Calibration and data processing of optical imaging data

Lecture 7

Course of:

Signal and imaging acquisition and modelling in environment

27/03/2024

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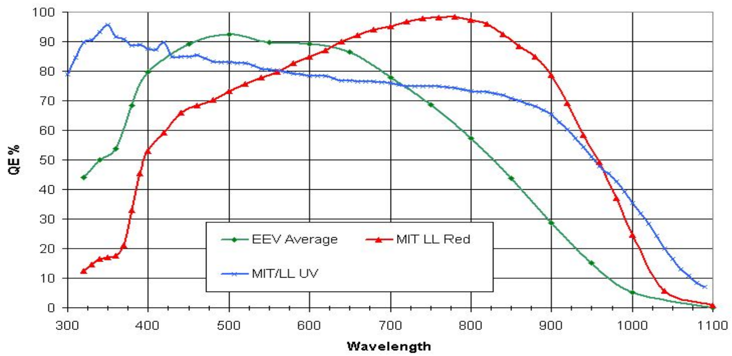
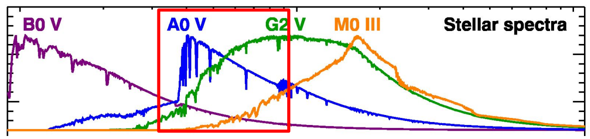
CCDs have a nearly zero spectral resolution

All photons converted into photoelectrons will be recorded by the detector, irrespective of their original wavelength. The flux from a source will be turned into a number of counts.

What if my source has different spectral properties at different wavelengths?





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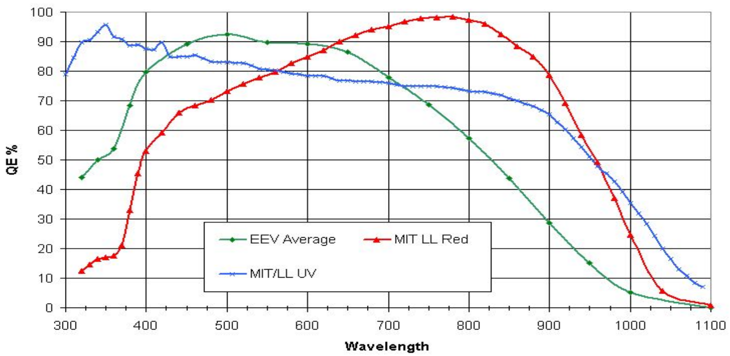
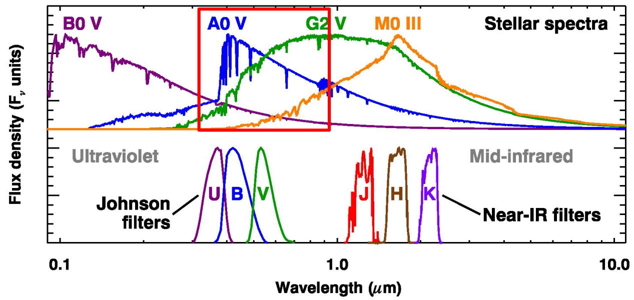
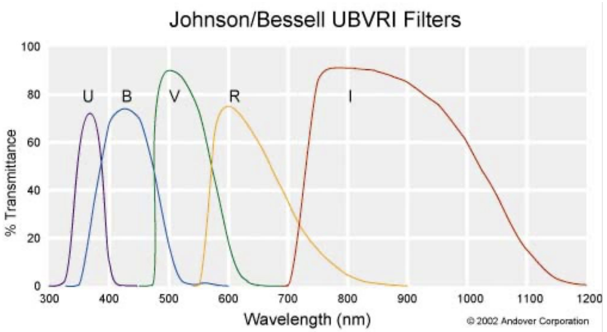


