
Errata to First Printing¹ 2nd Edition of *The Handbook of Astronomical Image Processing*

1. **Page 47:** In 2nd line of paragraph. Following Equ. 2.17, change 24 to 124. Text should read as follows:

The dark frame is a map of the dark current from the sensor. Note that the useful portion of the signal—the 124 ADUs of dark current—is uncertain with a standard deviation of 4.45 ADUs; so the dark frame is not a perfect map of the dark current, but a sample of the dark current with an accompanying error.

2. **Page 136:** In 3rd line of 4th para. in sec. on “Globular Clusters,” change “technolgoy” to “technology.” Text should read as follows:

Many other galaxies are surrounded by a halo of globular clusters. Before the advent of CCDs, most of these objects were too faint for amateurs to observe, but current **technology** places the globular clusters around the Andromeda Galaxy well within amateur reach.

3. **See Item 8**

4. **Page 276:** the term in the numerator of Equation 10.7 should be changed from $(C_{\text{aperture}}/n_{\text{annulus}})$ to $(C_{\text{annulus}}/n_{\text{annulus}})$ and should read as follows:

$$m = -2.5 \log \left(\frac{C_{\text{aperture}} - n_{\text{aperture}} (C_{\text{annulus}} / n_{\text{annulus}})}{t} \right) + Z \quad (\text{Equ. 10.7})$$

1. The printing of the book can be determined by looking at the book’s copyright page.

5. **Page 277:** the term in the numerator of Equation 10.8 should be changed from $(C_{\text{aperture}}/n_{\text{annulus}})$ to $(C_{\text{annulus}}/n_{\text{annulus}})$ and should read as follows:

$$S_{\text{star}} = g(C_{\text{aperture}} - n_{\text{aperture}}(C_{\text{annulus}}/n_{\text{annulus}})), \quad (\text{Equ. 10.8})$$

6. **Page 506:** Figure 19.5 is missing; caption for it appears below 2nd paragraph. Figure and caption should be as follows:



Original Image

50 Iterations, van Cittert

Figure 19.1 At a larger image scale, the restoration of small features is dramatic. In particular, note the improvement in the visibility of the chain of tiny craters, the terraces and benches in the interior crater walls, and the contact between degraded crater walls and mare flood lavas.

7. **Page 635:** At the beginning of last line on the page, delete extra "f" in "ffrom." Text should read as follows:
- Multiple-Image Photometry is an automated tool that measures either raw instrumental magnitudes or differential magnitudes **from** a series of images.
8. **Pages 229-234:** Based upon reader comments, we have decided to rewrite these pages which deal with basic CCD testing. The revised text follows on the next page. Revised text is as follows:

8.2 Basic CCD Testing

To be practical, CCD tests must be simple enough to be carried out without fancy test equipment. You can do basic testing without even taking your CCD off the telescope! This consists of shooting two bias frames, two flat-field frames, and one dark frame. That's it. The analysis takes about five minutes. Details are given in Section 8.2.1.

Advanced CCD testing is more complex. It requires building a low-level light source (L^3S), and with it shooting nine bias frames, nine low-level flat-field frames, 32 flat frames taken with differing integration times, and three long-integration dark frames. This test sequence can be done any place that can be darkened, including indoors on a cloudy night or in your observatory. Shooting a set of advanced test images takes about three hours, and analyzing the results takes about an hour. You will find a full description of advanced testing in Section 8.3.

8.2.1 How to Make Basic CCD Test Images

The purpose of making initial test images is to get a quick measurement of the gain (or conversion factor), readout noise, and dark current of your CCD camera. This method gives you accurate results, and it takes only a few minutes. Furthermore, you can test the camera while it is attached to your telescope, so you can easily fit it into your schedule during a night's observing.

To make the flat-fields, you will need a light box like the L^3S described later in this chapter, the evening sky, or your usual method for making flats. Make the bias frames and the dark frame immediately before or after the flats so there's no time for the CCD or electronics to drift or change.

Turn on the camera and allow it to reach thermal equilibrium. Using the readout mode that you use to make celestial images, shoot the following images:

Two Flat Frames. Make two flat frames using the same integration time. Adjust the integration time to produce average pixel values one-third to halfway to the maximum output of the camera. For 12-bit cameras, the flat should have an average value between 1,500 and 2,000 ADUs; for a 16-bit camera, the flat should average around 20,000 to 32,000 ADUs. Save the flat-frame files as BCT-FF1 and BCT-FF2.

