

Lesson 2: calibration

Useful references:

Adam Block, *Deep sky imaging: workflow 1*

In Rob Gendler (ed.) 2013, *Lessons from the masters* (New York: Springer), 159-192.

Ralph Bohlin et al. 2014, [PASP 126, 711B](#). (HST master calibration)

H II regions NGC 7635 (left) and NGC 7538, LRGB (Mees Observatory image)

Calibration

To get the ideal sensitivity discussed last time requires accurate calibration:

- ❑ subtraction of camera-electronics offsets (**bias**) and average dark current.
 - Requires additional data: low-noise dark and bias frames at same CCD temperature as for target data.
- ❑ correction of variation in responsive quantum efficiency (**flat field**).
 - Requires additional data: low-noise flat fields at same CCD temperature and filter as for target data.
- ❑ correction of permanently-troublesome (**hot** or **cold**) pixels.
 - Many instrument mavens create maps of these pixels, that can be used in correction.

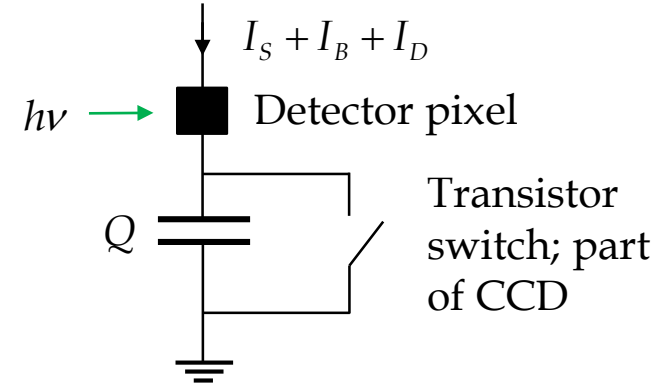
Calibration (continued)

- ❑ identification and removal of **transients**, such as cosmic-ray hits or satellite trails.
- ❑ correction of atmospheric extinction, from the variation of signal with zenith angle (**normalization**).
- ❑ scaling the signal to that of objects – usually stars, at visible wavelengths – with accurately-known flux density or magnitude (**flux calibration**).
 - Requires additional data: observation of flux standards – at visible wavelengths, usually faint-ish A0V stars – over a range of zenith angle.

The last two steps can sometimes be combined or rearranged.

Dark current and bias correction

- ❑ Dark current varies from pixel to pixel, and for good detectors decreases exponentially with decreasing temperature.
 - All intrinsic semiconductor photodetectors are like this: for a bandgap ΔE , carriers can be produced thermally at rates proportional to $\exp(-\Delta E/kT)$.

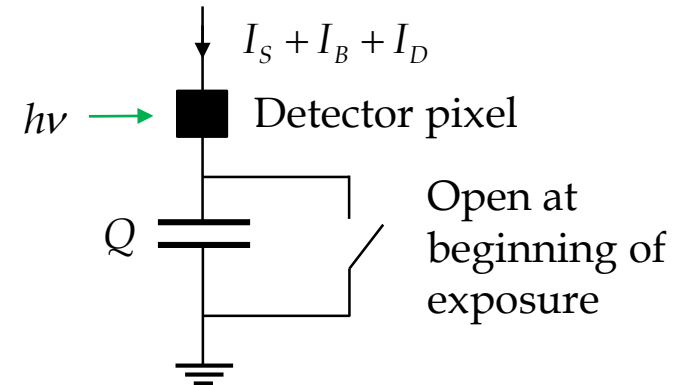


- ❑ The semiconductor-transistor switches in CCD circuitry always inject charge abruptly when opened at the beginning of exposures. This too is temperature dependent.
- ❑ These effects lead to offsets in the charge Q , that must be subtracted to leave the signal.
- ❑ Dark current has shot noise too. Subtraction gets rid of the average value but not the shot noise.

Dark current and bias correction (continued)

- Also the difference between (or sum of) two statistically independent images has noise no smaller than either one:

$$\begin{aligned}\bar{Q} &= \bar{Q}_2 - \bar{Q}_1 = q_e (\bar{N}_2 - \bar{N}_1) \\ \overline{(\Delta Q^2)} &= \overline{(\Delta Q_2^2)} + \overline{(\Delta Q_1^2)} \\ &= q_e^2 (\bar{N}_2 + \bar{N}_1) \quad \text{if Poisson-distributed}\end{aligned}$$



- Therefore detector arrays are operated at a low enough temperature to make both offset and shot noise small ...
- and dark current and bias correction are measured with averaging times long enough that the noise in these two corrections contribute insignificantly to system sensitivity.