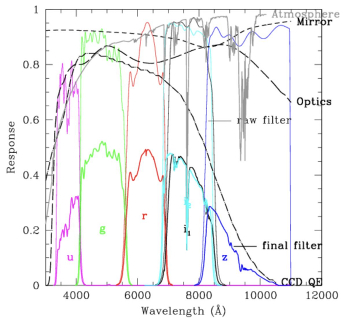


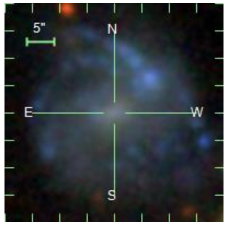
Photometric filters are a powerful way to identify the color of sources

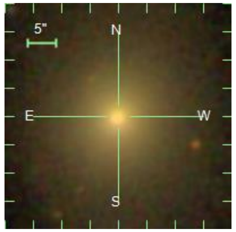
Obtaining spectra is expensive and impractical for large areas (on the sky but also looking on the ground). Hyper spectral Imaging in various filters can help us reconstructing the spectral energy distribution of a source.

There are many filter systems. When images from three are mapped onto the R G B channels you can generate pseudo color images.



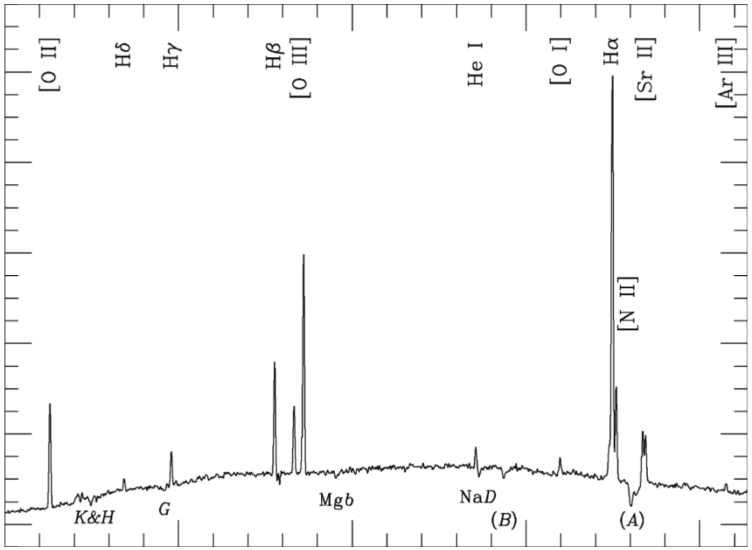






Photometric filters are a powerful way to identify the color of sources

When emission lines are of interest (e.g. from ionized Hydrogen, Metals or even from Methane), narrow band filters come in handy.



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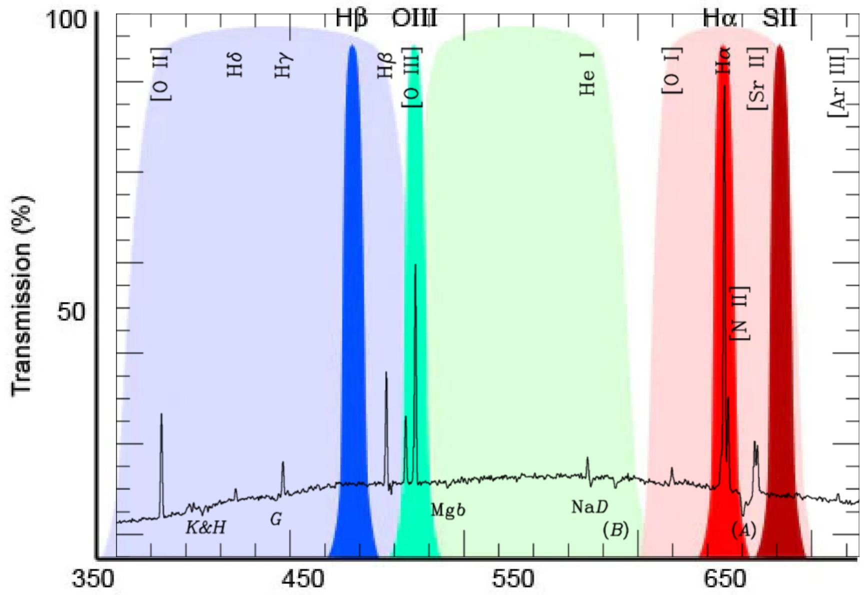


Planning and executing observations

Planning imaging observations is a complex task. One must know:

Which filter(s) do you want to use.
What is the expected flux of the source in these filters.

