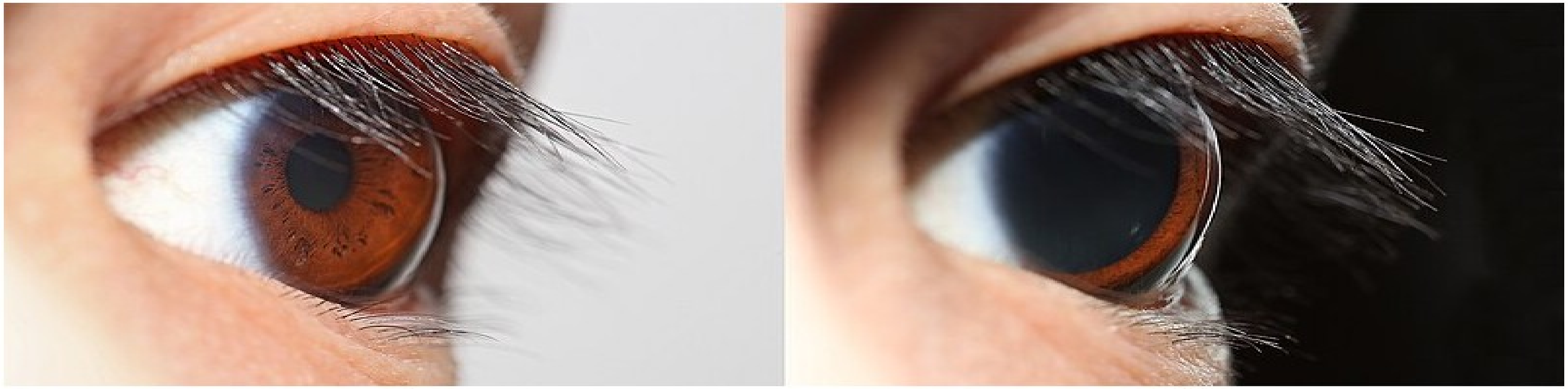
Introduction to Imaging and Photometry

European Southern Observatory
La Silla Observing School, 2026
Jonathan Smoker



A break the ice slide!

- What science do you want to do?

- Where do you want to obtain your data?

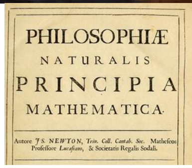
- Photometric systems

- The CCD equation

- Preparing your observations

- Post-observation data reduction

- Photometry



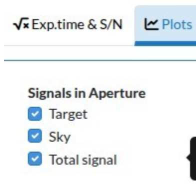
"B" stands for blue.

"G" stands for green.

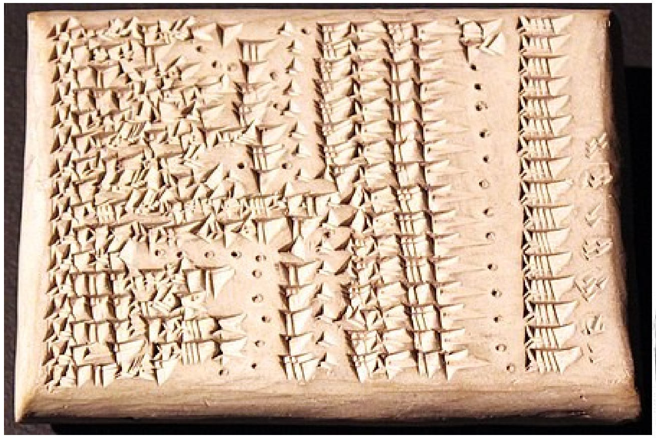
"V" stands for visual.

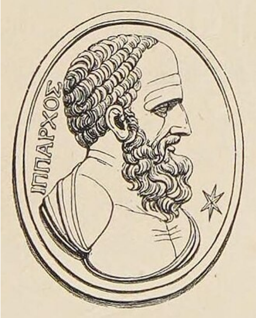
"R" stands for red.

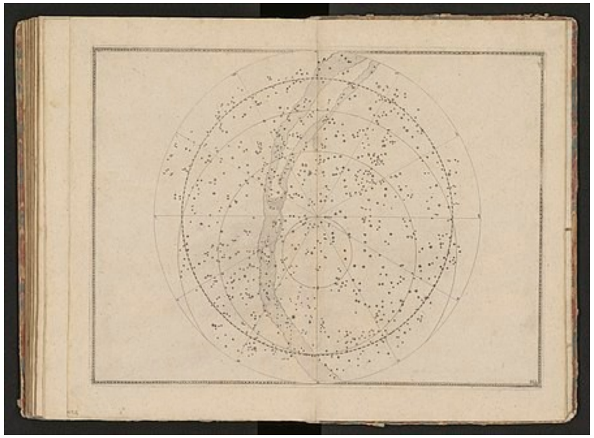
$$SNR = \frac{PQet}{\sqrt{PQet + Dt + Nr^2}}$$



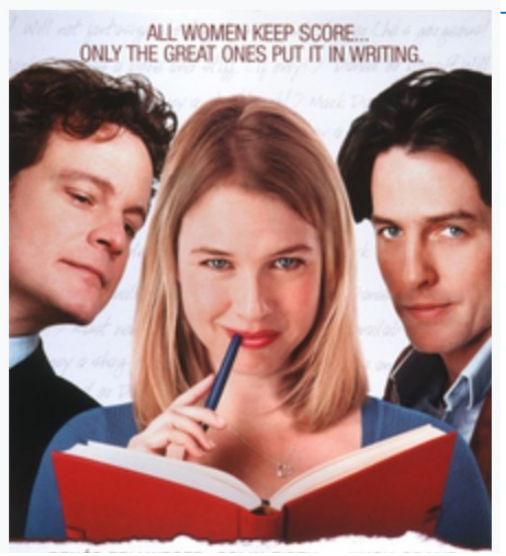
A long time ago….