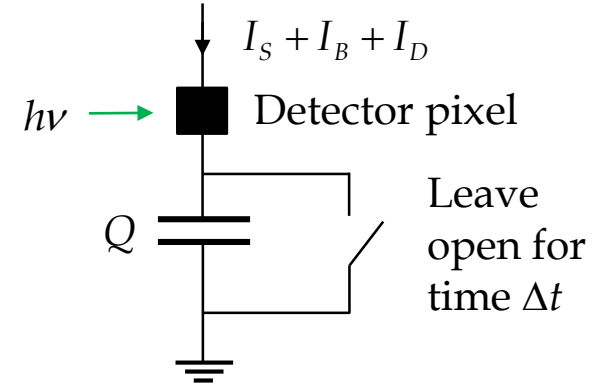
Dark current and bias correction (continued)

- Suppose, for example, that frame 2 is signal plus background plus dark current, and frame 1 is dark current, measured with exposure times Δt_2 and Δt_1 respectively.
- If the average value of dark current in each pixel is constant, and we average n frames of dark current instead of 1 before subtracting, then the signal plus background, and the noise in this quantity, is

$$\bar{Q} = \bar{Q}_2 - \frac{\Delta t_2}{\Delta t_1} \bar{Q}_1 = q_e \left(\bar{N}_2 - \frac{\Delta t_2}{\Delta t_1} \bar{N}_1 \right)$$

$$\overline{(\Delta Q^2)} = \overline{(\Delta Q_2^2)} + \frac{1}{n} \overline{(\Delta Q_1^2)}$$

$$= q_e^2 \left(\bar{N}_2 + \frac{1}{n} \frac{\Delta t_2}{\Delta t_1} \bar{N}_1 \right) \rightarrow q_e^2 \bar{N}_2 \quad \text{for } n \gg 1, \Delta t_1 > \Delta t_2 \quad .$$



Dark current and bias correction (continued)

In practice, for each temperature and binning in use, we usually

- ❑ take 38 dark frames, each with 30 minute exposure time.
- ❑ take 276 bias frames, each with the minimum possible exposure time (~50 msec).
- ❑ generate master dark and bias frames by averaging corresponding pixels, after discarding the smallest 2 (8) and largest 4 (12) values for each pixel in the stack of dark (bias) frames to reject cosmic rays.
- ❑ Then the dark current and bias correction is

$$\bar{Q}'_2 = \bar{Q}_2 - \frac{\Delta t_2}{\Delta t_1} \left(\overline{Q_{M\text{dark}}} - \overline{Q_{M\text{bias}}} \right) - \overline{Q_{M\text{bias}}}$$

where M denotes the master frames.

- ❑ Dark frames can be taken during the day if the camera surroundings are truly dark.

Dark current and bias correction (continued)

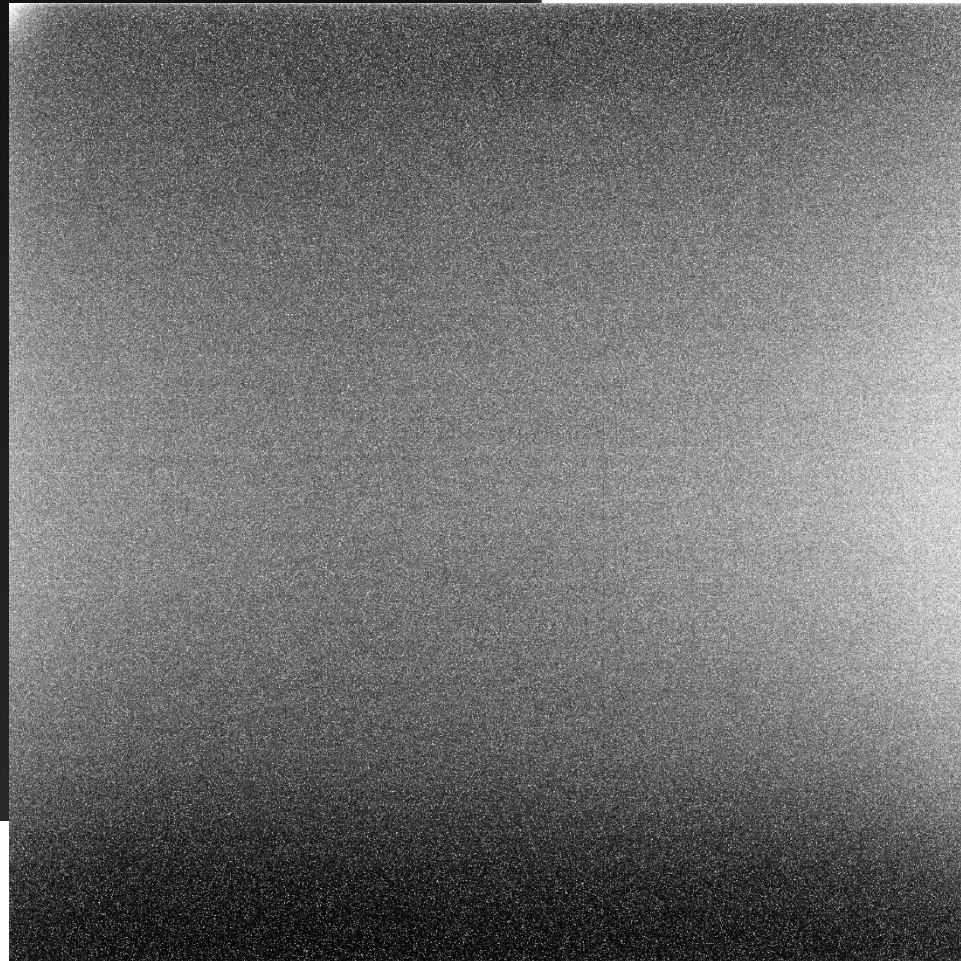
- And the resulting corrected frame has, to good approximation, **no noise added by the master**. Consider the dark frames:
- If the CCD temperature is stable, then each dark integration would have approximately the same average charge and noise per pixel, $q_e \bar{N}$ and $q_e^2 \Delta N^2$. And since the noise in each frame is statistically independent, the variance in the master is the quadrature sum of the variances of the n dark frames:

$$\overline{Q_M} = \frac{q_e}{n} \sum_{i=1}^n \bar{N}_i = q_e \bar{N}$$
$$\overline{\Delta Q_M^2} = \frac{q_e^2}{n^2} \sum_{i=1}^n \overline{\Delta N_i^2} = \frac{q_e^2}{n^2} \sum_{i=1}^n \bar{N}_i = \frac{q_e^2 \bar{N}}{n}$$

- That is, the dark master has rms noise smaller than the noise that dark current contributed (unavoidably) to the on-target exposures, by a factor of $\sqrt{n \Delta t_2 / \Delta t_1} \approx 13$ for five-minute frames.
- Similarly, the bias master has rms noise lower by $\sqrt{n} = 16$.

