You, too, can make useful and beautiful astronomical images at Mees: Lesson 3

Calibration and data reduction

Useful references, besides Lessons 1 and 2:

❑ The AST 142 Projects manual:
  http://www.pas.rochester.edu/~dmw/ast142/Projects/Project.pdf

❑ Rob Gendler (ed.) 2013, *Lessons from the Masters* (New York: Springer-Verlag), especially the articles by Adam Block (p. 159) and Johannes Schedler (p. 193).
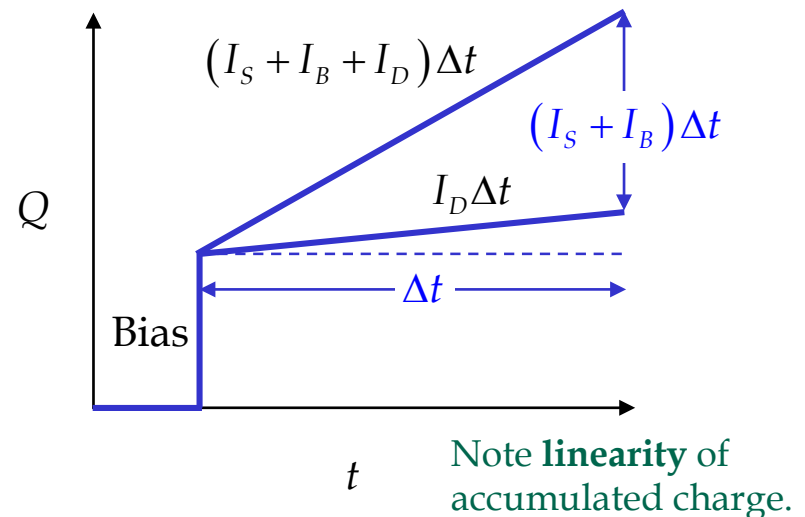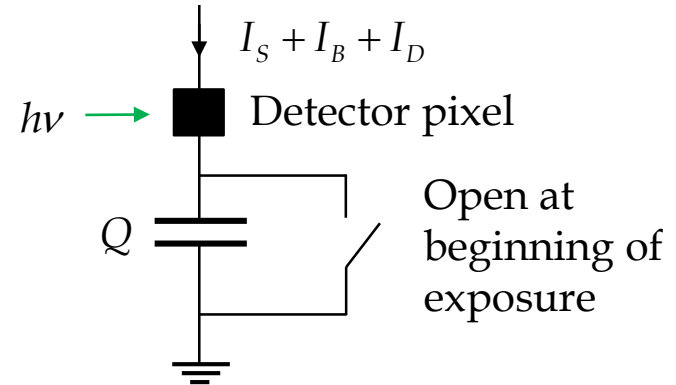
Software:

❑ CCDSoft v. 5.

❑ CCDStack v.2.9

❑ IDL v.8.2, with astrolib and ATV.

Work in progress: NGC 5985 (left) and NGC 5982 (right) in Draco, LRGB, result of 12x5 minutes in L and 4x5 minutes each in R, G and B, mostly with light from a gibbous moon last Thursday night. I plan to get 3-4 more hours of data on the same field this Saturday night -- with much fainter moonlight – in an effort to detect more extended structure in NGC 5985 and cooling-flow shells around NGC 5982.

Calibration 1: dark current and bias

❑ CCDs integrate photocurrent and dark current during an Exposure. Need to measure and subtract the parts of the current not due to Signal: that is, light from the celestial object.

❑ The switches which dump the accumulated charge between exposures also leave a spurious charge behind, called **bias**. This also must be removed and subtracted.

❑ Dark current and bias can be measured during the day, so we conserve nighttime and do so.

$I_S + I_B + I_D$

Detector pixel

$hv \longrightarrow$

Q

Open at beginning of exposure

$(I_S + I_B + I_D)\Delta t$

$(I_S + I_B)\Delta t$

$I_D \Delta t$

Q

Δt

Bias

t

Note **linearity** of accumulated charge.

Dark current and bias (continued)

❑ Dark current and bias differ from pixel to pixel but the differences are the same at a given CCD temperature.

❑ Both dark current and bias both suffer from noise.