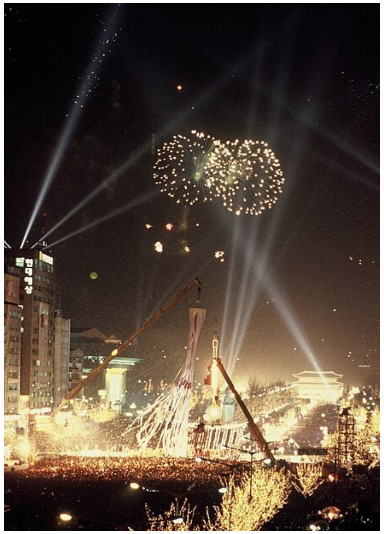






Slightly more recently….





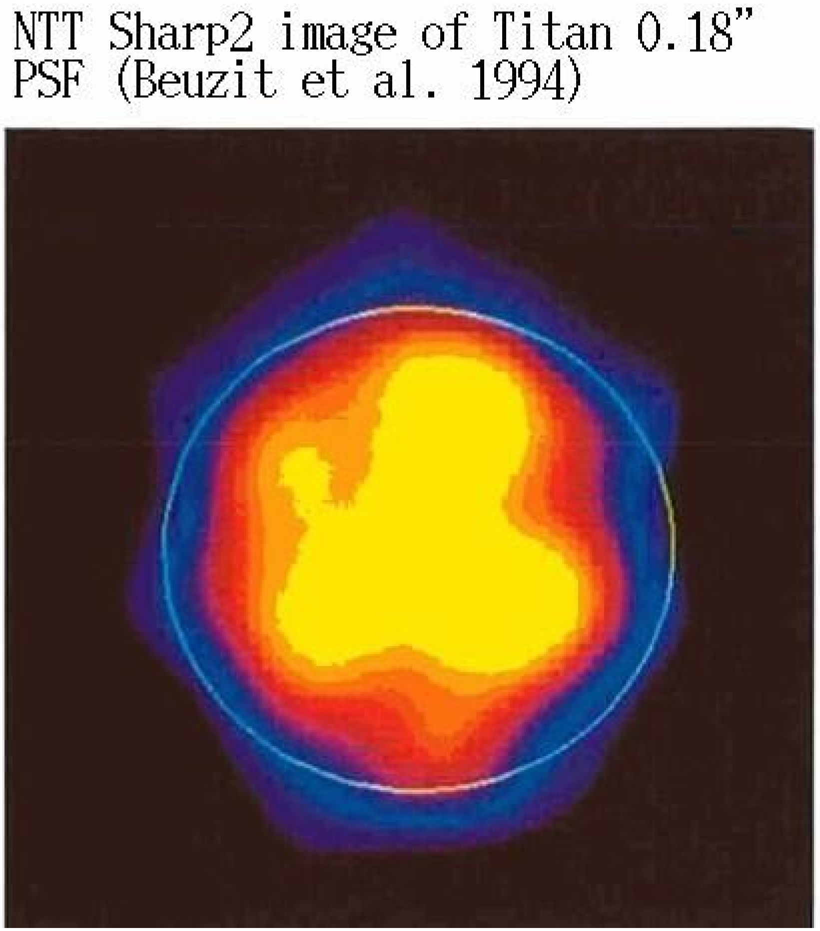
Imaging / Photometry:

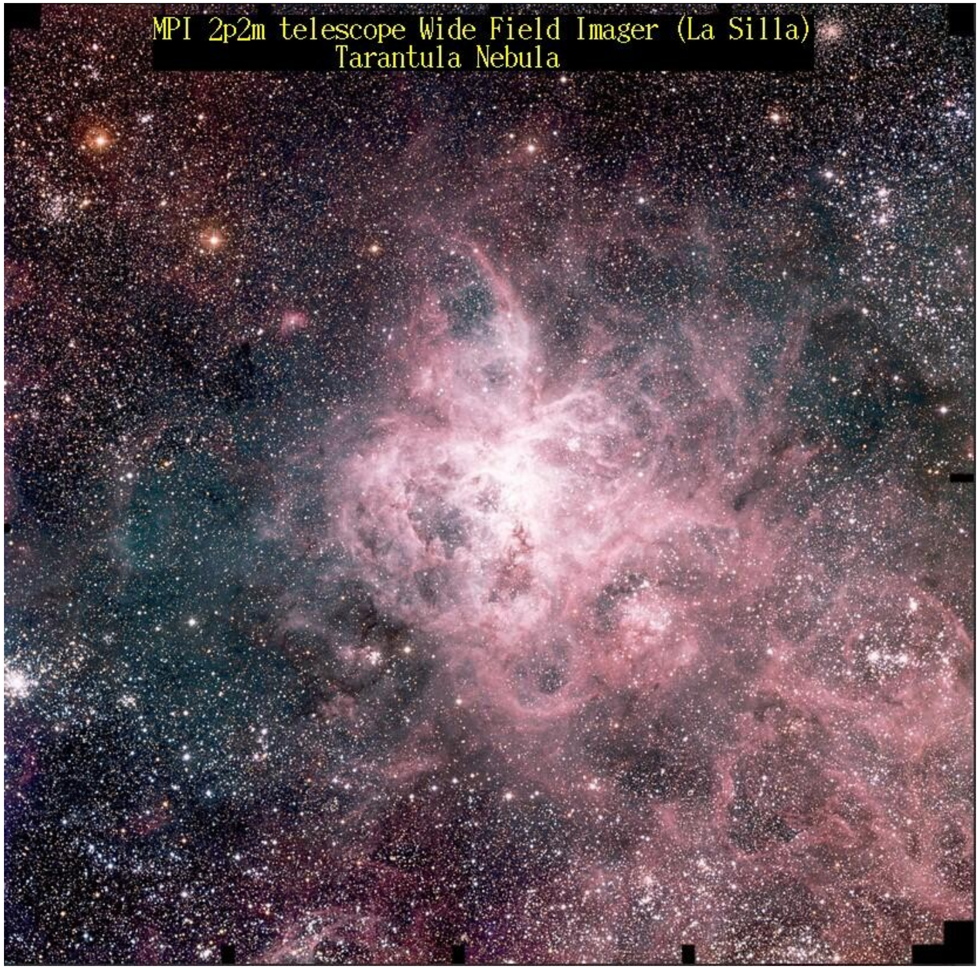
What science do you want to do?

