Principles of Optical Data Reduction

K. Nilsson

Finnish Centre for Astronomy with ESO (FINCA)

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Three kinds of data

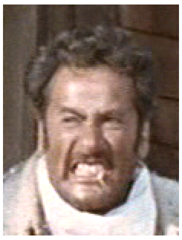
Massey & Jacoby (1992) ASP Conf. Ser. 23, 240 :

- Good data
  - perfectly linear
  - noise exactly Gaussian
  - pixel gain constant.

Does not exist!

- Bad data
  - highly nonlinear
  - highly non-Gaussian noise
  - pixel gain too constant (e.g. saturation).

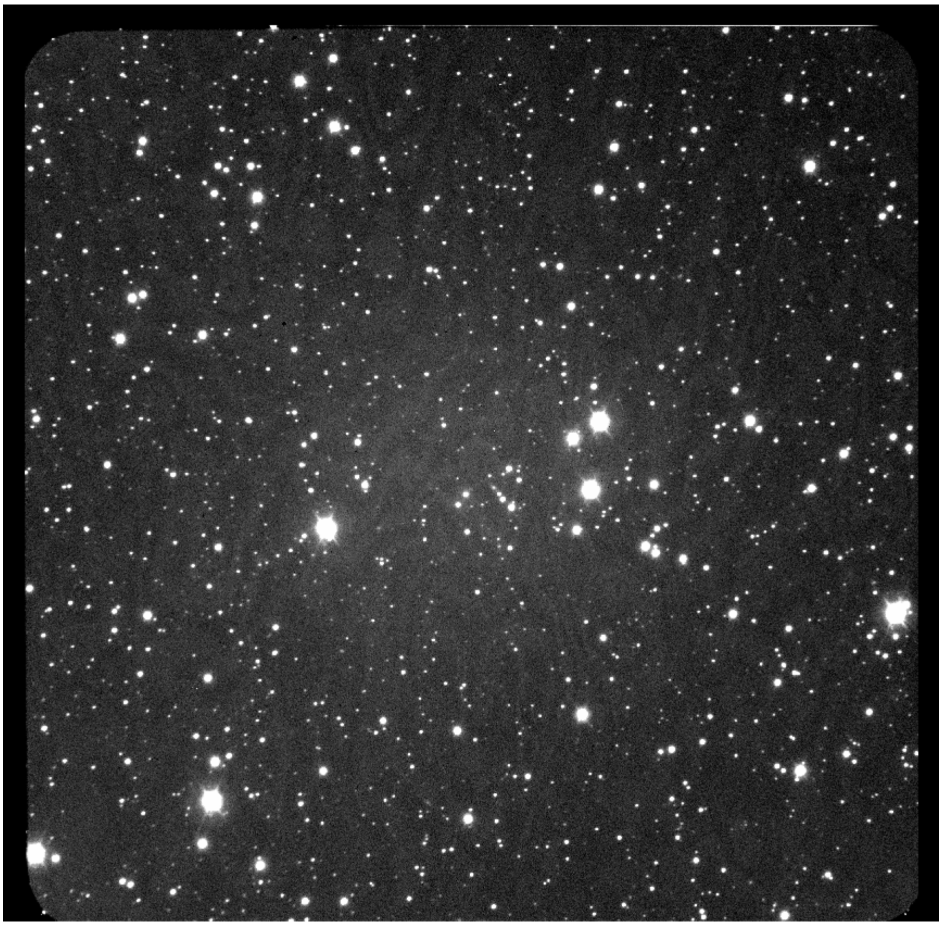
Throw away!



- Ugly data
  - close to linear
  - noise approximately Gaussian
  - pixel gain not constant, but correctable.

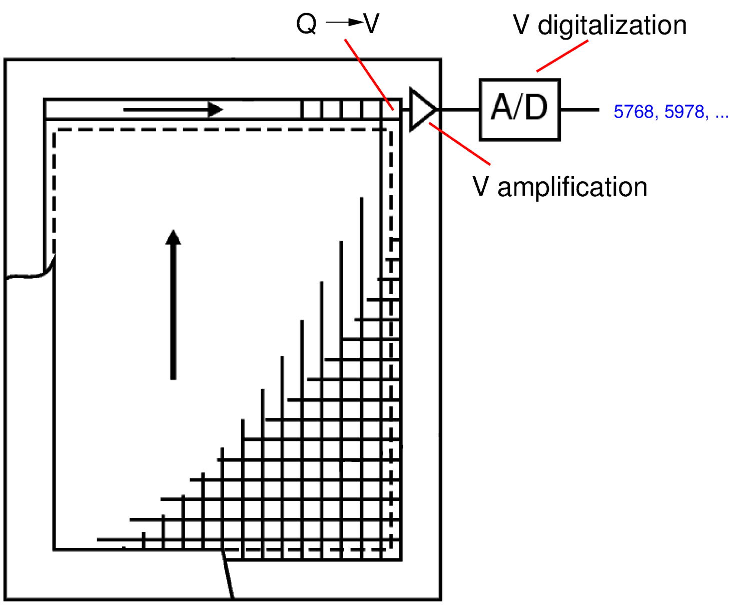
This is what you get!

Ugly (≠bad) CCD-data from the NOT

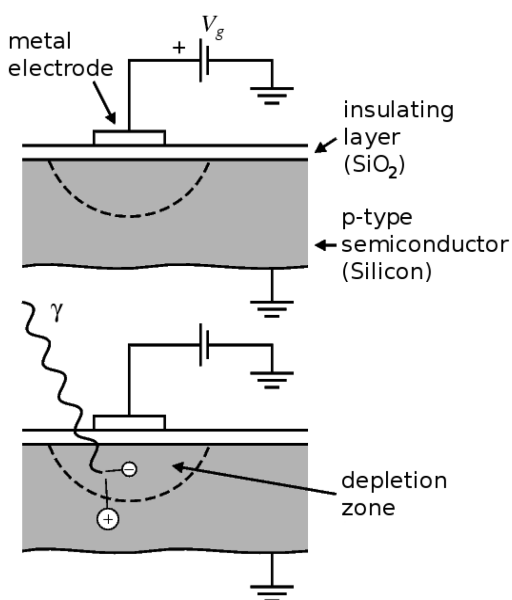


CCD = Charge Coupled Device

CCD array :

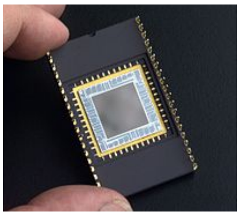


One pixel:



Pixel brightness is output in ADUs (Analog to Digital Units), whose relation to the recorded electrons is given by the *gain factor* [e^-/ADU] of the camera.

