A Primer on Flat Fielding Techniques

Introduction
With the advent of CCD detectors, astronomical imaging has entered the digital world. Fantastic images from the Hubble Space Telescope are part of popular culture, and amazing new astronomical discoveries are announced at a dizzying pace. The entire process of image processing rests on one very important step: flat fielding. This paper will outline several techniques for making flat field corrections.

Flat Field Basics
An ideal CCD detector is comprised of an array of pixels, each of which generates electrons in a way that is directly proportional to the photons that fell on it. Unfortunately several things interfere with this perfect detector: pixel-to-pixel variation in response to photons, vignetting of the optical system, and penumbral shadows from dust donuts somewhere in the optical stream. (Berry and Burnell 2005). Fortunately, flat field correction techniques can solve these three common problems.

Although modern CCD detectors are manufactured to very close tolerances, there will always be some variations in the sensitivity of individual pixels in the detector. The pixel-to-pixel variation can be seen when the detector is aimed at a uniformly illuminated source. Since each pixel would receive the same number of photons from this uniform source of illumination, each pixel should report identical electron counts; any deviation from uniformity is due to pixel-to-pixel variation.

Even when pointed to a uniformly illuminated field, most telescopes will suffer from some roll-off in intensity, called vignetting, toward the edge of the field. The exact signature of this roll-off must be known in order to correct the image.

Dust donuts will show up in raw images with a diameter proportional to their distance from the detector. These dust donuts diminish the photon counts of the affected pixels and must be accounted for in the final image.

All these errors can be corrected by proper application of flat field techniques.

To calibrate an image using a flat field, the raw image, I_{raw}, must first be corrected for bias and dark noise, then multiplied by the average value of the flat field image, M_{flat}, and finally divided by the dark and bias corrected flat field image as shown in figure 1[1].

$$I_{cal} = \frac{\left(I_{raw} - (bias + dark)\right)M_{flat}}{flat - (bias + dark)}$$

Figure 1

[1] Roper Scientific, 2006, Flat Field Correction, http://roperscientific.de/tflatfield.html

The key to the process is acquiring a truly flat field image. This image must have even illumination across the entire field, ADU counts well within the linear range of the detector, and a spectral signature that is similar to the intended object's spectrum.

Matching spectra is important because each pixel has some variation in its spectral response (Zhou et al 2004). This becomes more critical for dim targets that are just above the sky background level because the pixel-pixel variations may be greater than the difference between the sky background and the target.

Common Flat Field Methods

There are several common flat field acquisition methods: dome flats, twilight flats and sky flats. Each has its pros and cons, and selection of method depends primarily on the purpose of the final image.

Dome flats

Dome flats have several advantages when done right: they can be taken during the day, and have high signal-to-noise (S/N) because they can be adjusted to get detector counts at 80% of full well capacity.

In order to acquire a dome flat, the telescope is pointed to a uniformly illuminated panel on the wall of the observatory or dome. The detector is exposed to the panel for an exposure length that will render an ADU count that is well within the range of linearity of the detector. The telescope focus and filter must not have changed from the target image values. An alternative to a wall-mounted panel, especially for smaller telescopes, is a lightbox. This is essentially a movable dome flat, and has some real advantages over a conventional dome flat as discussed below.

Several considerations need to be taken into account when using dome flats: the spectrum of the panel illumination, the reflective characteristics of the panel, perpendicularity of the panel and telescope optical axis, size of the panel, and finally possible extraneous light from sources external to the panel. As noted already, the spectrum of the light source should match the intended target, and the panel must reflect the illumination evenly across this spectrum. Careful sizing of the panel to match the pupil of the telescope will help to minimize extraneous scattering, as will perpendicularity (Marshall and DePoy 2005).

Illumination sources vary, but newer systems are employing LED's as illuminators. The spectrum of the LEDs can be matched to specific filter bands (Marshall and DePoy 2005).

A lightbox is constructed of light material that can be placed directly on top of the telescope. It consists of several light sources pointed away from the telescope and arranged in such a way as to illuminate a reflective surface at the back of the lightbox. The reflected light then goes through a diffuser plate directly in contact with the top of the telescope. The diffuser makes a tight optical seal with the telescope that keeps any extraneous light from entering the telescope during exposure. This also ensures perpendicularity. I have made such a lightbox and it produces flats that are evenly illuminated to about 1% error across the field.

Zhou et al (2004) have employed a diffuser plate above the corrector plate of a Schmidt telescope with good success. This diffuser helps to minimize stray light from extraneous sources, and also to homogenize any variations in intensity across the pupil of the telescope. This is sort of a super lightbox for telescopes that are too big to employ a removable lightbox. Their system yields flats with around 1% error.