What science do you want to do ?

Single object?

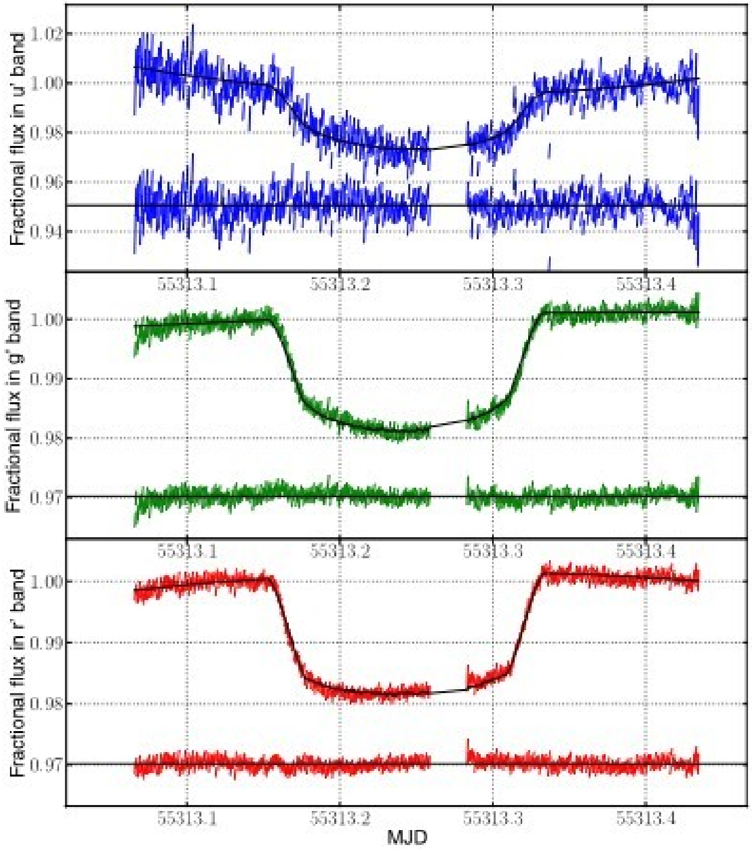
Wide field?





What science do you want to do ?

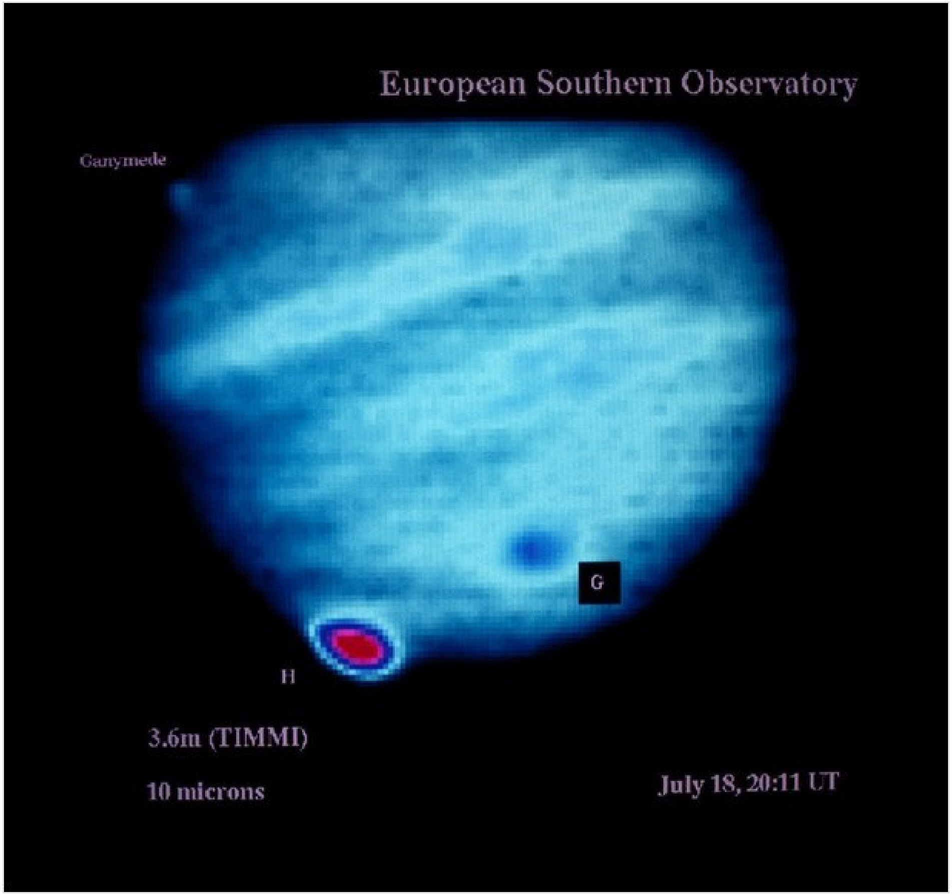
High time resolution?



NTT (Bento+ 2013)

Infrared?