❑ So we reduce the contribution of these quantities to noise in our final images by measuring a very large number of dark (64, 30 min) and bias (256) frames at each temperature (-20 C, -10 C) and binning (1x1, 2x2), and averaging them.

❑ Thus our Master Dark and Bias Frames.
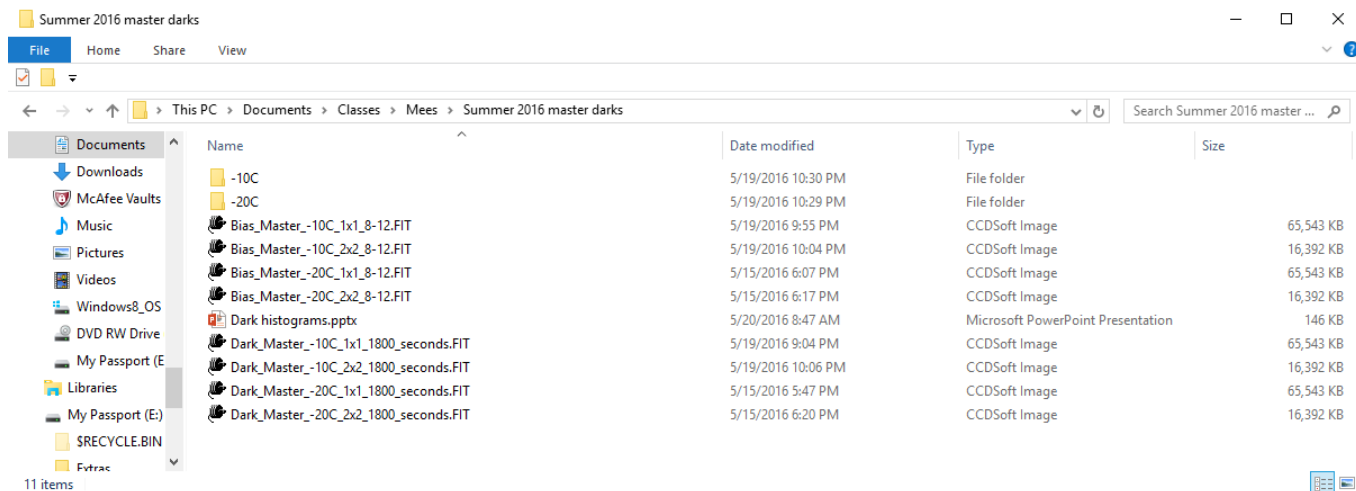
Calibration 2: flat field

❑ CCDs have variation of pixel capacitance and quantum efficiency between different parts of the array.

❑ The telescope and camera optics can also introduce systematic variation in signal, in effects all the way from vignetting to dust specks on the filters.

❑ The variation is different for different wavelengths and CCD temperatures.

❑ Thus we measure **flat field:** the response of the CCD and optics to a carefully-prepared uniform light input.
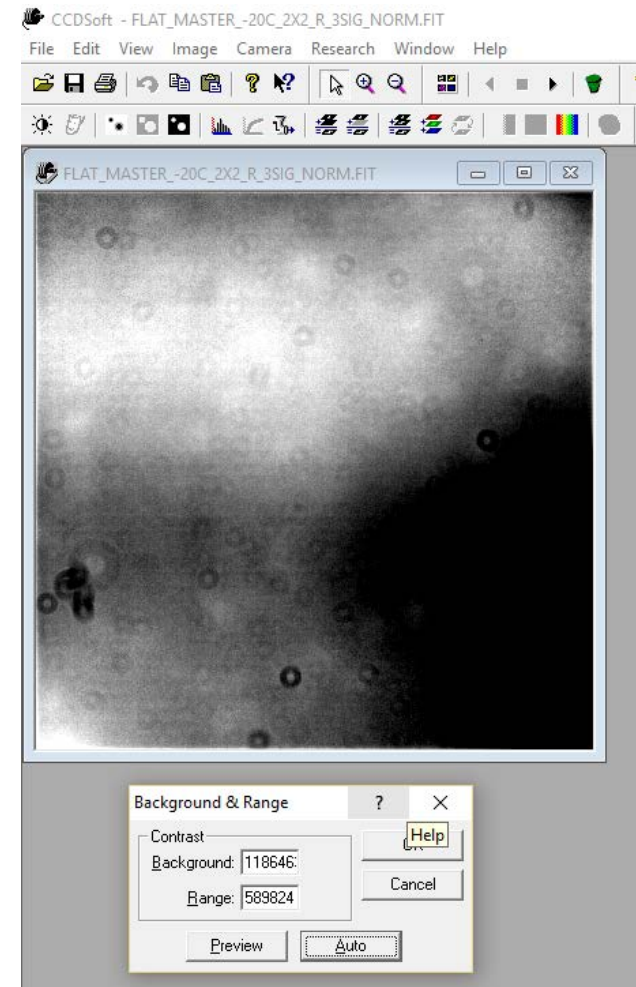
Flat field (continued)