Advantages of the CCD-chip

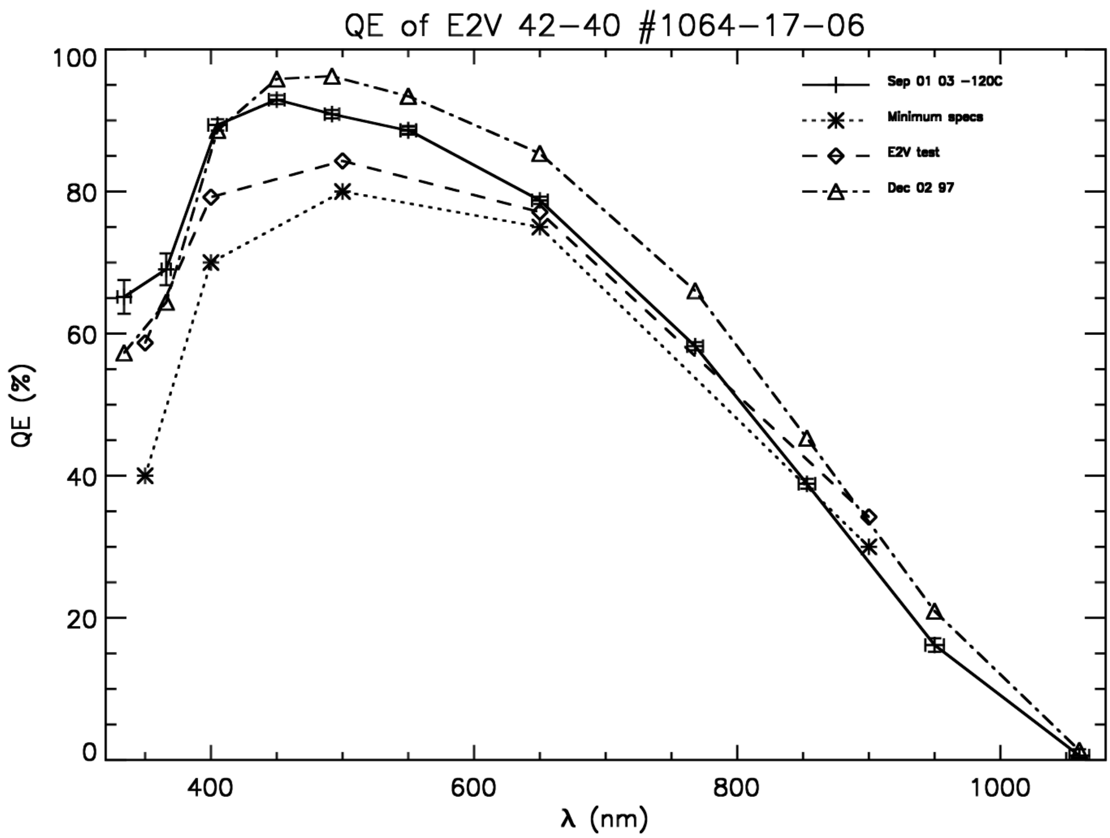


- Linear, i.e. the recorded signal is linearly proportional to the incoming light.
- Very sensitive, quantum efficiency (QE) close to 100%.
- Low noise compared to CMOS.

On the downside:

- “black and white”
- small field of view
- slow readout (e.g. 25 s with NOT/ALFOSC).

NOT ALFOSC CCD sensitivity



"Raw" CCD images

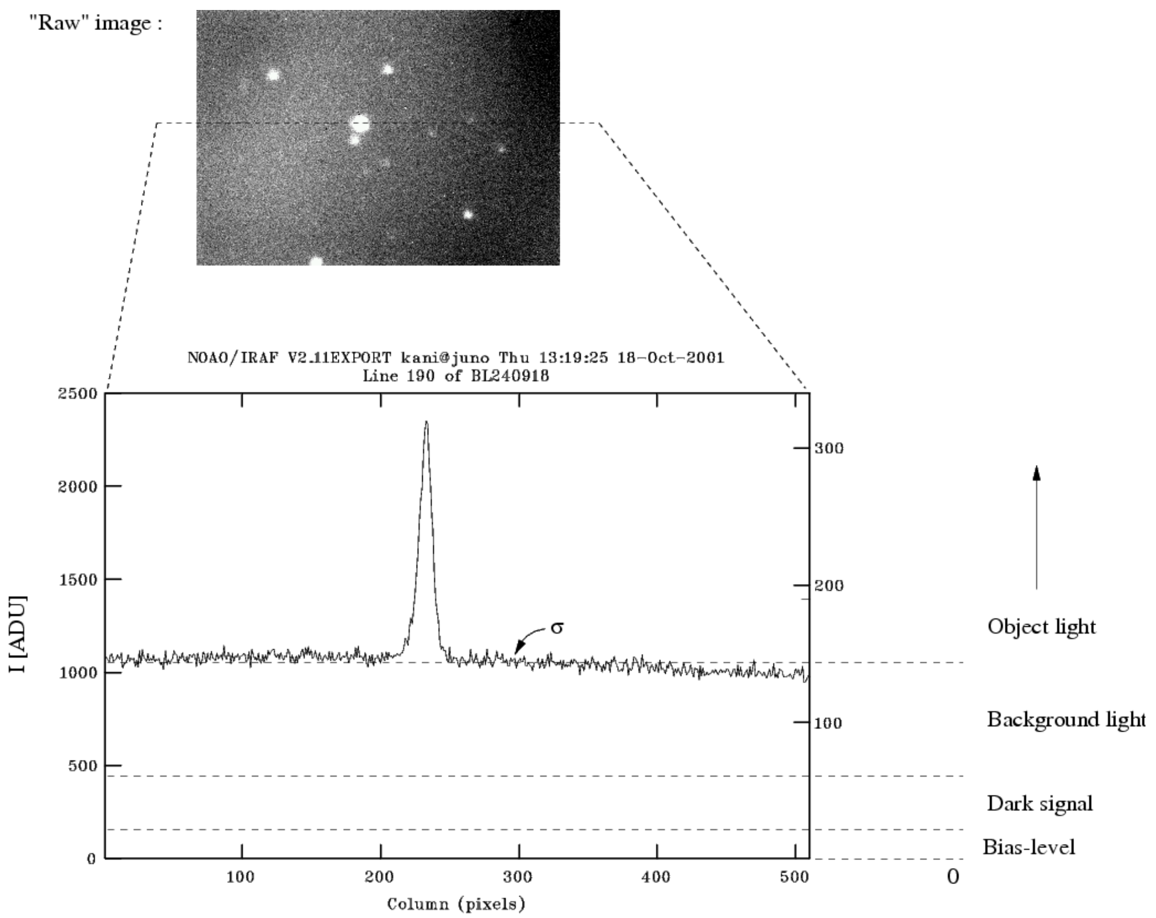
The image read from the CCD camera is a "raw" image, i.e. the pixel values do not represent the true light distribution in the sky.