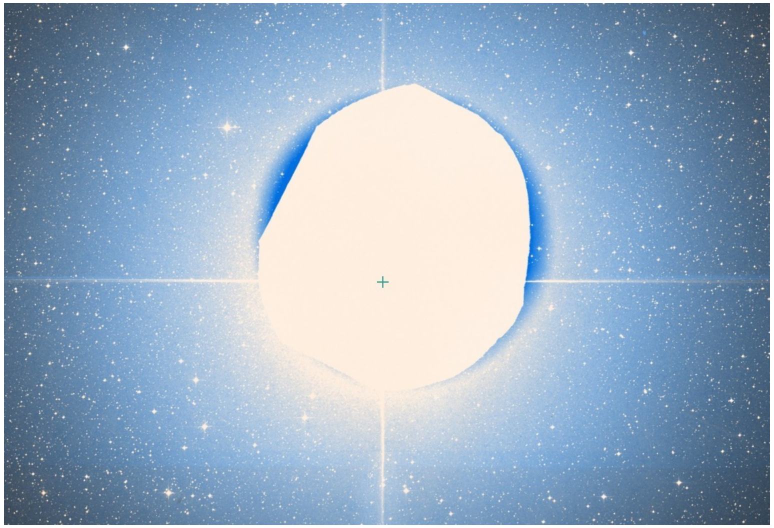
Comet Shoemaker–Levy 9 observations



Observations of comet Shoemaker–Levy 9 impacting Jupiter on July 18, 1994.

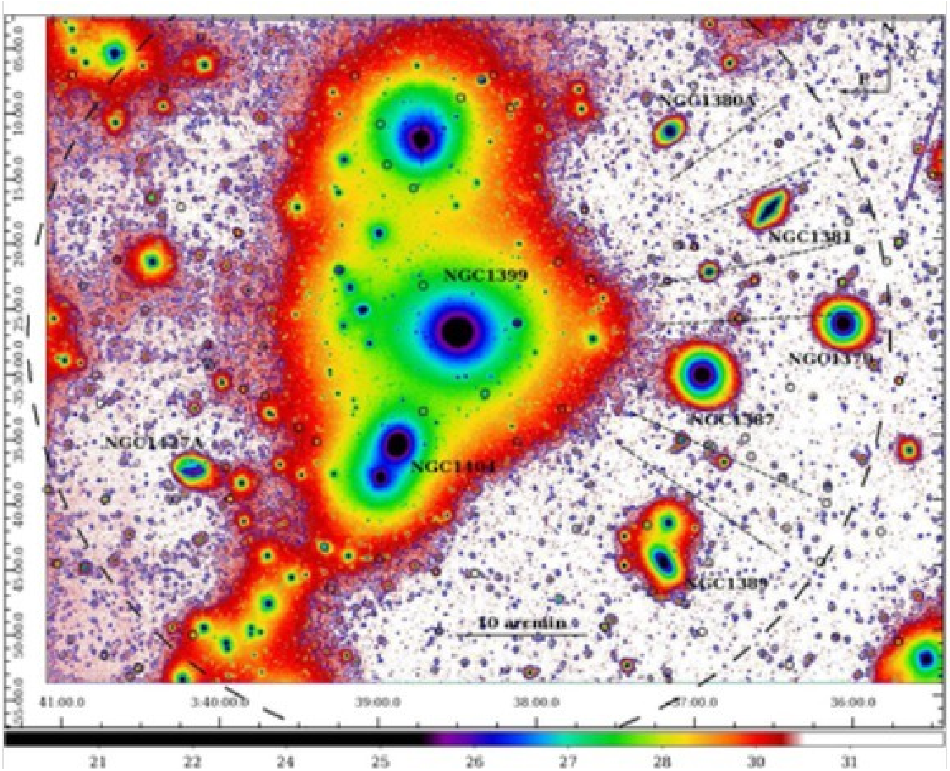
What science do you want to do ?

Bright objects?



(Sirius: SIMBAD / CRIRES+)

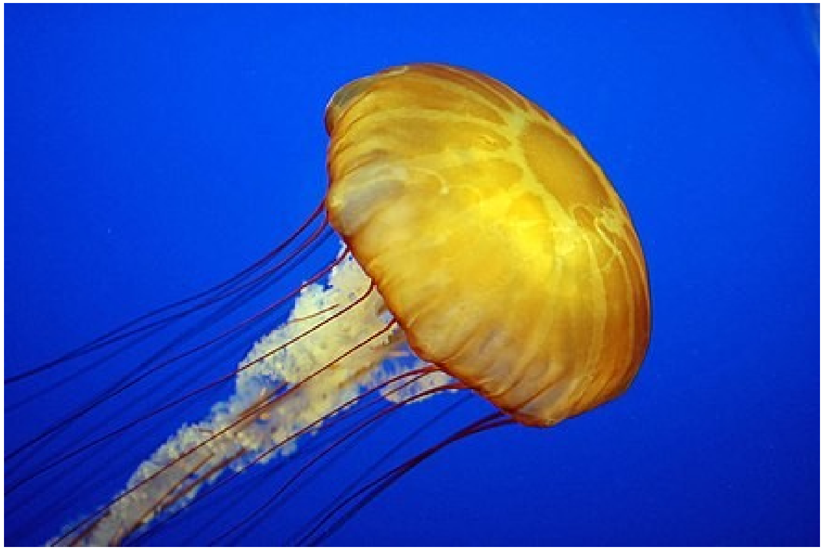
Or faint?



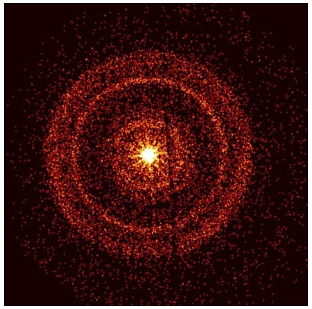
(Iodice+, 2017), OmegaCAM, Fornax

What science do you want to do ?

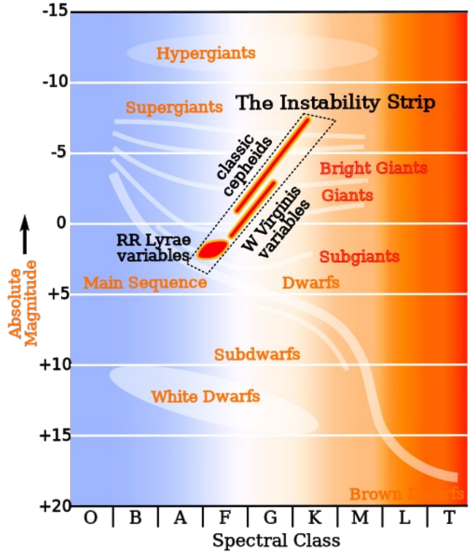
Fast reaction time needed?



