

Demystifying

Flat Fields

Understanding the workings of flat-field calibration will greatly improve your CCD images.

Peter Kalajian

Whenever I'm in the company of other astrophotographers, I like to take a quick survey: how many of you are calibrating your images using flat fields? The results are not surprising. Invariably, few beginner amateur imagers raise their hands. After all, flat-fielding techniques seem to have a mystique associated with them, even among professional astronomers. This need not be so. With a bit of study of the theory and practice, flat fielding can be understood and applied to great advantage by every imager.

Flat Fielding Explained

Every beautiful astrophoto begins with some basic calibration before the imager moves on to additional processing. Flat fielding is the part of this calibration that mitigates the effect of the CCD's pixel-to-pixel variation in sensitivity, vignetting in the optical system, and shadows created by dust on the components of the imaging system.

Let's imagine a perfect imaging system without hot or cold pixels, dust, and vignetting. If we expose this hypo-



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Producing the best astrophotos with CCD cameras requires more than just clear, steady skies. A series of calibration frames are needed to remove unwanted signal such as dark current and hot or dead pixels. One important calibration step involves flat-field frames, which correct for small variations of pixel sensitivity across the CCD detector, as well as vignetting in the optical system and dust shadows within the optical path. The pictures above show the results of an image processed without flat-field calibration (left) versus the same data processed with this important step (right).

thetical setup to a uniform light source, then every pixel in this image should have the same analog digital unit (ADU) or pixel value after exposure.

Of course, CCDs are not perfect, so pixel values in this “flat-field” image will vary. Just how much they vary tells us exactly how to modify each pixel in the image of an astronomical target to correct for the imaging setup’s imperfections.

The entire calibration process can be summarized succinctly by the following simple relationship:

$$\text{Calibrated PV} = \frac{(\text{Raw PV} - \text{Dark PV})}{(\text{Flat PV} - \text{Dark PV}) / (\text{Mean Flat PV} - \text{Mean Dark PV})}$$

This equation deals with pixel values (PV) from four separate images: a raw frame, a master dark frame made up of an average (or mean) of many dark frames of equal duration and temperature to the raw frame, a flat-field frame, and the flat field’s own appropriate master dark frame taken at the same exposure length and temperature of the flat-field frame.

The equation’s numerator is simply the raw exposure of an astronomical target corrected for any thermal “dark” signal due to non-photon-induced electrons in the CCD.

To understand the denominator, think back to the perfect CCD, where each pixel responded perfectly to the even illumination and needs no correction (in which case the denominator would have a normalized value equal to 1). Assuming the light source is perfectly uniform, the mean of all the pixel values in the flat-field image is a good approximation of the uniform pixel value from the perfect CCD. If a pixel value in the flat-field image is below the mean value, then it is “underreporting,” while any pixels that have values above the mean are “overreporting.”

Normalization

By dividing the flat-field pixel value by the mean of all the pixels in the flat-field image, we arrive at the normalized pixel value. A pixel that has a value equal to the mean will be normalized to 1, while a pixel that has a value less than the mean will be normalized to less than 1, and pixels with values above the mean will be normalized to more than 1. Any image-processing program that performs calibration takes care of this normalization automatically, but it’s important to understand the process, as we’ll see when we talk about how to get good flats.

Dark subtraction

It should now be apparent that master dark frames must be applied to both the raw image and the flat-field image in order for the pixel to be calibrated properly. Failure to subtract the dark current from a flat-field frame will



Author Peter Kalajian with his Flat Man XL, an electroluminescent panel used to record evenly illuminated flat-field images.

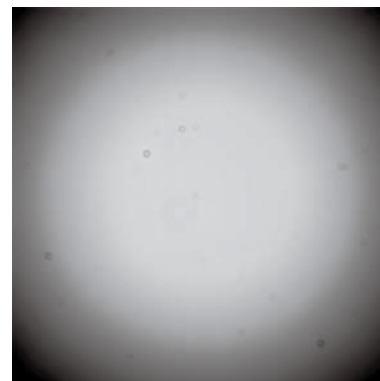
JACOB GERITSEN

make the denominator incorrectly large, resulting in an improper correction to the raw image. Always dark calibrate your flats!