The pixel value in a raw image is a sum of many components:

- target intensity
- sky background
- dark signal (a.k.a. dark current) (thermally generated electrons)
- bias level (a zero level added by camera electronics).

In addition, the pixel values are modulated by pixel gain variations.

A cut over a raw CCD image



Camera signatures

Bias

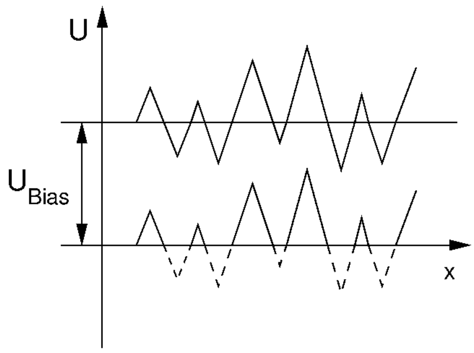
- Added by the camera electronics to avoid cutting of the signal.

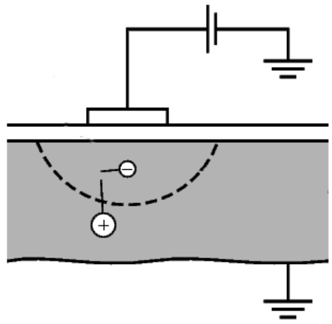
Dark

- Electrons are generated in a pixel due to thermal vibration of the silicon substrate.
- Increases linearly with exposure and drops exponentially with decreasing temperature.
- In LN_2 cooled systems ($T = -110°C$) dark current virtually insignificant (0.4 e^- hour^{-1} pix^{-1}).

Pixel gain variations

- Caused by manufacturing errors, dust, vignetting,...





Calibration frames

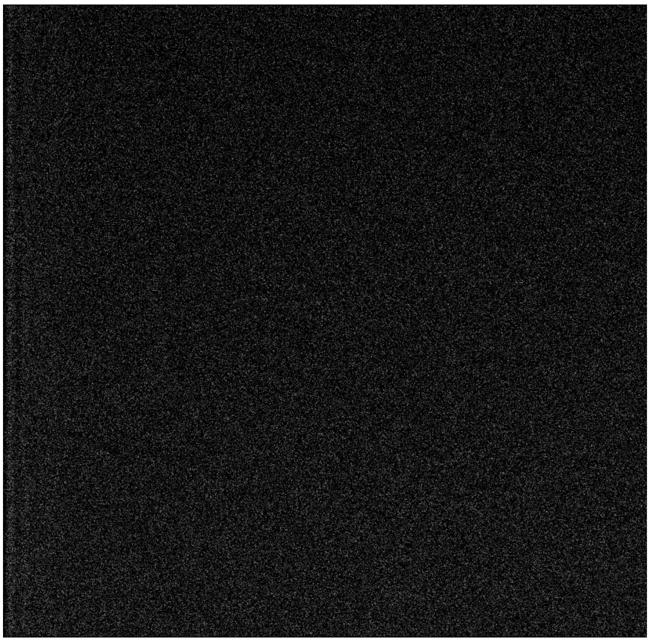
In order to process the raw images several calibration images need to be obtained:

- Bias frames : Read out the CCD without exposing.
- Dark frames : “Expose” the CCD with shutter closed (not needed at the NOT).
- Flat-fields : Obtain an image of an uniformly lit target, like the inside of the dome or twilight sky.

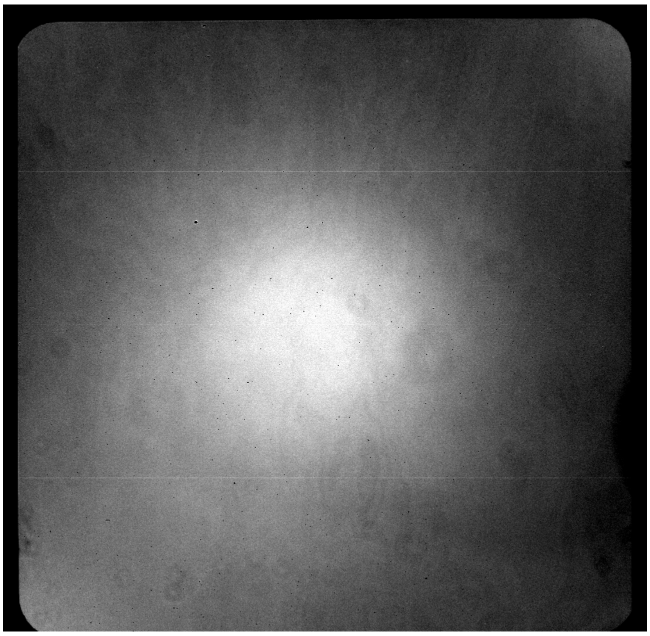
In order to reduce noise, several calibration frames of each type should be obtained.