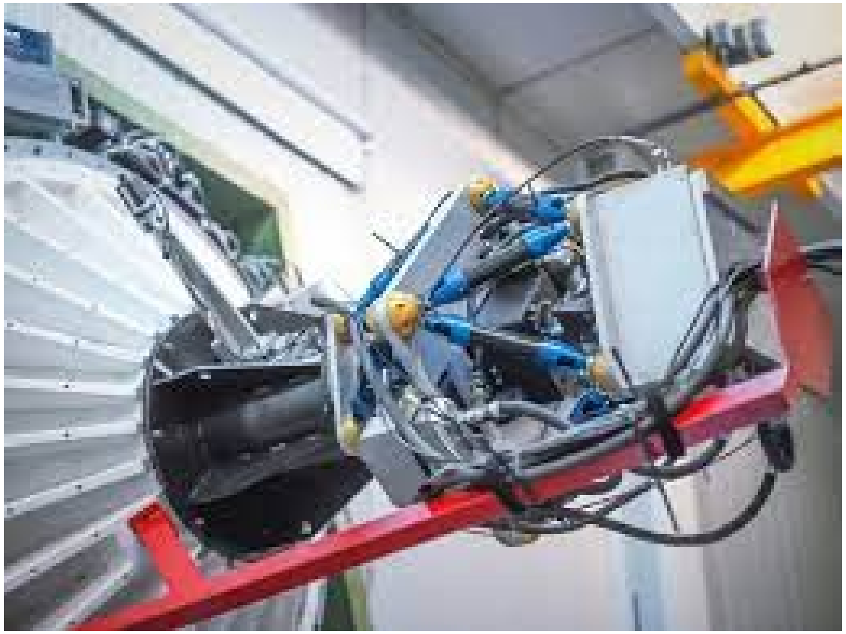
For example gamma ray bursts (below),
supernovae,
gravitational wave
event follow up
etc.



Or not?

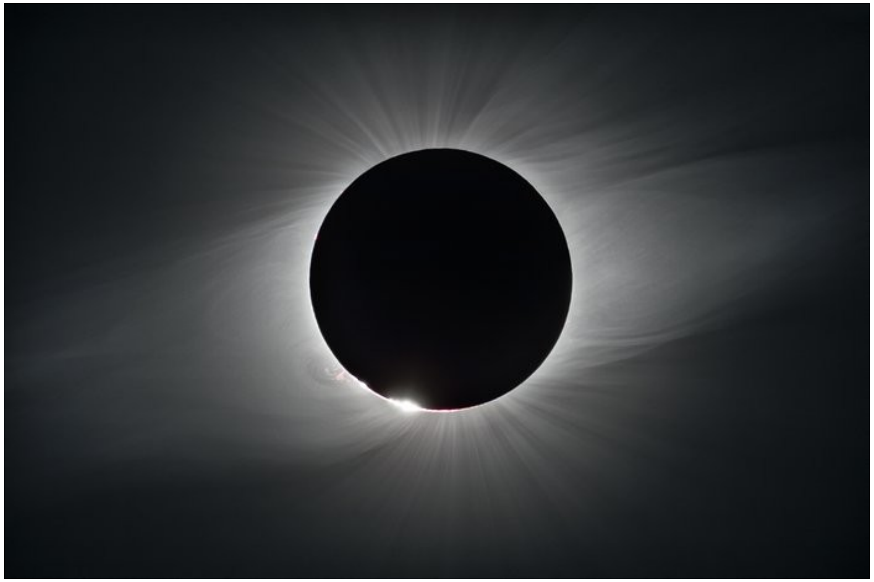


No instrument can do everything!



An interlude…. Degrees…. Arcminutes, Or Arcseconds ?

- The Moon and Sun subtend about 1 degree on the sky.