Characterizing Your CCD Camera

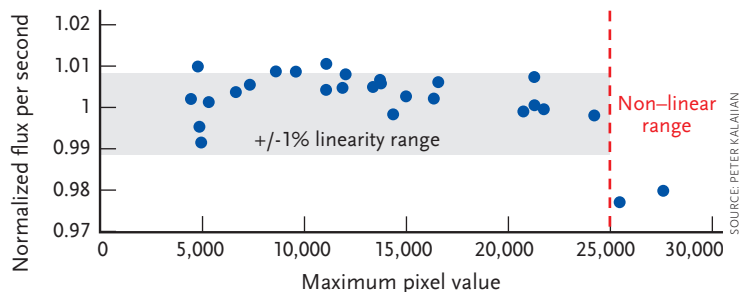
To reduce non-uniformity in your flats, make them with an exposure length that is long enough to eliminate the effects of the camera’s shutter sweeping across the detector, but short enough to obtain pixel values within the linear range of the CCD detector. Exposing for at least two seconds takes care of most cameras’ shutter latency problems, though larger chips may require longer exposures to truly mitigate its effect. How to decide on an upper-end limit depends on characterizing the linearity of your camera’s detector.

Most anti-blooming CCD detectors do not have a linear response to photons across their entire dynamic range, and because of slight differences in each CCD, no two cameras will have the exact same range of linear response. My SBIG ST-2000 CCD camera becomes non-linear when pixel values reach about 25,000, well below the 56,000 saturation limit. As such, I shoot for flat-field images with a maximum pixel value of about 24,000 just to be on the safe side. The consequence of using a flat-



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While both of these flat fields are suitable for calibrating their respective images, their different appearance arises from being recorded through a camera lens having very little vignetting, and the one at right being through a telescope.



Before shooting flat-field exposures, it's important for you to characterize your CCD camera. The author made this plot of a 9th-magnitude star near the zenith recorded with increasing exposures. As explained in the text, the plot shows that his CCD is linear until pixel values reach about 25,000. Flats must be exposed within the linearity range of a CCD detector.

field image with nonlinear response to photons is that the normalized pixel values will be too small, resulting in overcorrected images. Imagers using cameras with non-antiblooming detectors should shoot for pixel values close to full-well capacity (saturation), but avoid blooming. This ensures that the recorded flats take advantage of the majority of the CCD's entire dynamic range.

Characterizing the linearity of your CCD is fairly easy to do. A simple technique is to point the imaging system at a 9th-magnitude star near the zenith and take sets of five images at increasing exposure lengths until the star's image saturates (reaches the maximum pixel value). Using the photometry tool in your image-acquisi-