Bias

**Camera 1 master dark and bias,
-20 C, linear scale**



Dark - bias,
linear scale, 0.009 - 0.018 e/sec.

Dark

Flat field correction

- ❑ Good CCD detector arrays have small pixel-to-pixel variation in response, meaning that the responsive quantum efficiency is nearly uniform across the array.
- ❑ But the variation isn't zero, and would look like noise or systematic error in long enough exposures.
- ❑ Any optical surface close to the focal plane – e.g. windows and filters – can also contribute small variations in transmission among different areas of detector pixels.
- ❑ Ideally an image of a uniformly-bright object would be perfectly uniform.
- ❑ So take a high signal-to-noise, dark and bias corrected, image of a uniform-brightness object, normalize it, and divide each target-exposure frame by that image.
- ❑ This restores uniformity to the focal-plane response, and is called **flat fielding**.

Flat field correction (continued)

The hard part about flat-field correction turns out to be getting a uniformly bright object, with light taking the same optical path as that from celestial objects. Lots of obvious things don't work.

- ❑ Good: twilight-sky flats. (Professional-observatory standard.)
 - Point at the zenith, take lots of frames with large DN per pixel in each filter, after sunset and before the sky gets dark enough to see stars. (Reverse for morning.)
 - Disadvantages: has to be done at twilight; usually not enough time to take data for all the filters; sky emission is scattered sunlight and therefore polarized.
- ❑ Better: electroluminescent-panel flats. (Mees Observatory standard.)
 - Cover top of telescope completely with seamless EL panel, take lots of frames with large DN per pixel in each filter. Any time you want, even daytime.
 - At Mees: as good as the best twilight flats, and unpolarized to boot.

Flat field correction (continued)

- ❑ Currently our flats are taken with an electroluminescent panel that lives on the telescope side of the remote-control telescope cover.
- ❑ Normally take 32 frames in each filter, with exposure time set for signal that is typically half the maximum signal, or around 32000 DN.
 - (Maximum signal is 2^{16} DN = 65536 DN. This signal level is often called **full wells**.)
- ❑ That requires about 1 sec exposures for L, 0.5-2 sec for RGB at 2×2 binning, 10-20 sec for narrowband filters at 2×2 binning.
- ❑ Generate a master flat for each filter by bias-subtracting the individual frames and averaging the results.
- ❑ Takes more than an hour to flat field seven filters at this rate, so get started well before sunset or take only the flats you need.

Master L flats, 28 October 2019

At the end of the
season; very dusty.

Electroluminescent
panel. Linear scale,
33172-38112 DN.

Twilight sky. Linear
scale, 8343.2-9808.6
DN.

Sky/EL. Linear scale,
 1.00 ± 0.02 .

Most dust on CCD
cover window,
illuminated very
slightly differently by
EL panel and sky.

L

Master EL-panel flats, 28 October 2019

G/L

G

Linear scale,
 1.00 ± 0.03 .
The CCD cover
window is so dusty that dust on the
filters only shows up well in quotients.