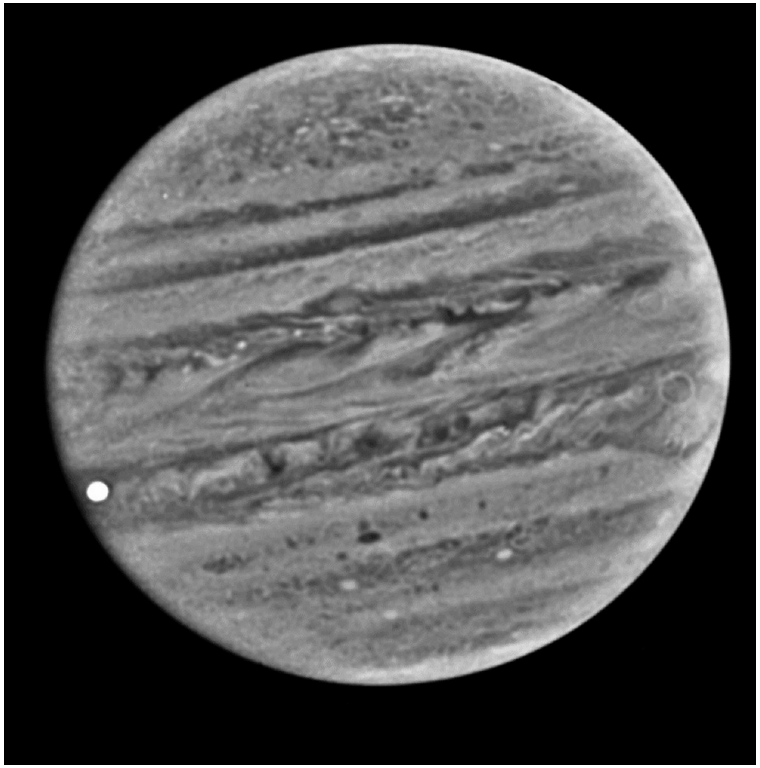


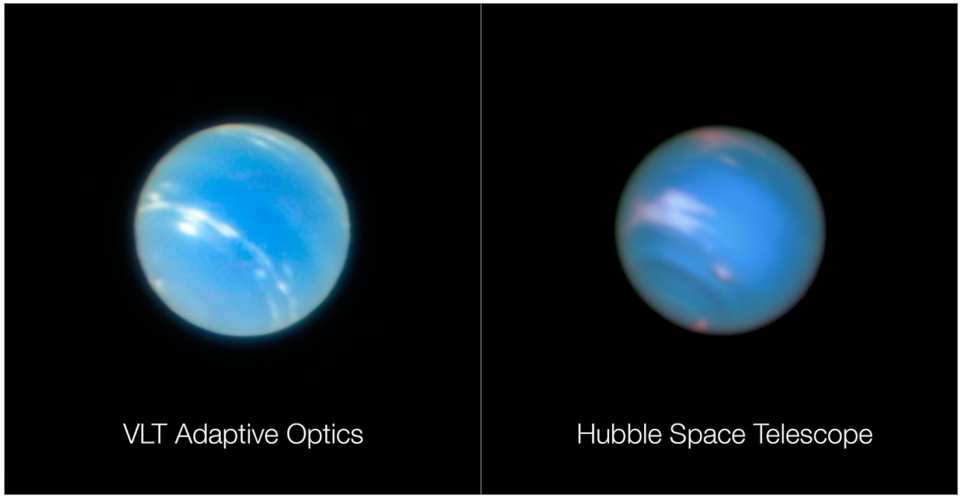
- One degree is 60 arcminues or 3600 arcseconds.

- Astronomical “seeing” on a good site is about 1 arcsecond.

An interlude…. Degrees…. Arcminutes or Arcseconds?

- Jupiter subtends about 0.5 to 0.9 arcminutes on the sky, depending on the time of observation (Left, VLT, optical), about 40 to 70 times smaller than The Moon.
- Neptune subtends about 2 arcseonds on the sky, about 15 to 35 times smaller than Jupiter (Right, VLT, HST).



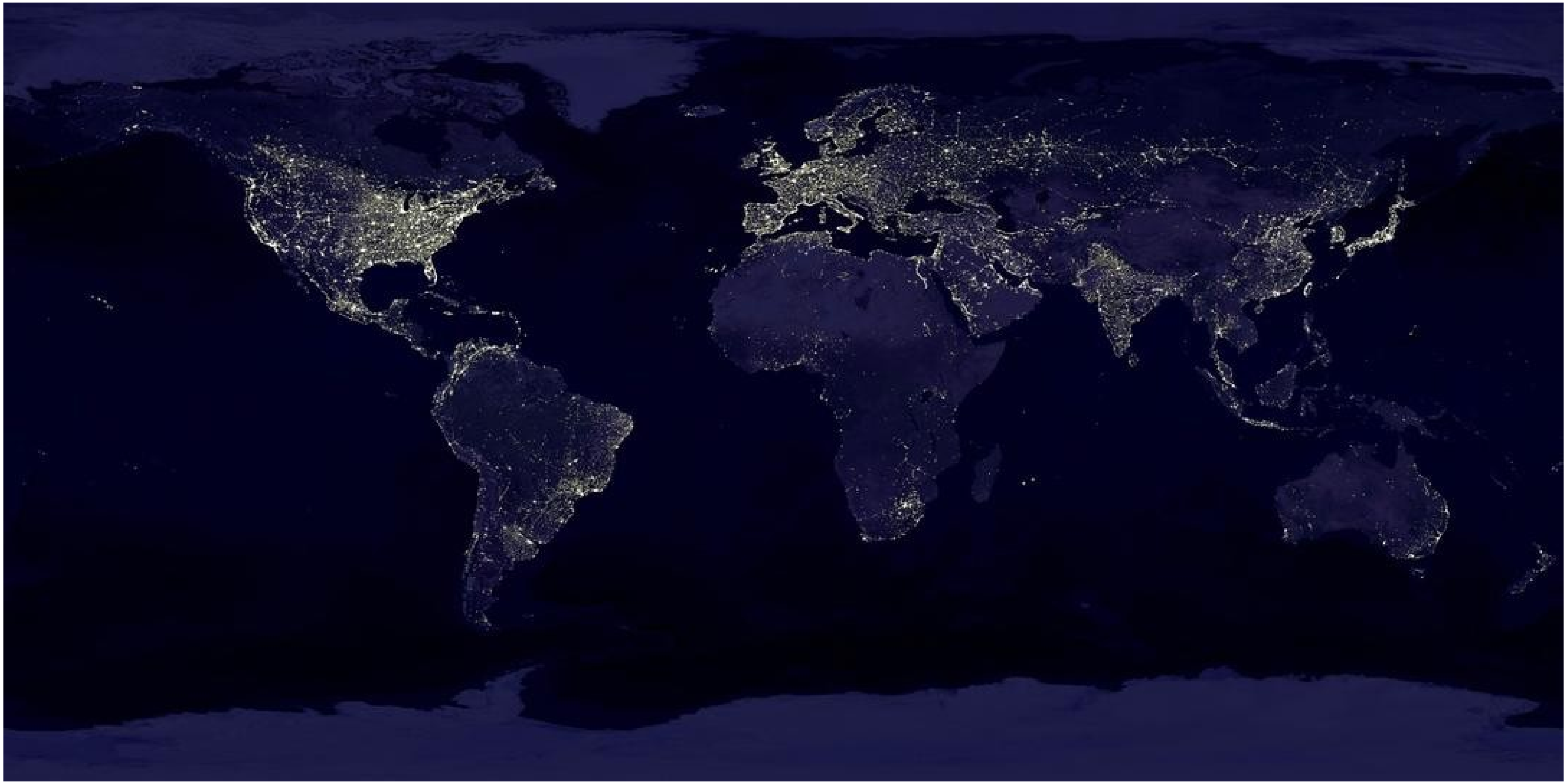


Can the human eye resolve Jupiter?