Knowing the properties of the telescope it is possible to turn the expected flux into an expected number of photoelectrons/s. Calling S the total number of counts collected in X seconds and N the uncertainty on the measurement of S we can define: SNR = S / N

The Signal-to-Noise Ratio, SNR measures how well an object is measured. Typical values:

- *S/N* = *2-3*: object barely detected
- *S/N* = 5: object detected, one can really start to believe what one sees
- *S/N* = 10: we can start to do measurements
- *S/N* = 100: excellent measurement.

As *N* is the error on the measurement, *1 / (S/N)* is the relative error on the measurement:

- *S/N* = 100: measurement at 1%
- *S/N* = 10: at 10%
- *S/N* = 5 : at 20% (+/- 20%)
- *S/N* = 2: +/- 50% !

Planning and executing observations

Various sources of noise should be considered:

Photons from the source generate electrons that follow Poisson statistics: N = sqrt(S) = sqrt(s * t)

This also applies to the sky: when we measure the object, we have to measure the sky "under" the object at the same time, then take it into account by subtracting it. Bottom line: we have to take into account the shot noise of the sky:

$$N_{sky} = \mathrm{sqrt}(Sky) = \mathrm{sqrt}(sky * t)$$

There are other noise terms adding quadratically, but source and sky are usually the dominant ones. **SNR increases 'almost' as sqrt with time.**

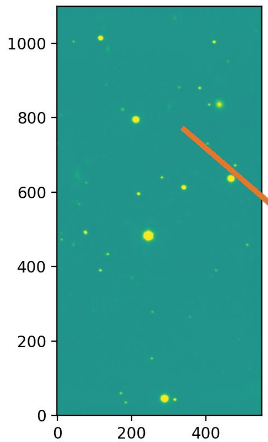
$$S/N = s * t \;/\; \mathrm{sqrt}(s * t + sky * t)$$

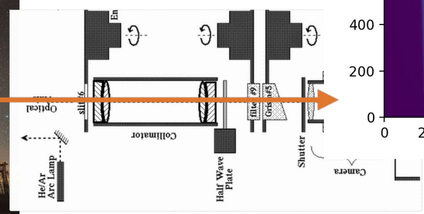
For a target SNR, one could get a minimum exposure time. Always wise to exceed the exposure time in case the circumstantial conditions are worse than expected.

Planning and executing observations

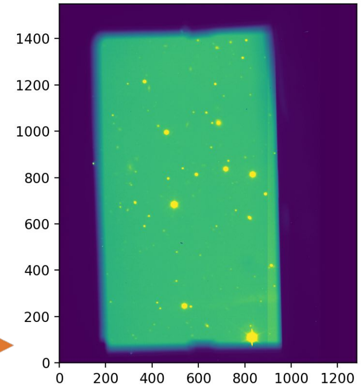
Once the observations are taken it is time to extract physical measurements from them. However….

This is how the sky looks like





This is what we get



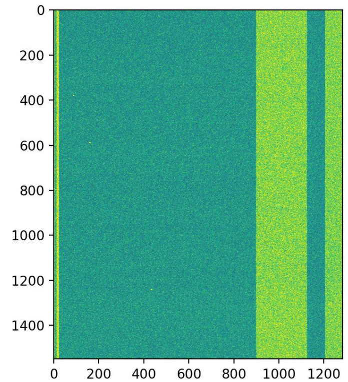
Data reduction - Bias Frame

Data reduction is the set of algorithms that we use to remove instrumental signatures using “calibration frames”.