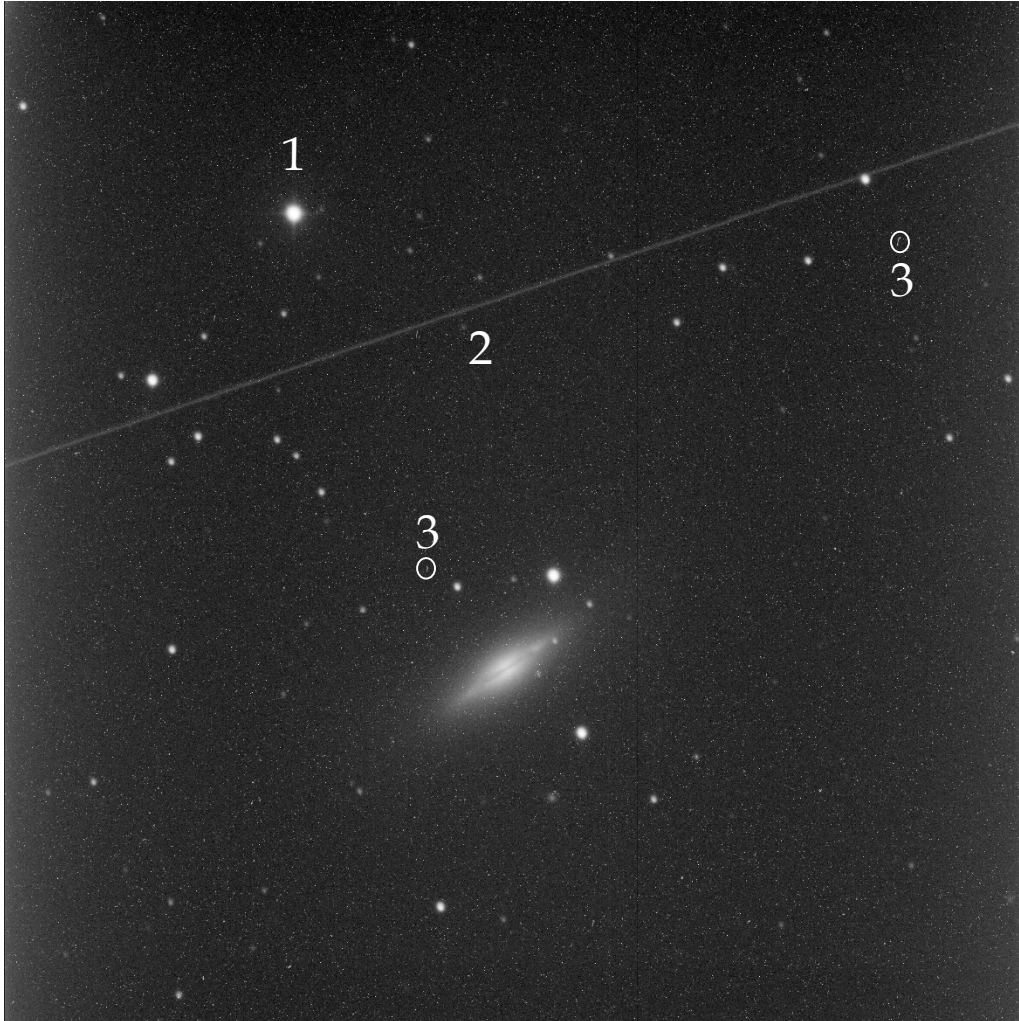
Transient removal

Last time, in Example 5, we designed a G observation that was background limited and reached 24th magnitude in five 10-minute frames.

Why not just take one 50-minute frame?

- ❑ Because the **average of five 10-minute background-limited frames has precisely the same sensitivity as one 50 minute background-limited frame**, as is also clear from that example, and today, page 8.
- ❑ Because multiple frames allow one to avoid other problems easily, such as
 - Overexposed bright stars. This can't be helped sometimes, but should be avoided when possible.
 - Cosmic ray hits. They occur in random locations and are easy to identify and correct in a stack of images.
 - Satellite trails: 1-2 per hour, especially at high declination.

Transients



Five-minute G frame on
NGC 5866, with

an overexposed star (1),

a satellite trail (2), and

many cosmic-ray hits of
which only a couple of
oblique-incidence ones
are labelled (3).

Transient removal (continued)

Nothing much you can do about overexposed stars, unless they were your main target.

But to get rid of transients,

- ❑ align the stack of frames so that every star occupy the same pixels in each frame.
- ❑ compute median, and the standard deviation σ for each pixel from the stack.
- ❑ reject each pixel that deviates by more than about 2.2σ from the median, replacing its value with that interpolated from its un-rejected nearest neighbors. This procedure is one form of **median filtering**.
 - It can take a few iterations to remove satellite trails and occasional clusters of cosmic-ray hits, for lack of enough un-rejected neighboring pixels.

Correcting atmospheric absorption

Presuming that atmospheric conditions are the same throughout the observations:

- ❑ Because of atmospheric scattering and absorption, the signal from each star is largest when observed at its highest elevation/smallest zenith angle z .
- ❑ To good approximation, the atmosphere is plane-parallel, and the path light takes through it varies according to $\ell = \ell_0 / \cos z = \ell_0 \sec z$, where ℓ_0 is the vertical thickness of the atmosphere.
- ❑ If atmospheric opacity and scattering is small, light is attenuated according to

$$f = f_0 \exp(-\sigma_0 \ell_0 \sec z) = f_0 \exp(-\tau_0 \sec z) \\ \cong f_0 - f_0 \tau_0 \sec z \quad ,$$

where f_0 is the **unattenuated** stellar flux in DN , τ_0 the **zenith optical depth** of the atmosphere (not to be confused with filter transmission), and $(1 - \tau_0)f_0$ the signal in DN that would be received at zenith.

Correcting atmospheric absorption (continued)

- ❑ So measure f from stars in the images as a function of z at which each image is taken;
- ❑ fit a line to the results, determining f_0 from the $\sec(z)$ intercept, and $f_0\tau_0$ from the slope;
 - τ_0 should be the same for all the stars in an image, though f_0 varies from star to star. If conditions are good, τ_0 will be the same for all images in the same filter.
- ❑ calculate a correction factor $\overline{f_0/f}$ for the stellar signals to which lines were fit;
 - If $\overline{f_0/f}$ does not have a small variance, look for evidence of changing atmospheric conditions.
- ❑ and multiply each image by its $\overline{f_0/f}$.
- ❑ Then images of the same object and filter can be averaged, making a high S/N image of the target object.

