias frames:

$$\text{Read noise} = \frac{G \cdot \sigma_{B_1-B_2}}{\sqrt{2}}$$