Two Bias Frames. With the dark slide closed or with telescope capped, set the integration time of your camera to the shortest available, and then make two bias frames. Save them as BCT-BF1 and BCT-BF2.

One Dark Frame. Close the dark slide or cap the telescope, and make a dark frame using a 60-second integration time. Save the dark frame as BCT-DF.

8.2.2 Basic Test Analysis

These images contain enough information to determine the conversion factor (also called the gain), g , the readout noise, σ_{Readout} , and the mean dark current, $\bar{D}_{\text{electrons}}$. Your measurements will be made in analog-to-digital units, or ADUs.

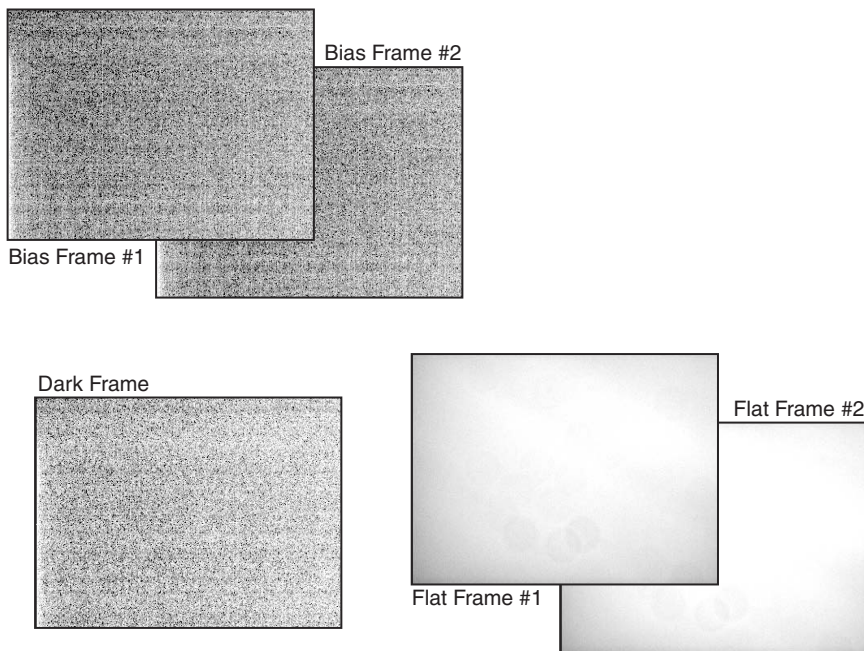


Figure 8.1 It takes only five images to determine your camera's conversion factor and readout noise. You can obtain a set of images like these without taking your CCD camera off the telescope during a regular observing session. Checking your camera assures that you are getting the performance you expect.

As you carry out each step, write your results in a format like that shown in Table 8.1. The tabular format keeps the data organized and ready for calculation.

8.2.2.1 Step 1: Mean and Standard Deviation of the Flats

Load the two flat frames, BCT-FF1 and BCT-FF2. Add them together and then measure the mean value of a region near the center of the image. The size of the region is not critical; an area 100 pixels on a side is entirely adequate. The result is $\bar{F}_1 + \bar{F}_2$ ADUs. (The notation \bar{F} is read as "F-bar," and the bar over the F says that it's a mean value.)

Next, subtract one frame from the other, and measure the standard deviation in pixel value for a region near the center of the frame. Subtracting the two flat frames removes any features in the flat, leaving the total noise in the two flat frames, $\sigma_{F_1 - F_2}$ ADUs. The noise you have measured is $\sqrt{2}$ times the noise in a single flat frame.

- **Tip:** In *AIP4Win*, you can add and subtract images using the *Image Math* tool. Measure the mean value of the summed frames and the standard deviation of the difference frames using the *Pixel Tool*.