NOT/ALFOSC calibration frames

Bias

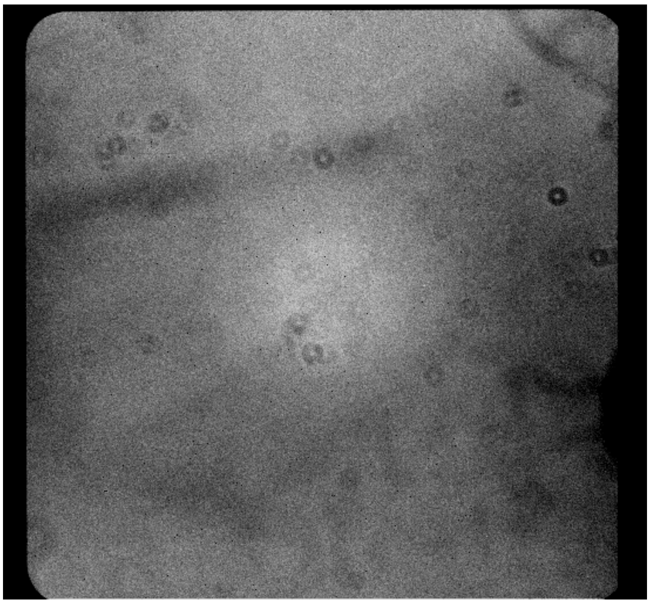


Flat-field

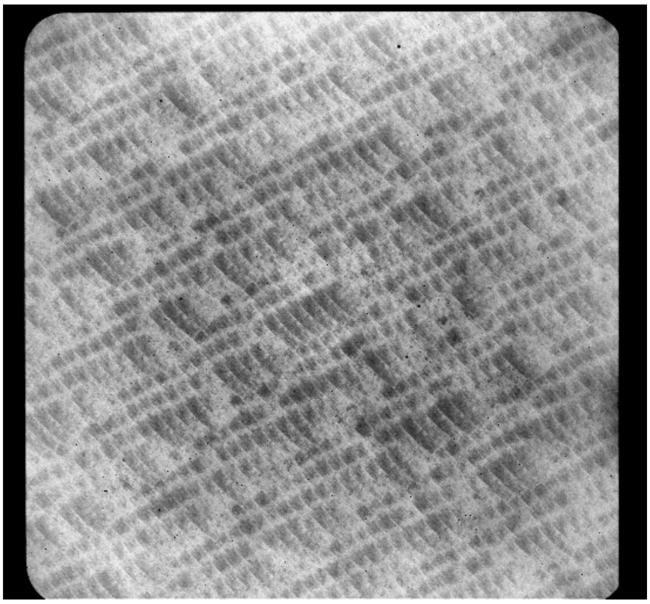


Flat-field depends on wavelength

R-band

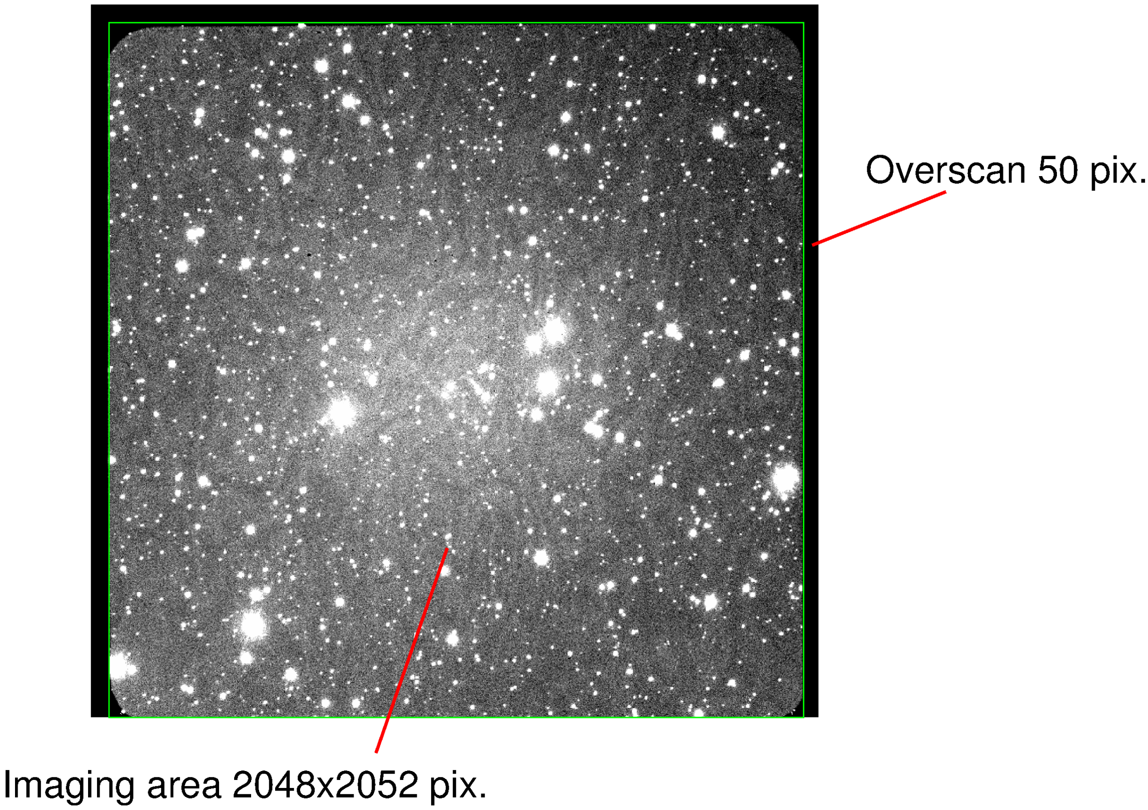


U-band

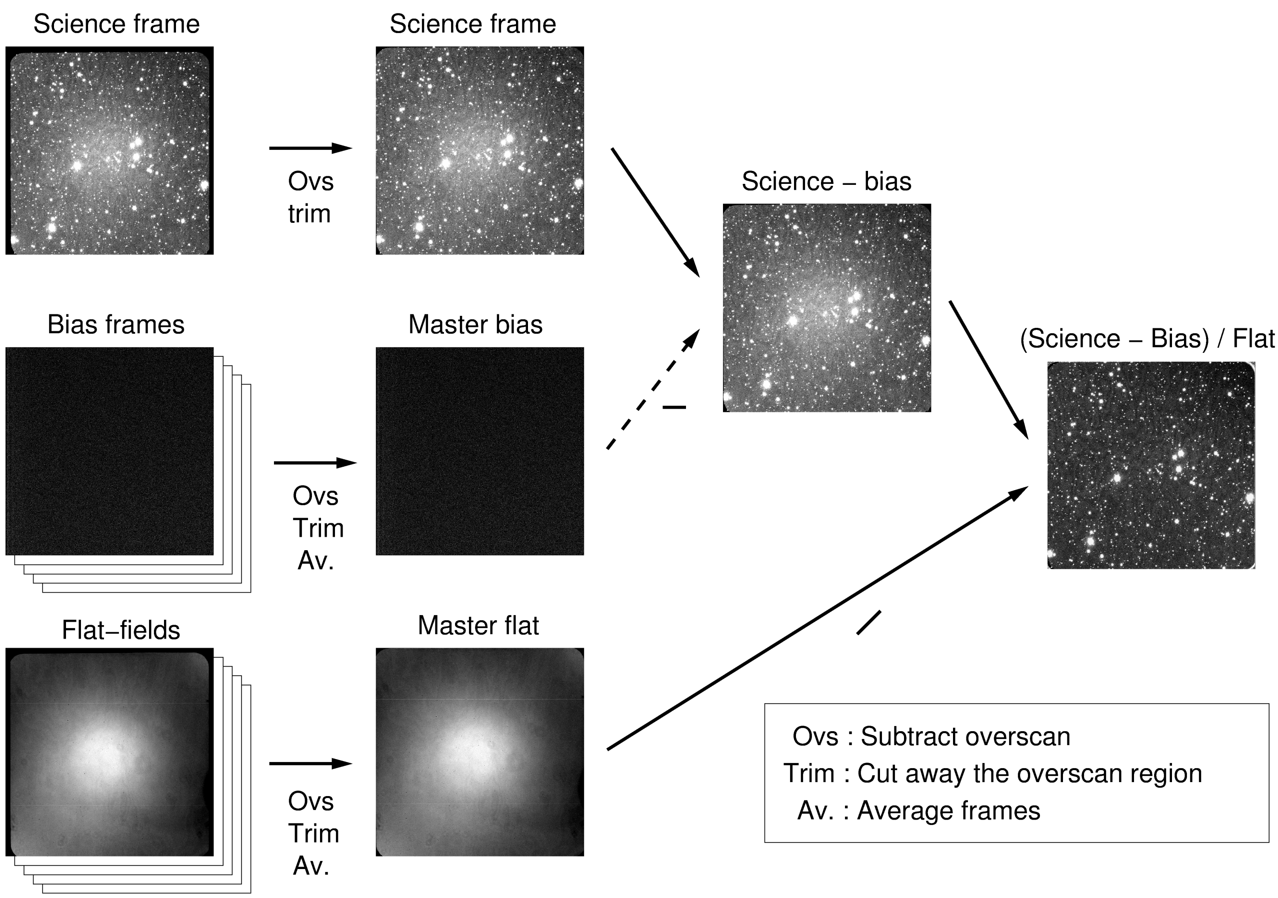


The overscan region

Records the bias level during the exposure.

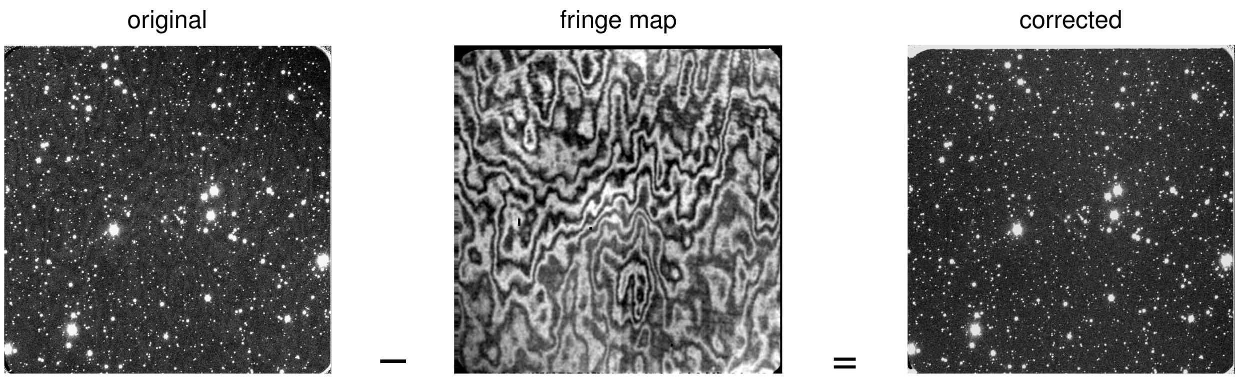


Reduction recipe for imaging data

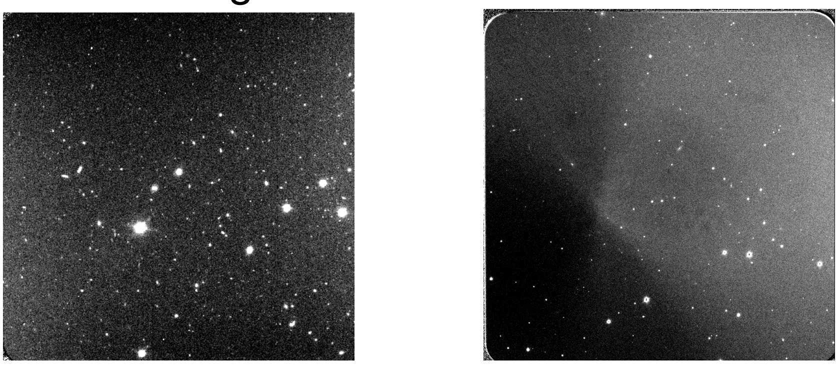


Some situations requiring post-processing

"Fringing" :



Scattered light:



Signal to noise

Signal to noise (S/N) is a key concept in image reduction too, since the idea is to improve the image, not degrade it by adding more noise to it $\rightarrow$ the calibration frames need to have high S/N.

Simple noise calculations of CCD images can be made using these three principles:

- The noise in a pixel consists of photon noise σ_{Ph}, dark noise σ_D and readout noise σ_R.
- The photon noise of n electrons is $= \sqrt{n}$.
- When summing two random variables s_1 and s_2 with standard deviations of σ_1 and σ_2 the standard deviation of the sum $s_1 + s_2$ is

$$\sigma(s_1 + s_2) = \sqrt{\sigma_1^2 + \sigma_2^2}$$

Example 1: combining bias frames

Q: How much lower is the noise in a master bias made by averaging 10 bias frames compared to a single bias frame?