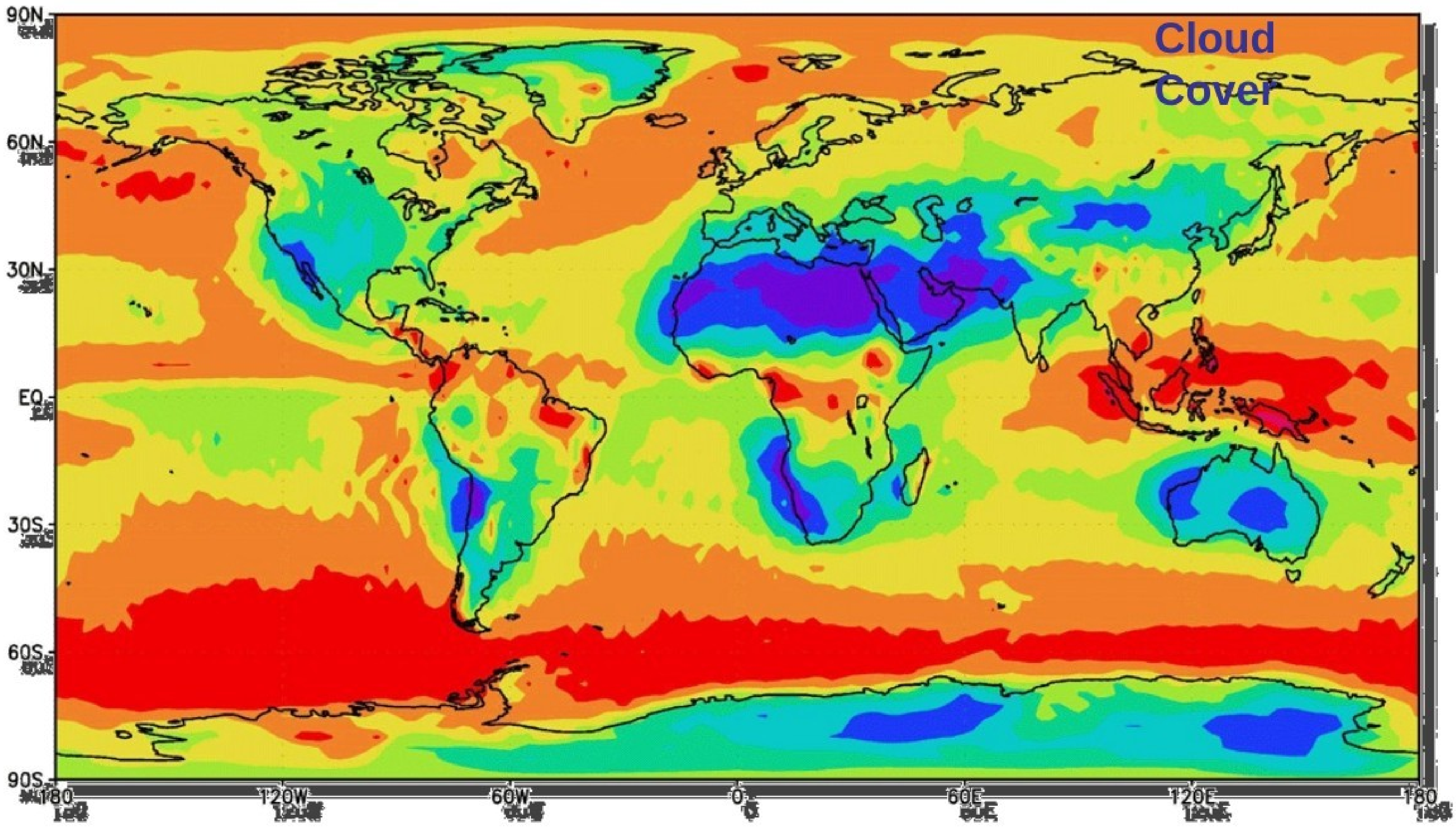
Imaging / Photometry:

Where do you want to obtain your data?

Somewhere with dark skies

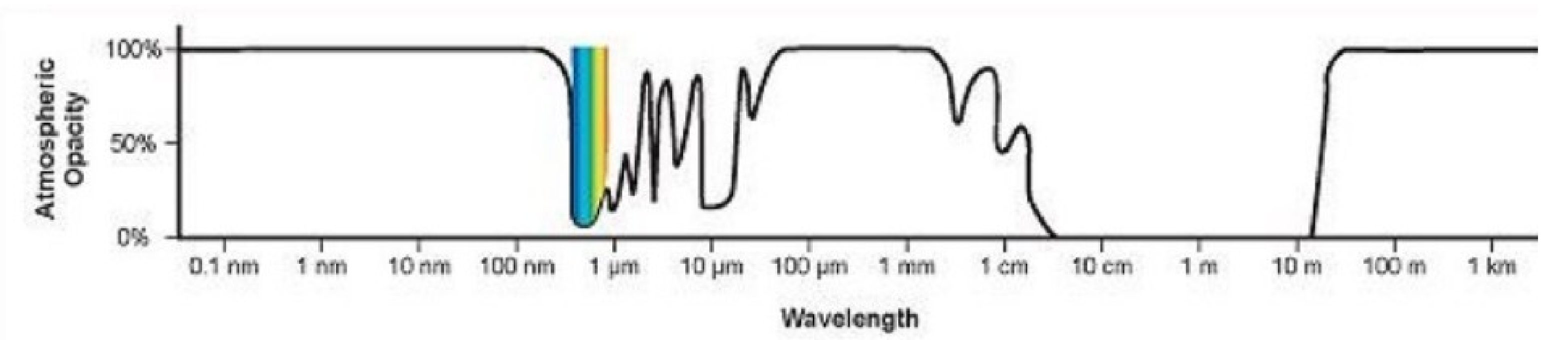


Somwhere with little or no cloud cover



High and remote mountains!