❑ A good method: observe twilight-sky emission. It's uniform, and right after sunset it's faint enough not to saturate the CCD but bright enough to produce big signals.

❑ Again, to minimize noise, take a large number (e.g. 32-64) of exposures at each wavelength (L, R, G, B), CCD temperature (-20 C, -10 C), and binning (1x1, 2x2), normalize them (for changing sky brightness) and average.

❑ Thus our master flat fields.
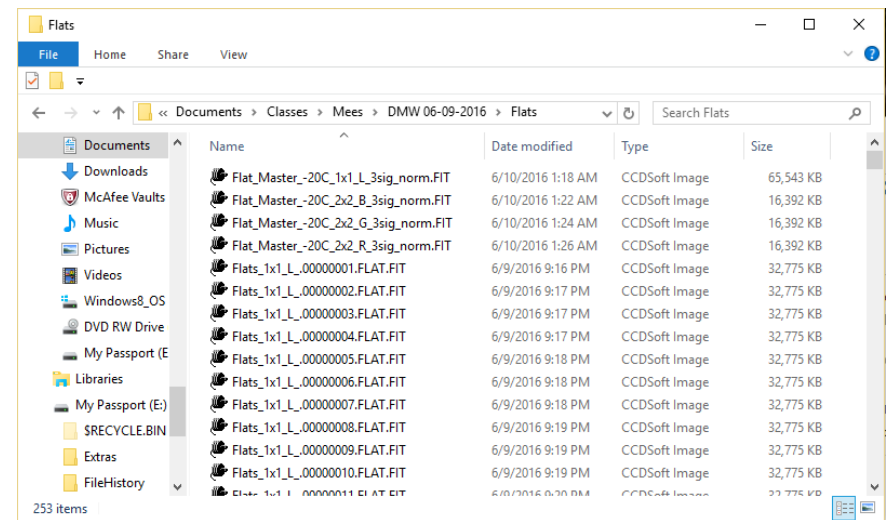
Calibration 3: flux calibration

❑ For APOD-quality images: don't bother. Start with the standard signal scaling for equal-length exposures of our filter set, when composing RGB images: 0.6, 0.8 and 1.2 for R, G and B respectively.

❑ For scientifically-useful images: use observations of standard stars, plus **aperture photometry** as built into several useful applications (e.g. ATV, shown here), to determine the total data-numbers (DNs) in the star's image at each wavelength.

❑ As you know P_S for the star, this gives one the ratio of P_S/DN, by which one can multiply pixel values to convert the image to real units.
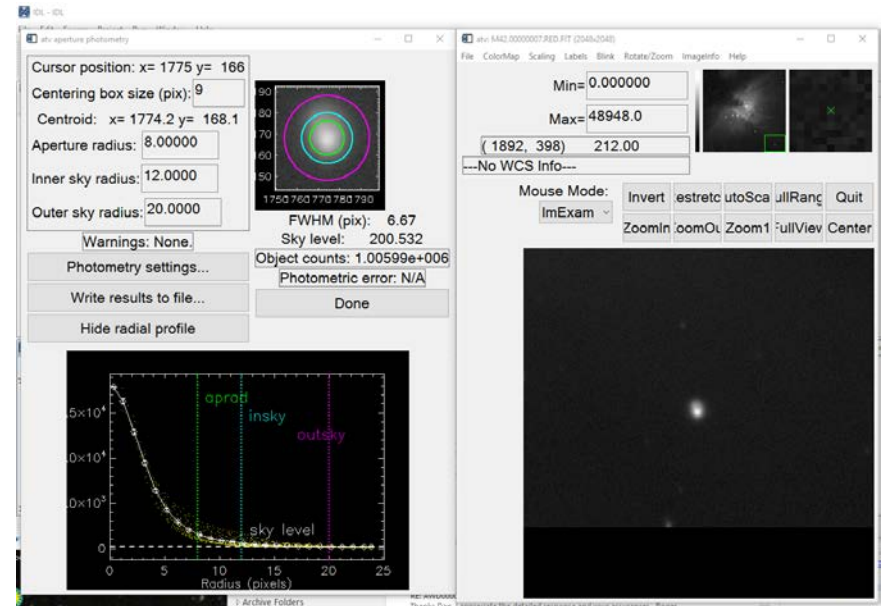
Example 1: flux calibration