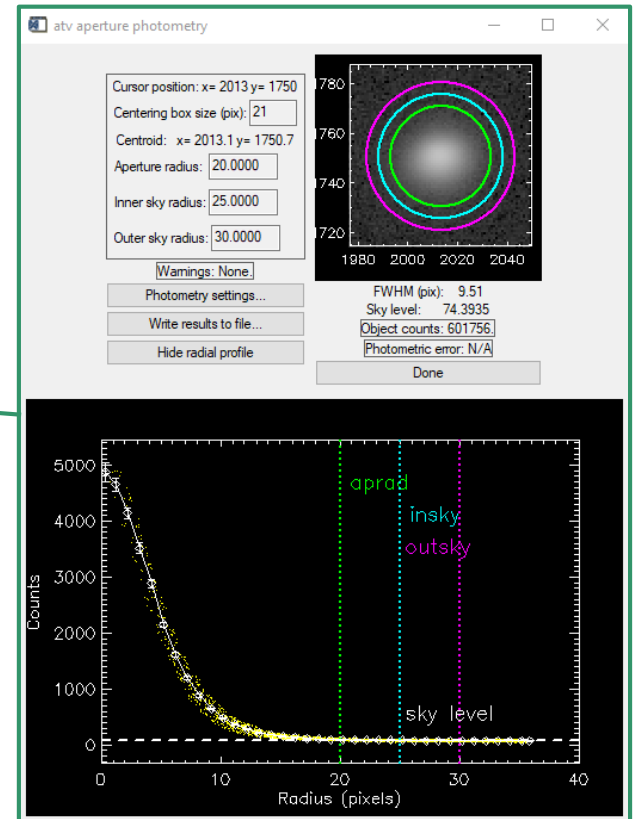
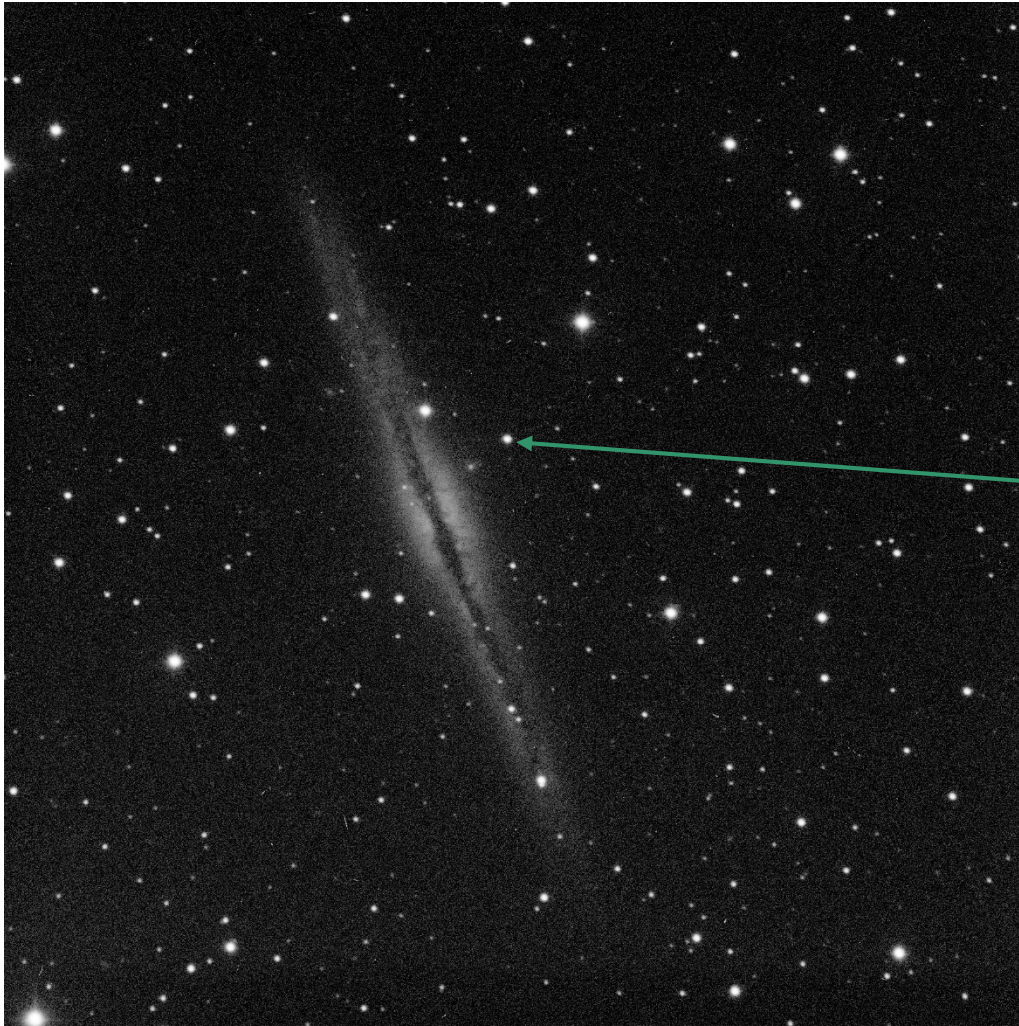
Example: atmospheric-absorption correction

1. During observations of NGC 891 last 28 October, a certain relatively isolated 13.3-magnitude star appeared in every frame. In the L frames, photometric measurements of this star, listed at right, were made for each frame. Find the L-band zenith optical depth τ_0 , and the absorption-corrected flux density f_0 for this star.

- ❑ First note that conditions were deteriorating as time went on, as is evident here in the seeing. So we may not want to use all the data.
- ❑ After editing the data, though, it's just plot-and-fit.