- No accumulated electrons $\rightarrow n = 0 \rightarrow \sigma_{Ph} = \sigma_D = 0$.
  $\rightarrow$ In a single bias frame the noise in a pixel = σ_R
- In a sum of 10 bias frames the noise per pixel = $\sqrt{10} * \sigma_R$
- In the average bias frame the noise per pixel =

$$\frac{\sqrt{10} * \sigma_R}{10} = \frac{\sigma_R}{\sqrt{10}}$$

A: The noise is reduced by a factor of $\sqrt{10}$.

Example 2: Sky noise

Q: The background level in an ALFOSC image is 1000 ADUs. What is the standard deviation of the background (sky noise)?

- Let's mark with N the signal in ADUs, so $n = G * N$, where G is the CCD gain factor (e^-/ADU).
- General formula for the noise in a pixel (dark signal = 0):

$$\sigma(\text{ADU}) = \sqrt{\sigma_{Ph}^2 + \sigma_D^2 + \sigma_R^2} = \frac{\sqrt{G * N + \sigma_R^2}}{G}.$$

- Plugging in the values for ALFOSC, G = 0.327 e^-/ADU and $\sigma_R = 4.2\ e^-$, we get

A: 56.8 ADUs.

Example 3: Flat-fielding

Q: You have obtained a single flat-field image with ALFOSC. The average level in the image is 94 000 ADUs. How much noise will be added to the image when you use this flat-field?

- The noise in a pixel

$$\sigma(\mathrm{ADU}) = \frac{\sqrt{G * N + \sigma_R^2}}{G} = 536\,\mathrm{ADU} = 0.57\%$$

A: 0.0057$\times$ the signal in a given pixel.

Example 3: Flat-fielding (continued)

Q: Is the noise increase in previous example significant?

A: It depends :

1) Consider a pixel with only sky emission with a value of N = 3000 ADUs. Noise in this pixel is

$$\sigma(\mathrm{ADU}) = (1/G) * \sqrt{G * N + \sigma_R^2} = 96.6\,\mathrm{ADUs}\ .$$

The flat-fielding error is 0.0057 * 3000 ADU = 17.1 ADUs
$\rightarrow$ not very significant.

2) In a bright pixel (like in stellar cores) N = 200 000 ADUs.

$$\sigma(\mathrm{ADU}) = 782\,\mathrm{ADUs}$$

The flat-fielding error is 0.0057 * 200 000 ADU = 1140 ADUs
$\rightarrow$ significant.

Reduction of spectra

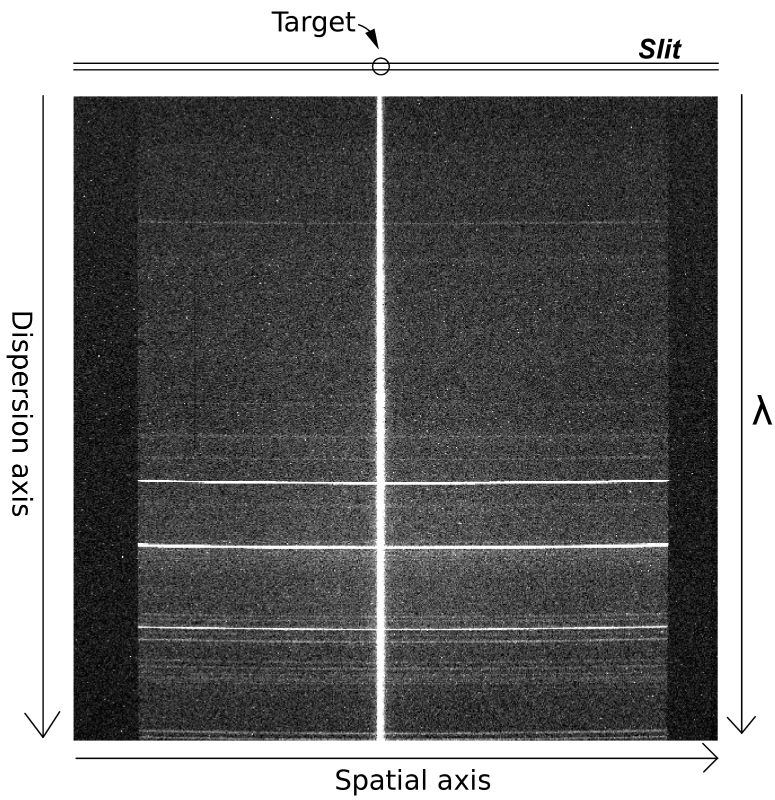
Reducing spectral data is more complicated than reducing imaging data due to higher number of calibration frames and reductions steps required.

In addition to the science frames you need:

- bias frames
- a continuum lamp frame (used for flat-fielding)
- a line lamp (a.k.a arc) frame (used for wavelength calibration)
- a standard star spectrum (used for flux calibration).

The continuum and line lamps are inside the spectrograph. They are turned on immediately before or after the science exposure to record the continuum and line lamp spectra.

An ALFOSC longslit spectrum



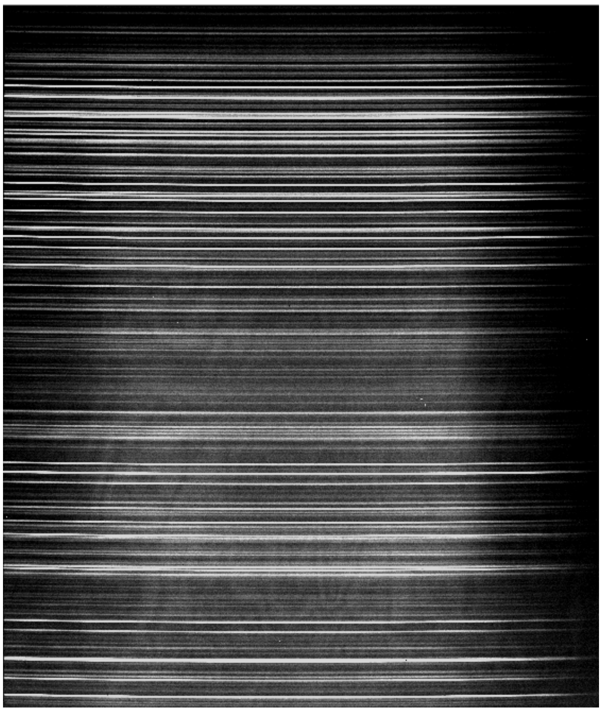
A simple rule:

The spectrum on the CCD can be thought as the *image of the slit at different wavelengths*.