Conveniently placed near the Orion Nebula is HD 36939, a 9.0 magnitude A0V star. A0V stars have the same magnitude at all wavelengths; this one is therefore a factor of $2.5^{9.0} = 3815$ fainter than a zero-magnitude star. From the table for zero-magnitude stars (lesson 1, page 16), this makes the flux density for HD36939 as follows:

HD 36939

$$f_\nu(B) = 1.16 \times 10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1} = 1.16 \, \text{Jy}$$

$$f_\nu(G) = 9.99 \times 10^{-27} \, \text{W m}^{-2} \, \text{Hz}^{-1} = 0.999 \, \text{Jy}$$

$$f_\nu(R) = 7.55 \times 10^{-27} \, \text{W m}^{-2} \, \text{Hz}^{-1} = 0.755 \, \text{Jy}$$

Note the commonly-used unit: Jansky = Jy = $10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1}$.

Example 1 (continued)

Aperture photometry on the various images of HD 36939 with ATV, and dividing by the exposure time, yields

$$B = 7.28 \times 10^4 \text{ DN sec}^{-1}$$

$$G = 7.89 \times 10^4 \text{ DN sec}^{-1}$$

$$R = 7.12 \times 10^4 \text{ DN sec}^{-1}$$

So a DN is worth $\text{DN} = 1.60 \times 10^{-5}$ Jy sec $= 16.0 \ \mu\text{Jy sec in B,}$

$$= 1.27 \times 10^{-5} \text{ Jy sec} = 12.7 \ \mu\text{Jy sec in G,}$$

$$= 1.06 \times 10^{-5} \text{ Jy sec} = 10.6 \ \mu\text{Jy sec in R.}$$

in that Orion image.
- ❑ Note the units. The B-filtered CCD in receipt of 1 DN doesn't know whether that came from a 16 μJy source and a 1 second exposure, or a 0.16 μJy source and 100 second exposure.

Example 1 (continued)

❑ If one were to want to scale the DNs in *color* (RGB) images so that the colors represent the right ratios in energy terms, one should multiply the individual images by factors with these same ratios:

$$R{:}G{:}B = 10.6 : 12.7 : 16.0 = 1 : 1.2 : 1.5$$

❑ Note once again that this scale is for A0V stars, which have the same magnitudes at all wavelengths. Many astronomers – especially amateurs – prefer to scale images to the colors of Solar-type stars (G2V) instead, getting results around

$$R{:}G{:}B = 0.6 : 0.8 : 1.2 = 1.0 : 1.3 : 2.0$$

Use of A0V stars gives images with a logarithmic or arcsinh stretch a true rendition in magnitudes, which I prefer. The G2V ratios make objects sometimes look <u>unnaturally blue</u>.

Flux calibration (continued)

❑ Note that P_S suffers a different atmospheric attenuation with the star observed at different elevation.

