The above is one way to answer the question, but it still relies on the fact that observers need to obtain good flat fields. Without them, near perfect agreement of final results is unlikely. While the ideal flat field would uniformly illuminate the CCD such that every pixel would receive equal amounts of light in each color of interest, this perfect image is generally not produced with dome screens, the twilight sky, or projector lamps within spectrographs. This is because good flat field images are all about color terms. That is, the twilight sky is not the same color as the nighttime sky, neither of which are the same color as a dome flat. If you are observing red objects, you need to worry more about matching the red color in your flats; for blue objects you worry about the blue nature of your flats. Issues to consider include the fact that if the Moon is present, the sky is bluer then when the Moon is absent, dome flats are generally reddish due to their illumination by a quartz lamp of relatively low filament temperature, and so on. Thus, just as in photometric color transformations, the color terms in flat fields are all important. One needs to have a flat field that is good, as described above, plus one that also matches the colors of interest to the observations at hand.

Proper techniques for using flat fields as calibration images will be discussed in Section 4.5. Modern CCDs generally have pixels that are very uniform, especially the new generation of thick, front-side devices. Modern thinning processes result in more even thickness across a CCD reaching tolerances of 1-2 microns in some cases. Thus, at some level flat fielding appears to be less critical today but the advances resulting in lower overall noise performance provide a circular argument placing more emphasis on high quality flats. Appendix A offers further reading on this subject and the material presented in Djorgovski (1984), Gudehus (1990), Tyson (1990), and Sterken (1995) is of particular interest concerning flat fielding techniques.

## 4.3 Calculation of read noise and gain

We have talked about bias frames and flat field images in the text above and now wish to discuss the way in which these two types of calibration data may be used to determine the read noise and gain for a CCD.

Noted above, when we discussed bias frames, was the fact that a histogram of such an image (see Figure 3.8) should produce a Gaussian distribution with a width related to the read noise and the gain of the detector. Furthermore, a similar relation exists for the histogram of a typical flat field image (see Figure 4.1). The mean level in the flat field shown in Figure 4.1

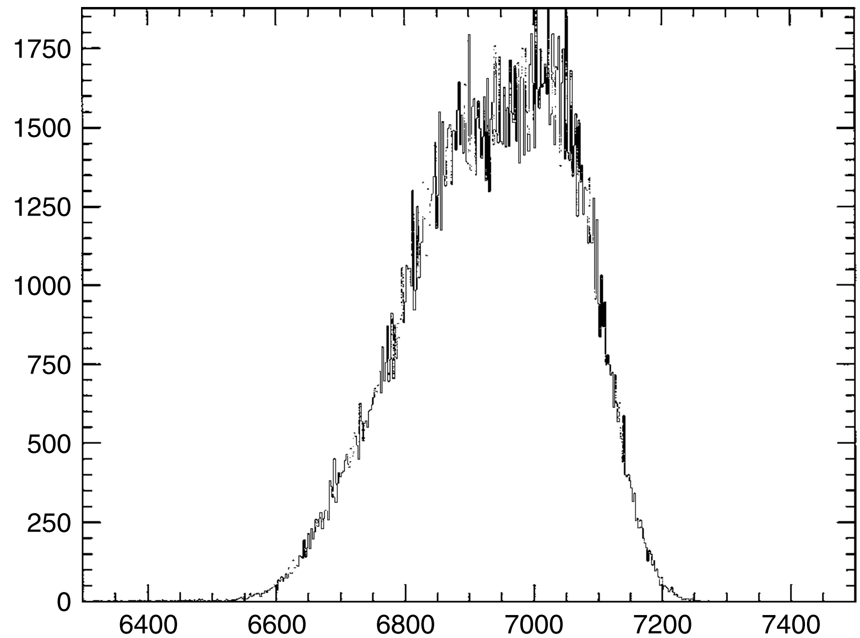


Fig. 4.1. Histogram of a typical flat field image. Note the fairly Gaussian shape of the histrogram and the slight tail extending to lower values. For this R-band image, the filter and dewar window were extremely dusty leading to numerous out of focus "doughnuts" (see Figure 4.4), each producing lower than average data values.

is $\bar{F} = 6950$ ADU and its width (assuming it is perfectly Gaussian (Massey & Jacoby, 1992)) will be given by

$$\sigma_{\text{ADU}} = \frac{\sqrt{\bar{F} \cdot \text{Gain}}}{\text{Gain}}.$$

We have made the assumption in this formulation that the Poisson noise of the flat field photons themselves is much greater than the read noise. This is not unreasonable at all given the low values of read noise in present day CCDs.

Let us now look at how bias frames and flat field images can be used to determine the important CCD properties of read noise and gain. Using two bias frames and two equal flat field images, designated 1 and 2, we can proceed as follows. Determine the mean pixel value within each image.[1] We will call the mean values of the two bias frames $\bar{B}_1$ and $\bar{B}_2$ and likewise $\bar{F}_1$ and $\bar{F}_2$ will be the corresponding values for the two flats. Next, create two difference images ($B_1 - B_2$ and $F_1 - F_2$) and measure the standard deviation

[1] Be careful here not to use edge rows or columns, which might have very large or small values due to CCD readout properties such as amplifier turn on/off (which can cause spikes). Also, do not include overscan regions in the determination of the mean values.

of these image differences: $\sigma_{B_1-B_2}$ and $\sigma_{F_1-F_2}$. Having done that, the gain of your CCD can be determined from the following:

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

and the read noise can be obtained from

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

## 4.4 Signal-to-noise ratio

Finally we come to one of the most important sections in this book, the calculation of the signal-to-noise (S/N) ratio for observations made with a CCD.

Almost every article written that contains data obtained with a CCD and essentially every observatory user manual about CCDs contains some version of an equation used for calculation of the S/N of a measurement. S/N values quoted in research papers, for example, do indeed give the reader a feel for the level of goodness of the observation (i.e., a S/N of 100 is probably good while a S/N of 3 is not), but rarely do the authors discuss how they performed such a calculation.

The equation for the S/N of a measurement made with a CCD is given by

$$\frac{\text{S}}{\text{N}} = \frac{N_*}{\sqrt{N_* + n_{\text{pix}}(N_S + N_D + N_R^2)}},$$

unofficially named the "CCD Equation" (Mortara & Fowler, 1981). Various formulations of this equation have been produced (e.g., Newberry (1991) and Gullixson (1992)), all of which yield the same answers of course, if used properly. The "signal" term in the above equation, $N_*$, is the total number of photons[1] (signal) collected from the object of interest. $N_*$ may be from one pixel (if determining the S/N of a single pixel as sometimes is done for a background measurement), or $N_*$ may be from several pixels, such as all of those contained within a stellar profile (if determining the S/N for the

[1] Throughout this book, we have and will continue to use the terms photons and electrons interchangeably when considering the charge collected by a CCD. In optical observations, every photon that is collected within a pixel produces a photoelectron; thus they are indeed equivalent. When talking about observations, it seems logical to talk about star or sky photons, but for dark current or read noise discussions, the number of electrons measured seems more useful.