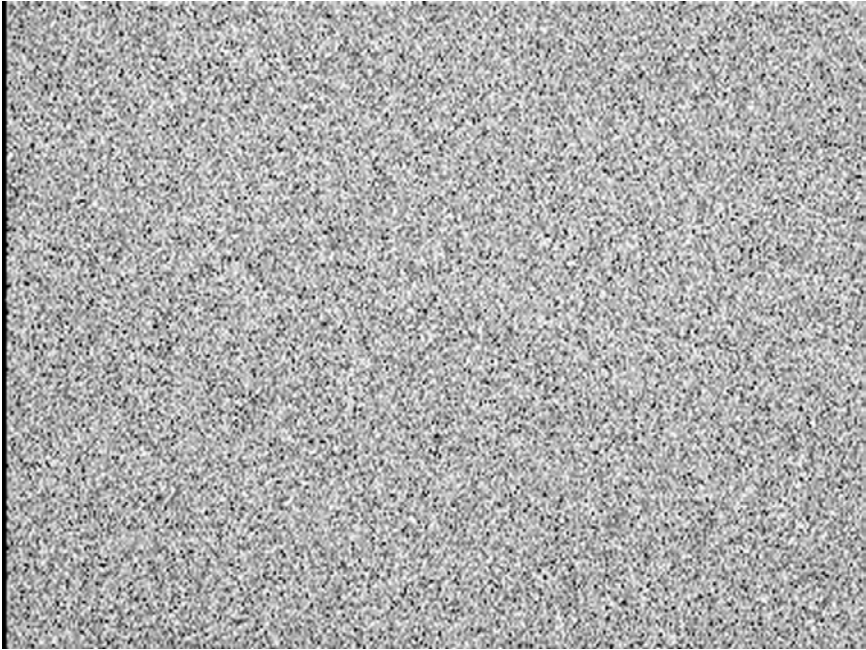


Figure 8.2 The difference between two seemingly identical flat-field frames is noise—in this case, the random variation in the number of electrons generated at each photosite. This image has been stretched by a factor of 20 relative to the two flat-frames, shown in Figure 8.1, that were subtracted to create it.

8.2.2.2 Step 2: Mean and Standard Deviation in the Bias

Load the two bias frames, BCT-BF1 and BCT-BF2. Add them together and measure the mean value of a region near the center of the image. The mean value is the quantity $\bar{B}_1 + \bar{B}_2$ ADUs.

Next, subtract one bias frame from the other, and measure the standard deviation in pixel value for the same region at the center of the frame. Subtracting the two bias frames removes any fixed bias patterns, leaving only noise from the two bias frames, $\sigma_{B_1-B_2}$ ADUs, which is $\sqrt{2}$ times the noise of one bias frame.

8.2.2.3 Step 3: Measure the Dark Current

Load the dark frame, BCD-DF, and the bias frame, BCD-BF1. Subtract the bias frame from the dark frame. Measure the mean pixel value for a region at the center of the frame. This is the dark current, \bar{D}_{ADUs} , in ADUs, that accumulated during the integration time, t , measured in seconds.

8.2.2.4 Step 4: Compute the Conversion Factor (or Gain)

Because the signal obeys Poisson statistics, the relationship $\sigma_{\text{electrons}} = \sqrt{F_{\text{electrons}}}$ should hold true. However, you measured the mean of a high signal level and its standard deviation in pixel-value units, or ADUs. The conversion factor—also

called the gain—expresses the relationship between photoelectrons and pixel-value units. To use the Poisson-noise relationship, you need to multiply the signal in ADUs and the noise in ADUs by the factor g to convert them to electron units:

$$gF_{\text{ADUs}} = F_{\text{electrons}}, \text{ and}$$

$$g\sigma_{\text{ADUs}} = \sigma_{\text{electrons}}.$$

The Poisson relationship can therefore be expressed as:

$$g\sigma_{\text{ADUs}} = \sqrt{gF_{\text{ADUs}}}.$$

Solving this equation for g yields the conversion factor:

$$g = \frac{F_{\text{ADUs}}}{\sigma_{\text{ADUs}}^2} \text{ [electrons/ADU]}. \quad \text{(Equ. 8.1)}$$

Although this relationship is adequate as a rough measure of the conversion factor, it makes two assumptions:

1. the flat-field illumination is perfectly uniform, and
2. the bias is small compared to the flat-field exposure.

Variations in the “flatness” of the flat-field frame are a special problem because they increase the standard deviation of the flat field even though they are not noise. To get around this, we employ a clever trick by making two flat frames and subtracting one from the other. Thus variations in the signal level cancel, but because noise is always additive, the difference frame has twice the variance due to noise we would expect in a single frame. We use the same trick to measure the noise in a pair of bias frames. Since the mean values of the flat-field and bias sum frames are twice those of single frames, the factors of two cancel.

To compute the gain (conversion factor), g , evaluate:

$$g = \frac{(\bar{F}_1 + \bar{F}_2) - (\bar{B}_1 + \bar{B}_2)}{(\sigma_{F_1 - F_2}^2) - (\sigma_{B_1 - B_2}^2)} \text{ [electrons/ADU]}. \quad \text{(Equ. 8.2)}$$

Because this equation is free of the assumptions implicit in Equation 8.1, it yields a significantly more robust result for a small increase in effort.