Time	Altitude (°)	sec(z)	Signal (DN)	Noise, rms (DN)	Seeing (arcsec)	
1945	28-Oct-19	34.399	1.7701	5.90E+05	9.21E+02	2.2
1956	28-Oct-19	36.136	1.6958	5.86E+05	9.09E+02	2.4
2001	28-Oct-19	36.933	1.6642	5.80E+05	9.12E+02	2.4
2007	28-Oct-19	37.894	1.6281	5.99E+05	9.32E+02	2.2
2012	28-Oct-19	38.699	1.5994	6.01E+05	9.15E+02	2.0
2017	28-Oct-19	39.508	1.5719	5.98E+05	9.11E+02	2.2
2022	28-Oct-19	40.321	1.5454	6.10E+05	9.24E+02	2.3
2028	28-Oct-19	41.301	1.5151	6.17E+05	8.95E+02	2.1
2033	28-Oct-19	42.121	1.4910	6.03E+05	8.95E+02	2.4
2038	28-Oct-19	42.945	1.4678	6.04E+05	9.37E+02	2.5
2043	28-Oct-19	43.772	1.4455	6.16E+05	9.09E+02	2.2
2049	28-Oct-19	44.769	1.4199	6.22E+05	9.23E+02	2.2
2054	28-Oct-19	45.603	1.3996	6.19E+05	9.06E+02	2.3
2209	28-Oct-19	58.438	1.1736	6.31E+05	9.01E+02	2.4
2215	28-Oct-19	59.486	1.1608	6.35E+05	9.23E+02	2.4
2220	28-Oct-19	60.361	1.1505	6.39E+05	9.47E+02	2.4
2225	28-Oct-19	61.238	1.1407	6.40E+05	9.36E+02	2.4
2230	28-Oct-19	62.117	1.1313	6.39E+05	9.40E+02	2.4
2236	28-Oct-19	63.174	1.1206	6.32E+05	9.81E+02	2.6
2241	28-Oct-19	64.056	1.1121	6.28E+05	9.68E+02	2.8
2246	28-Oct-19	64.939	1.1039	6.37E+05	9.53E+02	2.6
2251	28-Oct-19	65.824	1.0961	6.38E+05	9.50E+02	2.6
2257	28-Oct-19	66.887	1.0873	6.36E+05	9.77E+02	2.5
2302	28-Oct-19	67.774	1.0803	6.34E+05	9.79E+02	2.6
2307	28-Oct-19	68.661	1.0736	6.41E+05	1.00E+03	2.6
0015	29-Oct-19	80.744	1.0132	6.19E+05	1.13E+03	3.1
0020	29-Oct-19	81.619	1.0108	6.18E+05	1.17E+03	3.0
0026	29-Oct-19	82.661	1.0083	6.04E+05	1.20E+03	3.5
0031	29-Oct-19	83.517	1.0064	6.14E+05	1.09E+03	3.3
0036	29-Oct-19	84.358	1.0049	6.01E+05	1.13E+03	3.5
0041	29-Oct-19	85.175	1.0036	5.79E+05	1.49E+03	3.7

Example: atmospheric-absorption correction (continued)