Twilight Flats

Twilight flats have the advantage of being bright enough for good S/N, but are not typically a good spectral match to the night sky.[2] Careful planning of the acquisition is important in order to get a sufficient number of flats to ensure a high S/N ratio because there is only a short window where the sky brightness values are in the proper range for the detector. It is difficult to get twilight flats for many filters in one session. Focus may have shifted (or will shift) from the science images due to temperature changes of the optics.

Twilight flats are made by pointing the telescope to a point in the sky that is evenly illuminated by the rising or setting sun. This null point has been experimentally determined to be near the zenith by Chromey and Hasselbacher (1995). The telescope tracking is turned off so that the stars will trail in the flat frames. Individual flat frames are median combined to eliminate the trailed stars. Since the sky brightness is changing rapidly, the exposure time for each frame must be adjusted to keep the detector ADU values at 30-50% of full well value (Berry and Burnell 2005). There are several software packages that will do this exposure adjustment automatically, including CCD Autopilot[3].

Sky Flats

For spectral matching, sky flats are unparalleled. This is because the illumination source is the sky itself. Because the ADU values of a sky flat are low, pixel-to-pixel variations are not well corrected using this method.

A common approach is to find a sparse field near the science field and do an "expose and shift" program[4] of many frames. By moving the telescope slightly between frames, pixel-to-pixel variations are minimized. These frames are median-combined to remove stars and produce a uniform sky background. Since background ADU values are low, it is difficult to obtain enough photons to ensure a good S/N ratio without resorting to taking hundreds of frames.

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[2] Oliver, J. P, 2004, Techniques of Observational Astronomy, http://www.astro.ufl.edu/~oliver/ast3722/lectures/CCDImaging/CCDimaging.htm

[3] CCDWare, 2008, CCD Autopilot, http://www.ccdware.com/products/ccdap3/

[4] Crabtree, D., Date Uknown, A User's Manual for the CFHT Visible Imager: FOCAM,http://www.cfht.hawaii.edu/Instruments/Imaging/FOCAM/calib.html

Unfortunately, the cost of getting a good sky flat in terms of telescope time is high. This premium, and few amateurs are willing to put in the time it takes to assemble a good sky flat.

Combination Methods

Two or more of these methods can be combined to good effect. A sky flat could be combined with a dome flat to maximize S/N and spectral response. [5]

Other methods

The basic methods outlined above all assume that the CCD detector is used in the conventional manner while attached to a telescope that is tracking at the sidereal rate. This ensures that each source in the sky will be mapped to the same set of pixels on the detector for the entire exposure interval.

Another approach to CCD detector use is to have the sky source move along a column of pixels by leaving the telescope tracking off. If each pixel is read at a rate that corresponds to a source's movement up one row of pixels, the sky source intensity will have been read by each pixel in that column. This method is variously called drift scanning or time delay integration by internet sources. There seems to be some confusion over the terms. The seminal paper appears to be Gibson and Hickson's 1992 paper and I've adopted their naming system for the two main methods.

In time delay integration, the CCD detector is carefully aligned so that a point in the sky will track along one column of pixels. The CCD is read out at the sidereal rate so that each point in the sky is sampled by each pixel in the column in turn until the point moves off the detector. The total integration time is the proportional to the length of the column. This works well for targets near the celestial equator, but requires that the detector be movable to keep the same point of the sky on the same column for targets away from the equator. Zaritsky et al (1996) describe one such mechanism.

In drift scanning the detector is placed on a stage that can be mechanically moved so that a point in the sky will follow along a pixel column. The rate of motion of the detector stage is determined by the rate of readout. Integration times will depend on readout frequency.

Both of these methods eliminate any inherent pixel-to-pixel variation by averaging the column pixels. Any column-to-column variations can be corrected by taking a one dimensional flat field image. This technique has been employed to obtain flat fields with < 0.1% RMS errors. (Gibson and Hickson 1992).

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[5] Ostlin, G., 2002, Stellar populations in Globular Clusters and Dwarf Galaxies Observational exercise, http://72.14.205.104/search?q=cache:P203ecllCx4J:www.astro.su.se/~jesper/NOTKURS/Goranobsex.ps+combination+technique+flat+field&hl=en&ct=clnk&cd=40&gl=us&client=firefox-a

Conclusion

Modern CCD detectors have revolutionized observational astronomy. Because of their inherent linearity they can be gainfully employed for photometry, but corrections must be made to raw images before meaningful information can be gleaned. Flat fielding corrects for detector sensitivity variability, vignetting of the detector by the optical system, and penumbral shadowing from dust on optical surfaces in the image train. There are a variety of flat fielding techniques available to the observer, each with its own benefits and drawbacks, and a choice of technique depends on the objectives of the observing program. Proper flat fielding can yield images that are uniform across the field to less than 1% error.

References

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