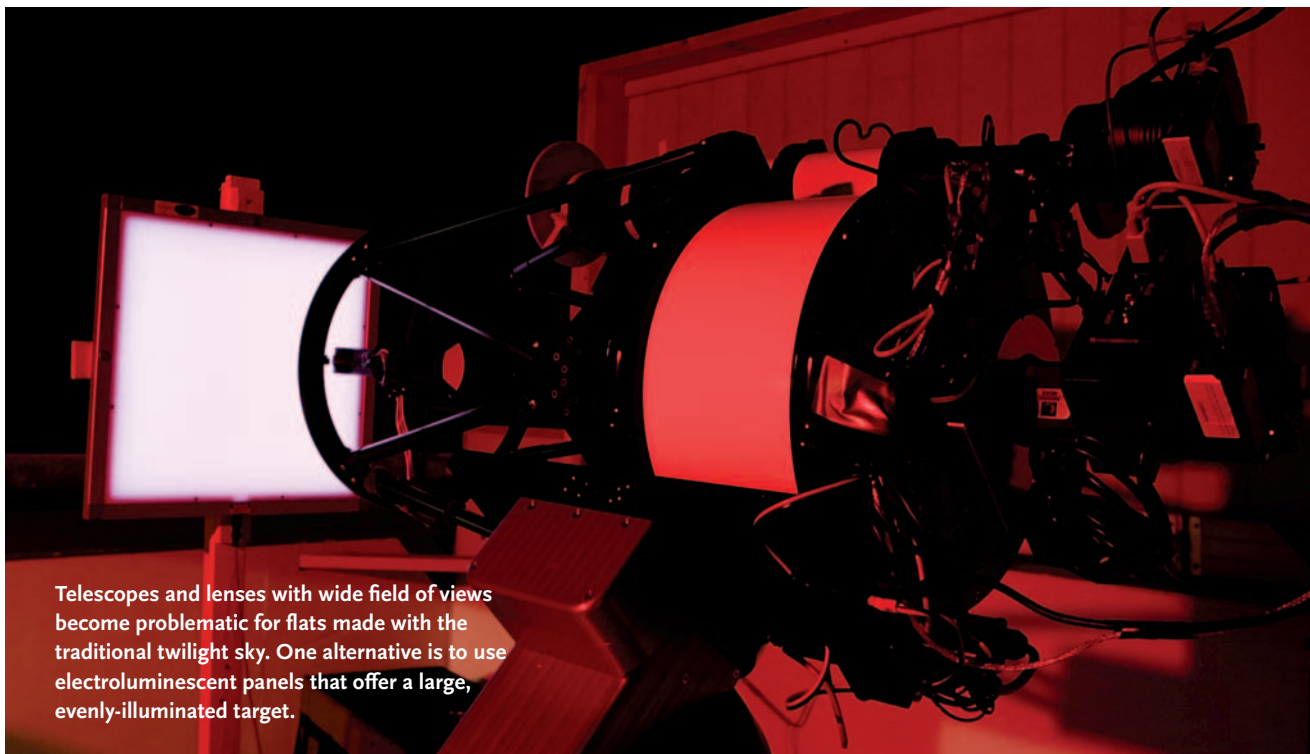
tion software, draw a box around the star, then measure the total flux and maximum pixel value inside the box for each image.

Enter the data into a spreadsheet and make a column that divides the total flux by the exposure time, which gives us the flux per second. Since the star's flux is constant over time (be careful not to choose a variable star), the flux per second will remain constant when it is within the linear range of the CCD, but will start to drop off as the CCD's anti-blooming gate kicks in. When this happens there will be a noticeable drop in flux per second and the CCD will be at the top of its linear range. Armed with this measurement, you should expose your flat-field frames to keep the pixel values below those where the flux per second starts to diminish.

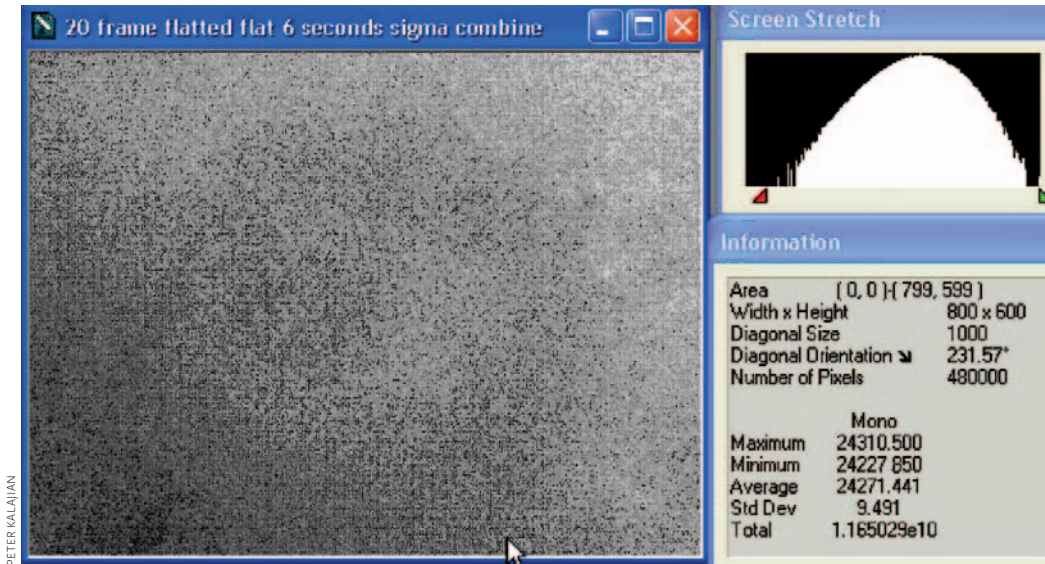
Uniform Illumination

This is the toughest part of the flat-field process; generating a perfectly uniform illumination source for your flat-exposures. Knowing when you have a uniform source is harder still.