Calibration spectra

Continuum lamp
(For flat-fielding)

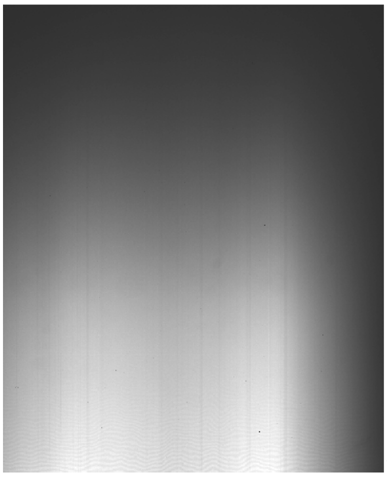
Line lamp
(For wavelength calibration)



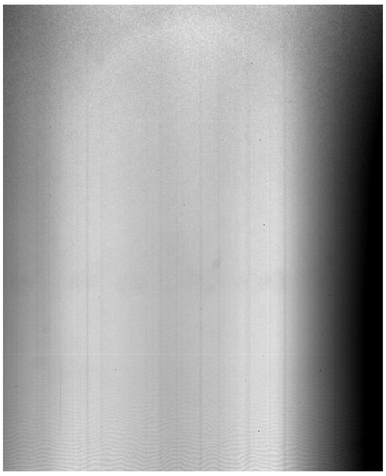
Minimal calibration steps (10)

Assumption: 1 frame of each type (science, continuum, line standard).

1) Subtract bias and/or overscan from all images (IRAF task: `ccdproc`).
2) Flatten the continuum lamp spectrum → flat-field frame (`response`).

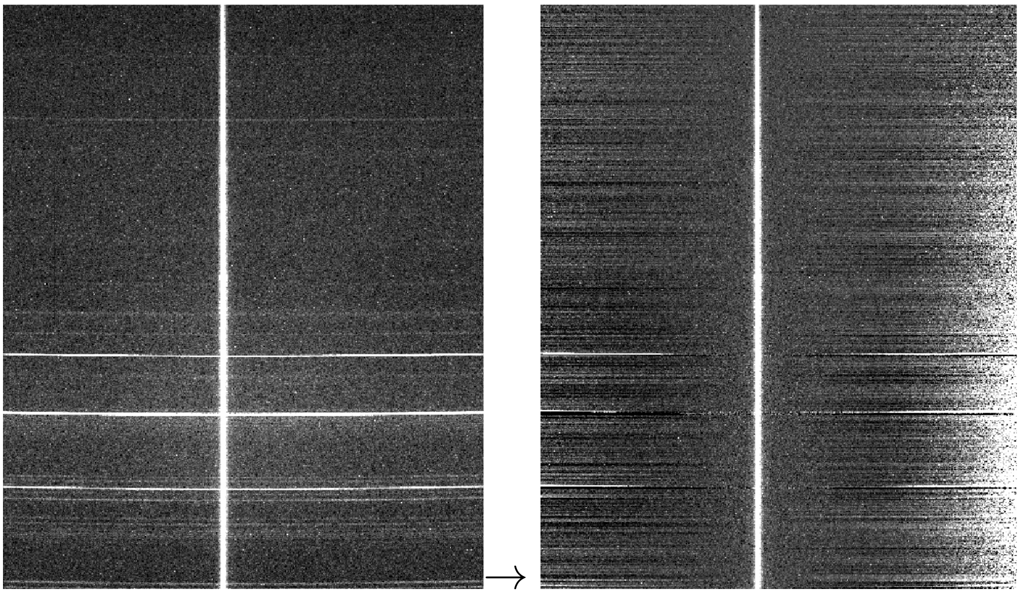


→

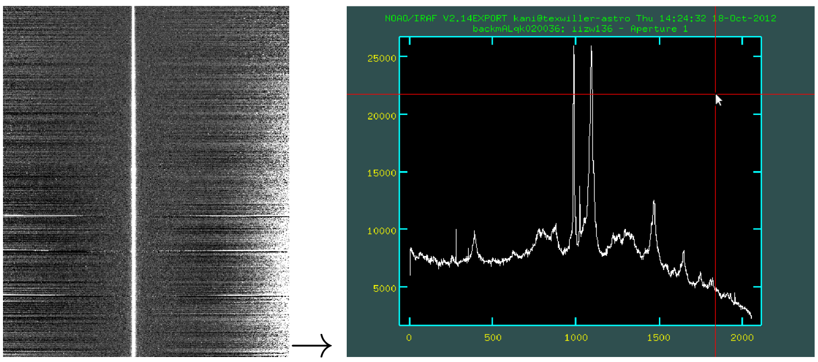


3) Flat-field science and standard frames (`ccdproc`).

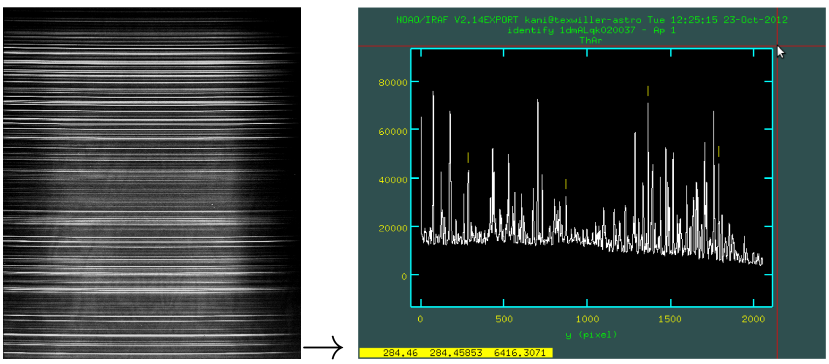
4) Subtract background from science and standard frames (`background`).



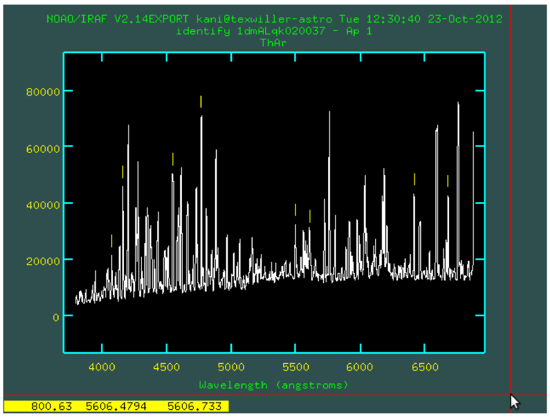
5) Extract one-dimensional spectrum (`apall`).