8.2.2.5 Step 5: Compute the Readout Noise

The only source of noise in a bias frame should be readout noise. You have measured the sum of readout noise in two bias frames.

To compute the readout noise, evaluate:

$$\sigma_{\text{Readout}} = \frac{g\sigma_{B_1 - B_2}}{\sqrt{2}} \text{ [electrons r.m.s.]}. \quad \text{(Equ. 8.3)}$$

Table 8.1 Sample Basic CCD Test Data

Frame	Sum Frame	Std Dev'n of Difference Frame	Mean Dark
Flat Frames	39675 ADUs	247.7 ADUs	—
Bias Frames	213.3 ADUs	32.84 ADUs	—
Dark – Bias Frame	—	—	6.43 ADUs
$g = \frac{(\bar{F}_1 + \bar{F}_2) - (\bar{B}_1 + \bar{B}_2)}{(\sigma_{F_1 - F_2}^2) - (\sigma_{B_1 - B_2}^2)} = \frac{39675 - 213.3}{(247.7)^2 - (32.84)^2} = 0.65 \text{ [e}^- \text{ / ADU]}$ $\sigma_{\text{Readout}} = \frac{g\sigma_{B_1 - B_2}}{\sqrt{2}} = \frac{0.65 \times 32.84}{\sqrt{2}} = 15.1 \text{ [e}^- \text{ r.m.s.]}$ $\bar{D}_{\text{electrons}} = \frac{g\bar{D}_{\text{ADUs}}}{t} = \frac{0.65 \times 6.43}{60} = 0.07 \text{ [e}^- \text{ / pixel / sec]}$			
<p>Note that “electrons” is often abbreviated as e⁻ (the letter e with a superscripted minus sign). For example, the term “electrons per ADU” is written as e⁻ / ADU.</p>			

8.2.2.6 Step 6: Compute the Dark Current

Convert the dark current measured in ADUs to electrons per pixel per second by evaluating:

$$\bar{D}_{\text{electrons}} = \frac{g\bar{D}_{\text{ADUs}}}{t} \text{ [e}^- \text{ / pixel / sec]}. \tag{Equ. 8.4}$$

Recall that *t* is the dark frame exposure time in seconds.

Some CCDs have dark current rates as low as 0.001 electrons per pixel per second. For these low-dark-current CCDs, it may prove necessary to use an integration time considerably longer than 60 seconds to accumulate a sufficiently large dark current to measure.

8.2.3 What Results to Expect

The conversion factor (or gain) is the number of electrons per ADU. It is determined by the CCD camera’s electronics. The designer’s goal is to divide the full-well capacity of the CCD chip into the number of steps resolved by the analog-to-digital converter:

$$\frac{\text{full-well capacity}}{\text{levels available}} = \text{conversion factor}. \tag{Equ. 8.5}$$

For example, for a commercial-grade chip with a full-well capacity of 40,000 electrons and a 16-bit analog-to-digital converter, most camera designers would set the conversion factor at some value close to 80,000/65536 = 0.6 electrons per ADU. For 16-bit CCD cameras, gain values around unity are typical.

Readout noise is primarily determined by the CCD's on-chip amplifier and the readout speed. Science-grade chips that are read out slowly may have readout noise levels of 3 electrons r.m.s. or better; top-notch commercial-grade models with moderately fast readout speeds have readout noise around 6 electrons r.m.s.; and CCDs made for video camera applications and digital SLRs typically have a readout noise between 8 and 30 electrons r.m.s. If your camera has a CMOS sensor, you can expect the conversion factor and readout noise to be larger than you might find in a comparable CCD, but somewhere in the same ballpark.

In a cooled CCD camera, the mean dark current is typically around 1 electron per pixel per second. Dark current depends critically on the intrinsic properties of the sensor and the temperature of the sensor. A CCD that has a dark current of 1 electron per pixel per second when it's cooled to -30 C will have between 100 and 1000 times that much dark current operating at room temperature. Since low-dark-current technologies can push the dark current down to roughly 10 electrons per pixel per second at room temperature; and these devices, when cooled to -10 C, turn in quite remarkable dark current figures. CCDs made by Sony employ a proprietary process that produces very low dark currents at room temperature, and extraordinarily low levels—on the order of 0.002 electrons per pixel per second—when cooled to -10 C. With such low dark currents, dark current subtraction may not immediately appear to be necessary, but remember that dark-frame subtraction also removes the bias value, which is necessary for proper flat-fielding.