Traditionally, imagers start out using the twilight sky as an illumination source. The trick is to point the telescope at a neutral point in the sky once the Sun has gone down enough so that the CCD detector does not saturate, but when there's still enough light to obtain good photon statistics. You have to race against the clock to get enough flat-field frames to assemble a master frame with enough of a signal-to-noise ratio so that the flat doesn't add noise



Telescopes and lenses with wide field of views become problematic for flats made with the traditional twilight sky. One alternative is to use electroluminescent panels that offer a large, evenly-illuminated target.



Analyzing a “flatted flat,” the author measured the uniformity of his electroluminescent panel and ST-2000M CCD camera using *MaxIm DL*. He found the image’s average (mean) pixel value to be 24,271.441 and the standard deviation 9.491. His results yielded an impressive uniformity of 0.3%. Astrophotographers should shoot for a uniformity of 1% or less to achieve the best results when calibrating their exposures.

to your final image. To make matters worse, you have to do this for each of the filters that you plan to image through for the night.

These “twilight” flats can be good, especially in systems with small fields of view, using automated acquisition software that adjusts exposure time to compensate for changing lighting conditions. Wide-field imagers will be disappointed with twilight flats on the whole, since there’s always some brightness gradient present in the sky. Some imagers mitigate the gradient by covering the telescope’s aperture with some sort of diffuser, like a piece of translucent white acrylic or even a tee shirt stretched across the front aperture.

The problem with twilight flats is that you never know what the quality of the flat is like until it’s applied to your image. Were there some high clouds that interfered with the evenness of illumination? Did you choose an appropriate neutral point in the sky? Were there gradients from ambient lighting in your neighborhood?

To avoid the problems with twilight flats, many imagers use artificial illumination. This can range from specially constructed light boxes placed over the telescope to white screens that are illuminated by multiple light sources. Recently, electroluminescent panels with the proper diffusion and power-supply regulation have shown great promise for producing evenly illuminated flats.

To evaluate the uniformity of illumination of your flat field, you can perform this simple test. Take an image of your illumination source, and then rotate your camera by 90° and take another image. Now calibrate the first image using your master dark and using the second image as the flat field. Doing this is essentially “flat-fielding a flat”, so your resulting calibrated image should be completely uniform.

The best way to evaluate the uniformity is to check

the histogram of this flattened flat. It should look like a symmetrical Gaussian distribution or bell curve, and the width of the distribution is proportional to the uniformity of illumination. To make a numerical estimate of uniformity, look at the standard deviation of pixel values in the image using the information window of your acquisition program. In a Gaussian distribution, 99.7% of all values lie within three standard deviations (commonly referred to by the symbol σ) of the mean on either side, so you can calculate the degree of uniformity of your flat field using this simple formula:

$$\% \text{ of variation from uniformity} = \frac{100\% \times 2 \times 3\sigma}{\text{Mean pixel value of "flatted flat"}}$$

Our goal is to try to shoot for less than 1% variation from uniformity for best results. Non-uniform flats will result in poor image calibration where artifacts are still visible in the final image.

Proper flat-fielding techniques are critical steps in the image-processing workflow. With a little understanding of the math behind the calibration process, you can begin to hone your calibration techniques. Getting to know your CCD’s linear range is an essential first step in the quest for good flat-field images. Astrophotographers who evaluate their flat-field illumination for uniformity may find that twilight flats aren’t up to the task of wide-field image calibration, and those who use artificial light sources can check to see if their flat boxes are uniform. ♦

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