❑ For observations reasonably above the horizon, the observed flux density f decreases with increasing zenith angle ZA according to

$$f = f_0 - f_0 \tau_0 \sec ZA$$

and with two or more measurements of f and ZA one can determine the flux at the top of the atmosphere and the zenith optical depth, f_0 and τ_0. In the example at right, $f_0 = 4797.4$ DN and $\tau_0 = 0.24$.
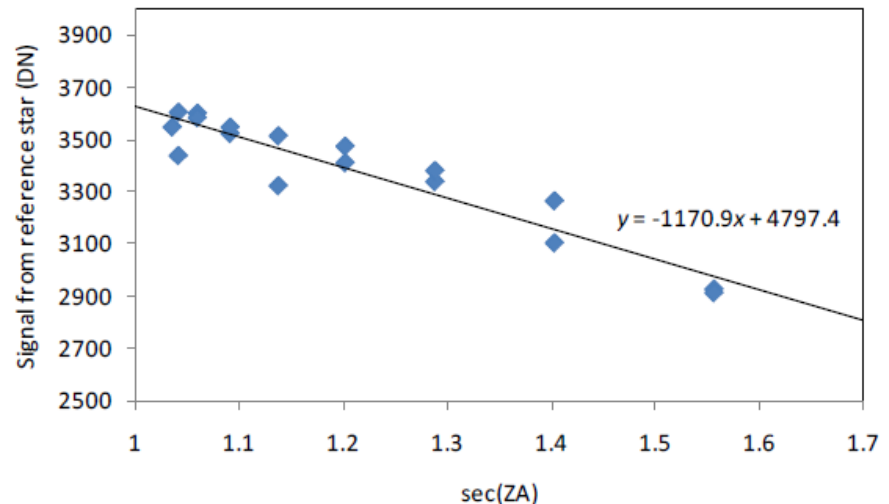
Example 2

In Example 1, HD 36939 was observed in *B* near transit, for which the zenith angle is 48.7° (sec*ZA* = 1.52, or "1.52 airmasses"). If the vertical optical depth were $\tau_0 = 0.24$ as on page 11, how many DNs would be registered for this star as it passed through the zenith, if it could have?

❑ We know ZA and the optical depth:

$$f = f_0 \left(1 - \tau_0 \sec ZA\right) = 0.63 f_0$$

and we also know *f* in DNs (72,800 DN) from page 9, so

$$f_0 = 1.16 \times 10^5 \text{ DN}.$$

❑ This does not change how the 1.52-airmass observation could be used to calibrate the Orion Nebula observation, though. The star and the nebula were observed in the same frame – practically the same *ZA*, and therefore the same τ_0 too. We know f_0 in real units *a priori* (page 8), but not in DNs.

How often does one need to calibrate?

Because electronics and the sky both change over time, one has to recalibrate repeatedly.

❑ Bias and dark current: every three or four months.

❑ Flat field: every night or two.

  • Maybe more frequent dusting of the camera parts will decrease this rate.

❑ Flux calibration: every hour or two.

Data reduction steps

Tools for all of these within CCDStack (preferred) and CCDSoft.

1. Subtract dark current and bias from each light frame.

2. Flat field each frame.

   ❑ CCDStack automates these steps very well.

3. Identify the small number of misbehaving pixels in each frame: "hot" or "cold."

   ❑ Dark current too variable to capture in master darks

   ❑ Fewer at lower temperatures: good reason to work at -20 C.

   ❑ Easier to find in a stack of images, as they're repeat offenders.

4. Interpolate them out of the images. (Again, in CCDStack or CCDSoft.)

Data reduction (continued)

5. Register the frames taken at the same wavelengths: that is, shift them so that their stars all line up.

6. Normalize the frames at each wavelength; that is, make sure the stars have the same brightness in each frame.

    ❑ Pretty pictures: nice feature in CCDStack which automates this.

    ❑ Scientifically useful: use flux calibration at appropriate zenith angle; apply with "pixel math" functions of the data reduction programs.

7. Identify cosmic rays and satellite tracks

    ❑ "Only" appear in single frames, so can be identified by comparing each pixel's value with the mean or median of that pixel in the whole stack of frames. CCDStack does this brilliantly.

Data reduction (continued)

8. Interpolate the cosmic rays and satellite tracks out of the frames.

9. Combine the frames, generating a new frame equal to the average of the others.

10. Repeat for each wavelength (filter), individually.

One would now have four (pretty pictures) or three (science) low-noise images of one's target, one in each wavelength.

Next time: composing calibrated RGB color images (science) or balanced LRGB images; the basic features of PhotoShop.