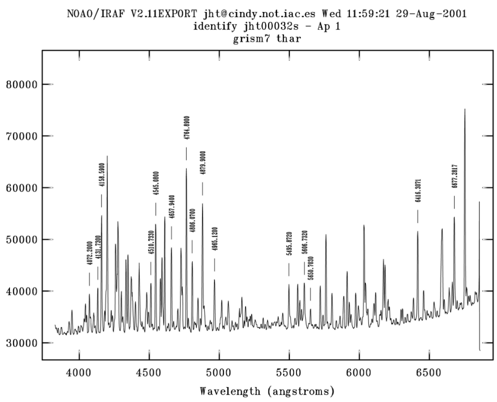
6) Extract the line lamp spectrum (`apall`).



7) Determine line lamp spectrum wavelengths and the transformation equation from pixel coordinates to λ (`identify`).



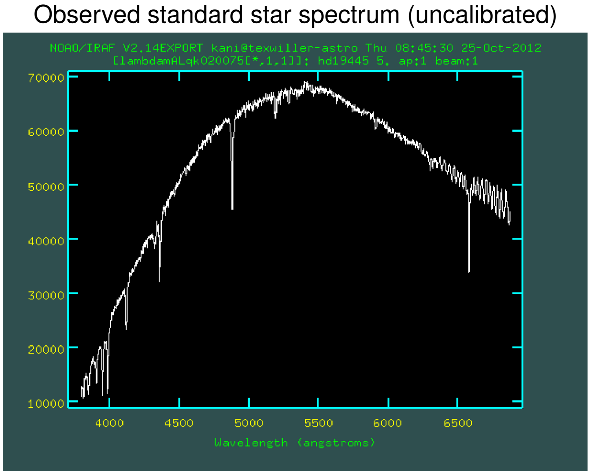
↔



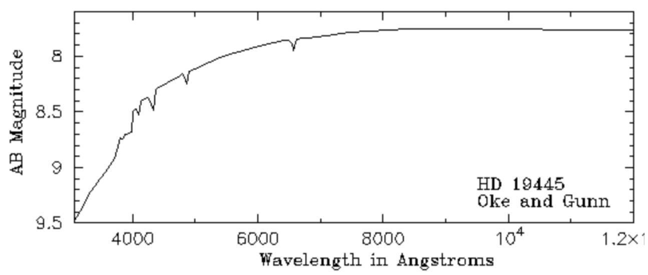
8) Wavelength calibrate the science and standard spectrum using the pix. $\rightarrow \lambda$ transformation (`hedit, dispcor`).

9) Determine the sensitivity of the spectrograph as a function of λ using the standard star spectrum (`standard, sensfunc`).

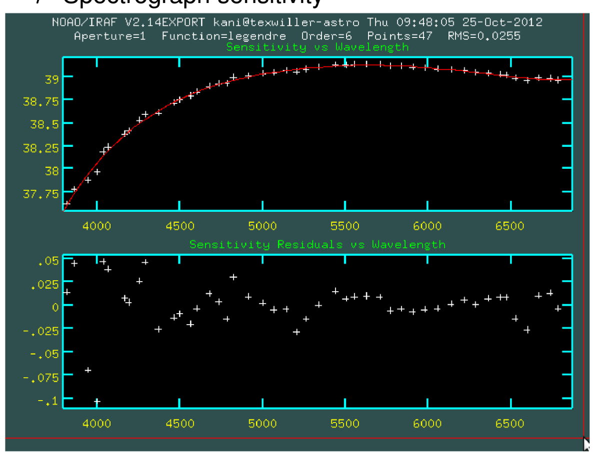
Observed standard star spectrum (uncalibrated)



Literature spectrum (calibrated)

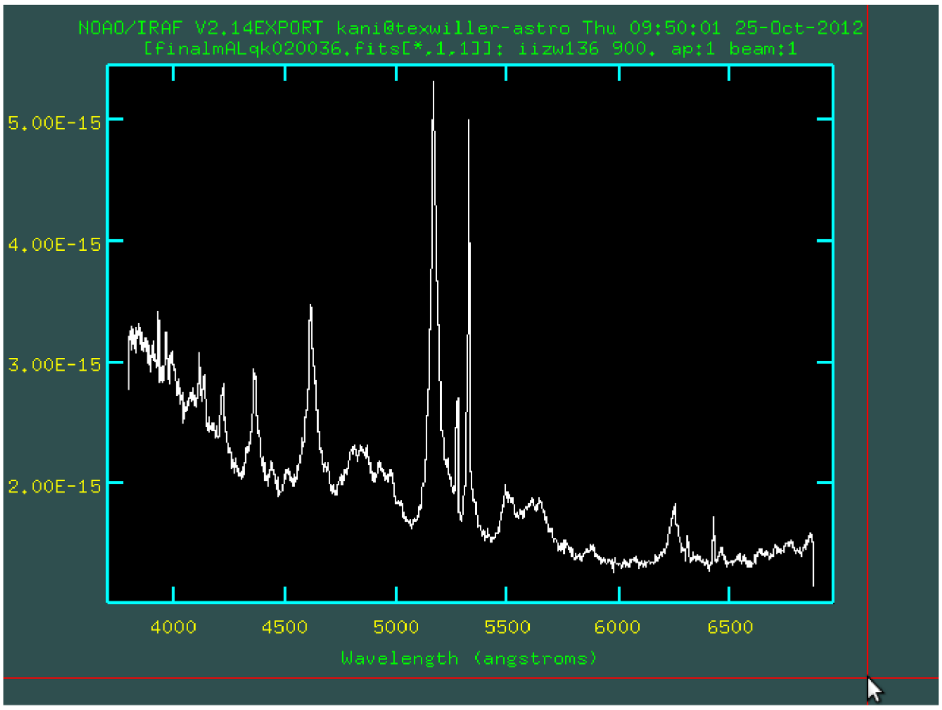


→ Spectrograph sensitivity



10) Flux calibrate the science spectrum (`calibrate`).

→ Final spectrum:



Things to remember

- The idea of image reduction is to improve the raw frame.
- Take many calibration frames to reduce noise.
- At each reduction step, check that the result is reasonable (noise not increased significantly, no negative values, ...).