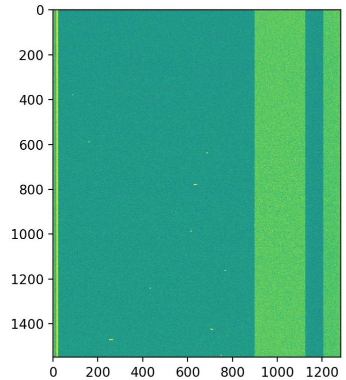
The Bias is a step value in the CCD images due to the detector electronics. It can be evaluated by reading the CCD at zero exposure time. The Bias can have a structure so it is not enough to evaluate it as a single value. We reduce the uncertainty on the bias value (per pixel) by averaging many bias frames.

In case of long exposures, the bias frame should be replaced with the dark frame (detector read after the same exptime used for the science frame).

Single Bias

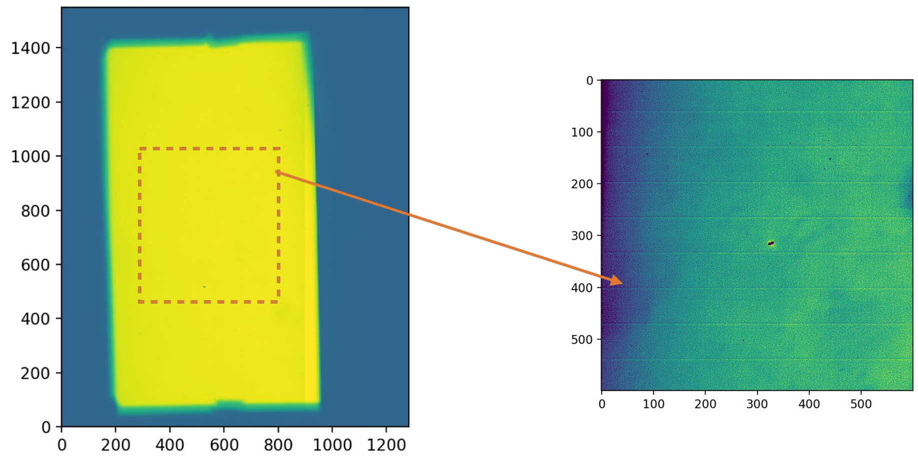


Master Bias

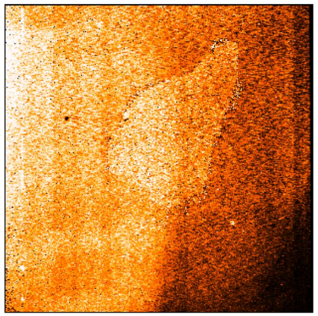


Data reduction - Flat Field Frame

The response of the detector (efficiency) is not the same in every pixel. This includes optical effects (vignetting), dust on the CCD, and the properties of the CCD itself.
The flat frames are images of the twilight sky (why?) or a special lamp that illuminates the detector uniformly. Variations in the flat images are then due to the response of the instrument to incoming light.
Flat frames **must be bias/dark subtracted** and combined to reduce noise. Then we normalize the counts to their median value such that the flat is a multiplicative correction with a mean/median of 1.



IR detector

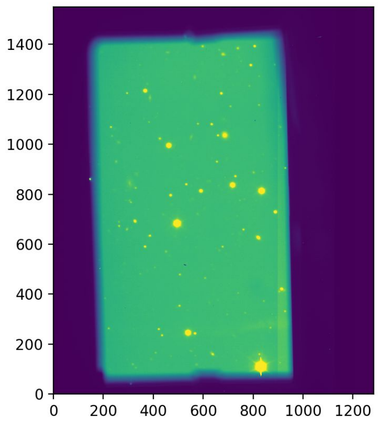


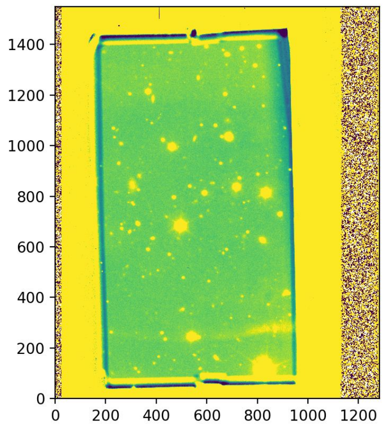
Data reduction - The calibration cascade