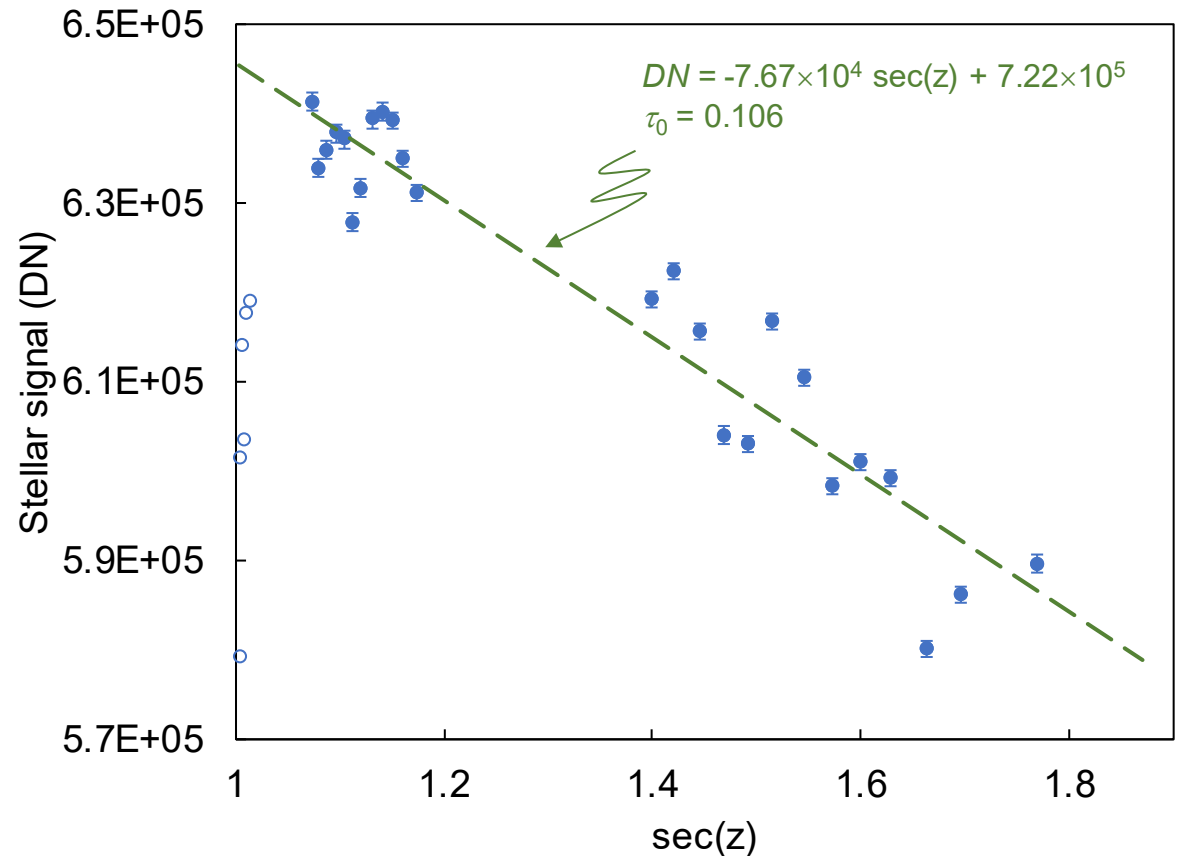


Example: atmospheric-absorption correction (continued)

- ❑ Here's the plot and the fit, omitting the last six frames (open circles) from the fit.
- ❑ Note that scatter is \gg noise: conditions were "not photometric."
- ❑ (As it was bad and getting worse fast, I went home after the 12:41 frame.)
- ❑ From the fit:

$$\tau_0 = \frac{7.67 \times 10^4}{7.22 \times 10^5} = 0.106$$

$$f_0 = 7.22 \times 10^5 \text{ DN}$$



Normalization in CCDStack

Some image-reduction software packages have handy routines for normalizing the stack of images to a chosen part of one of the images. CCDStack is one of those packages.

- ❑ This automatically corrects images so that the stars in the stack have the same signal (on average) as those in the chosen part of the chosen image...
 - ...thus reducing the photometric scatter considerably, though it doesn't often reduce the scatter to the level of the background noise.
- ❑ To correct the stack for atmospheric absorption after that:

Scalar-divide every frame (i.e. divide every pixel) by the factor $(1 - \tau_0) \sec z_0$, where

- τ_0 is the zenith optical depth determined as above, and
- z_0 is the zenith angle at which the “chosen frame” was observed.

Flux calibration

Finally, the images need to be multiplied by the factor that converts DNs to physical units.

- ❑ The basis for this conversion: observations, interleaved with your target-object observations, of at least one **standard star**: one of a set of stars
 - which cover the sky and a useful range of magnitudes;
 - which are monitored to ensure that they aren't variable; and
 - whose flux density is traceable to laboratory standards with high precision and accuracy, and thus **for which $f_0(\lambda)$, in physical units, is known.**

- ❑ Hereabouts we prefer to use Vega-like A0V standards in almost all observations:
 - same magnitude at all visible wavelengths, and
 - essentially no absorption lines except for the hydrogen recombination spectrum.

Flux calibration (continued)

- ❑ If you are observing with an H α filter, your choices are
 - (preferably and more easily) to add observations of another standard star without significant hydrogen absorption, such as a K giant (e.g. ξ Draconis; K2III); or
 - to build your own chain of secondary calibrators from the later-type stars detected in your H α image.

- ❑ Either way:
 - select and observe standards near your target, or at least covering a similar range of zenith angle on the same night; in every filter, of course;
 - correct them for atmospheric attenuation;
 - measure their DNs – mean and standard deviation – in each filter.
 - scalar-multiply all target frames by the appropriate f_0/DN ratio.

Where zero points come from

The flux or flux density for zero magnitude,

$$f_0 = \int_{\text{filter}} \tau(\lambda) F_\lambda(\lambda) d\lambda \quad \text{or} \quad F_{\lambda 0} = \int_{\text{filter}} \tau(\lambda) F_\lambda(\lambda) d\lambda / \int_{\text{filter}} \tau(\lambda) d\lambda ,$$

of a standard star like Vega (flux density F_λ) in a given filter, is one form of the **zero point** for a photometric system.

Zero points are, in turn, built from a network of calibrations that took decades to get extremely precise and accurate:

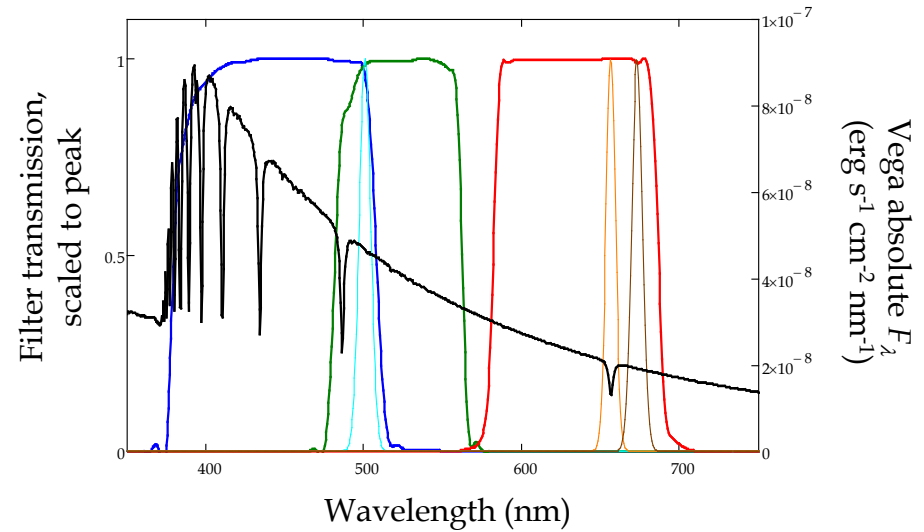
- ❑ observation of laboratory light sources and bright standard stars with the same telescope and instruments, usually by [Bev Oke](#);
- ❑ detailed spectra of the bright standards;
- ❑ fits of detailed stellar-atmospheric models, usually by [Bob Kurucz](#), to the spectra;

See the [CALSPEC](#) database for the calibration data in use on HST.