The corrected science frame is obtained from the following equation:

Science = (RAW - Master Bias/Dark) / Master Flat

Note: The Dark/Bias does not depend on the filter used, but the Flat frame does so an appropriate flat must be used for each science frame.





Going deeper than the detector saturation

We have seen that the SNR increases if more photons are collected from the source. How do we arbitrarily increase the SNR of faint sources if the CCDs have a finite full well capacity?

Co-adding various images

We have seen that the SNR increases if more photons are collected from the source. How do we arbitrarily increase the SNR of faint sources if the CCDs have a finite full well capacity?

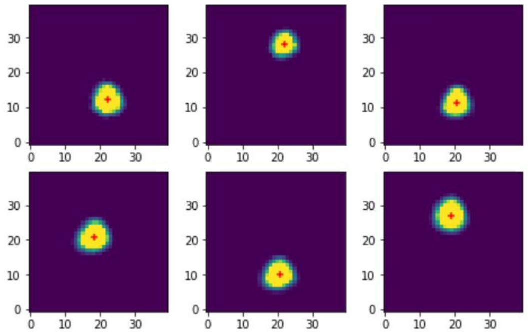
The answer is: by observing the same object several times and co-adding the data with mean (or median) statistics in order to reduce the noise in the coadded image (ideally) by sqrt(Nexp).

There are additional limitations though:

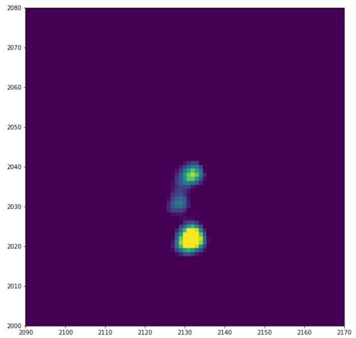
1. If your object lands on a poorly sensitive region of the CCD (due to dust, issues in the detector substrate, defects in the optics), increasing the number of exposures will expose the systematic imperfections of the light sensitive device.
2. On the other hand keeping an object exactly still on the detector frame might be impractical for the mechanics of the telescope/satellite.

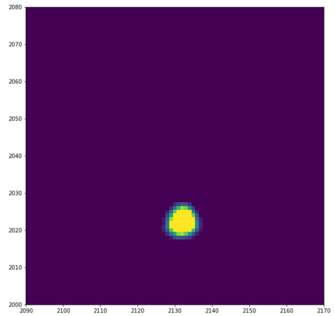
As a result your object will often shift on the detector frame. Prior to coadd we therefore have to shift all the exposures w.r.t. one of them (usually the first one).

Co-adding various images



Unshifted co-add





Shifted co-add

Your Turn

Today’s lab activity

- Complete the characterization of the Dark current from Lecture 6
- Fully reduce the science data provided in the directory Telescope Data / Imaging Science

  Note: The Dark/Bias does not depend on the filter used, but the Flat frame does so an appropriate flat must be used for each science frame. You also need to derive a Dark frame for 300s exposures, based on what you found in activity 1

- Make an estimate of the brightness of a source (a star).

Notebooks:

Darks https://colab.research.google.com/drive/1Hz78IKq1jIPXF4HZ5fba-695749BKSjp?usp=share_link

Science
https://colab.research.google.com/drive/1RSP5csGnKWblauMQwv8psxFFvmHsSMVo?usp=share_link