Zero points for Mees Camera #2

On the Vega = 0 magnitude scale, using the CALSPEC spectrum, and the transmission spectra of the six filters we'll use for photometry.

- ❑ Fluxes given for the spectral-line filters, as this is the output one would normally want for spectral-line images.
- ❑ For those filters, f_0 turns out to be close to $F_{\lambda_0}(\lambda_0)\Delta\lambda\sqrt{\pi/4\ln 2}$, which indicates that the narrowband filter profiles are essentially gaussian.
- ❑ For broadband filters, take flux to be the product of $\Delta\lambda$ and F_{λ_0} , if need be.



Filter	Wavelength λ_0 and bandwidth $\Delta\lambda$ (nm)		Flux density F_{λ_0} ($\text{erg s}^{-1} \text{cm}^{-2} \text{nm}^{-1}$)	Flux f_0 ($\text{erg s}^{-1} \text{cm}^{-2}$)
B	442	128	6.18×10^{-8}	
[O III]	500.7	8.5	4.67×10^{-8}	4.22×10^{-7}
G	521	80.5	4.10×10^{-8}	
R	633	101	2.32×10^{-8}	
H α	656.3	7.0	1.76×10^{-8}	1.31×10^{-7}
[S II]	670.0	8.0	1.92×10^{-8}	1.63×10^{-7}

Example flux calibration

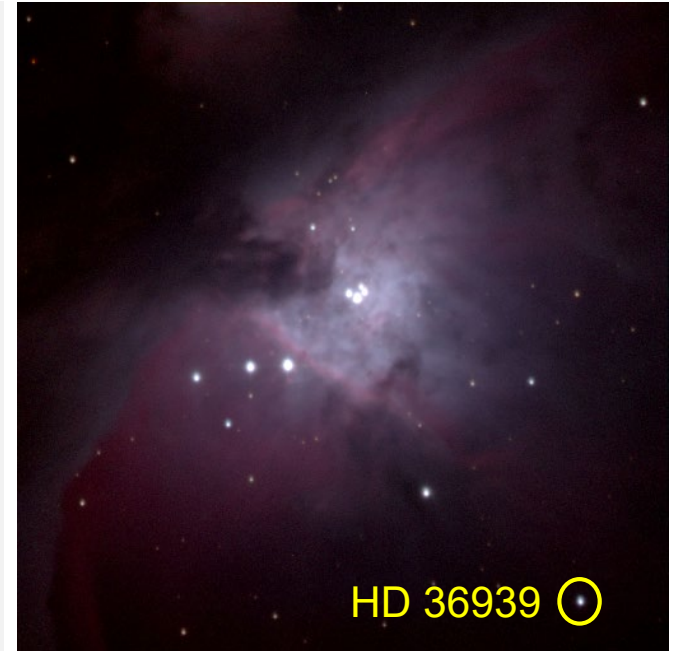
2. Conveniently placed in M 42 is HD 36939, a 9.01 magnitude A0V star. One night we measured

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

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

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

for HD 36939. What flux conversion factors should we use for that night's RGB frames of M 42?



- This is a special circumstance: we don't need to measure atmospheric absorption because HD 36939 and M 42 are always observed in the same frame, **and there's negligible difference in sec z and absorption within each frame.**

Example flux calibration (continued)

- So, if indeed the signal (current DN values) is in original DNs divided by exposure time, scalar multiply the B, G, and R frames by the factors

$$f = \frac{F_{\lambda_0}(\lambda_0)\Delta\lambda}{\text{signal}} ;$$

$$f_B = \frac{(6.18 \times 10^{-8})(128)(2.5)^{-9.01}}{7.28 \times 10^4} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ DN}^{-1} = 2.82 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ DN}^{-1}$$

$$f_G = \frac{(4.10 \times 10^{-8})(80.5)(2.5)^{-9.01}}{7.89 \times 10^4} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ DN}^{-1} = 1.09 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ DN}^{-1}$$

$$f_R = \frac{(2.32 \times 10^{-8})(101)(2.5)^{-9.01}}{7.12 \times 10^4} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ DN}^{-1} = 0.855 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ DN}^{-1}$$

- Since M 42 is an H II region: now every pixel without a star has a flux equal to the sum of the spectral line fluxes spanned by the broadband filters.

When and how to calibrate

Taking calibration data:

- Dark and bias: every six months or so.
- Flat fields: every night.
- Standard stars: a few times a night.
- Atmospheric opacity: from stars in the images frames; no additional observation required.

When and how to calibrate (continued)

The actual calibration happens during data reduction, not while observing:

- Apply dark, bias, flat field correction: every frame, before alignment.
- Remove hot and cold pixels: frame by frame, before alignment.
- Remove transients: frame by frame, after alignment.
- Measure zenith optical depth: from stars in target frames, after transient removal and before normalization or averaging.
- Apply atmospheric absorption correction and/or normalize: right before averaging.
- Flux calibration: last step, after averaging calibrated and aligned frames.