The Earth's Atmosphere



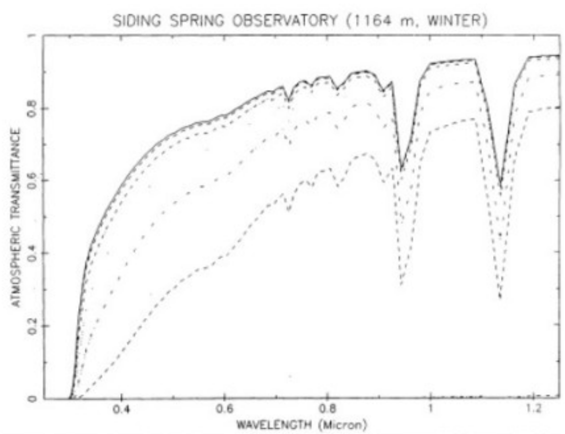
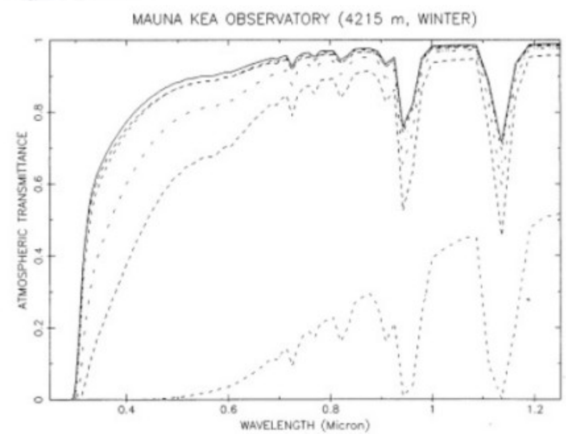


FIGURE 4. — Siding Spring Observatory transmittance between 0.25 µ and 1.25 µ during the Fall-Winter season (1164 m).

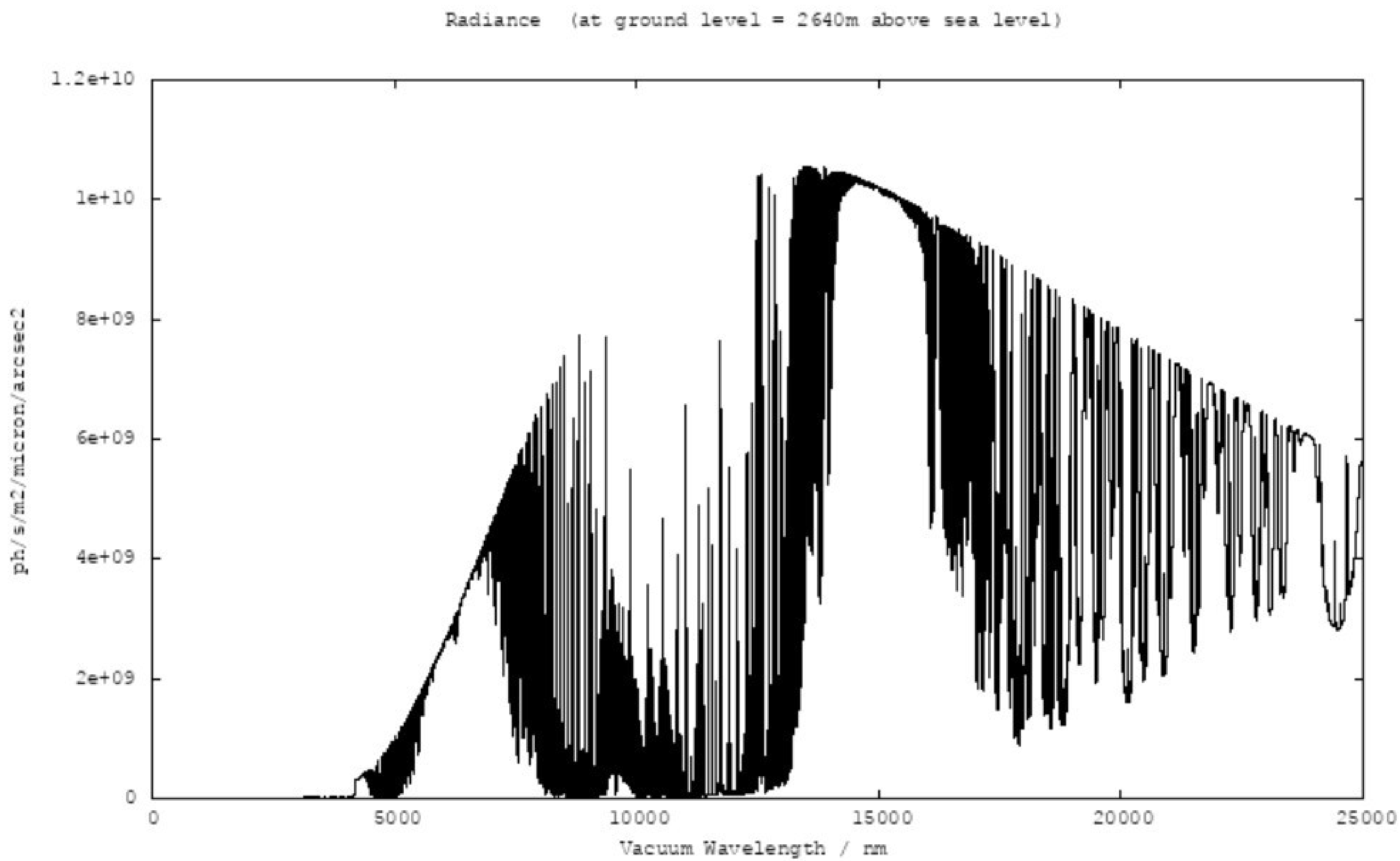


C. Nitschelm

FIGURE 10. — Hawaii Mauna Kea Observatory transmittance between 0.25 µ and 1.25 µ during the Fall-Winter season (4215 m).

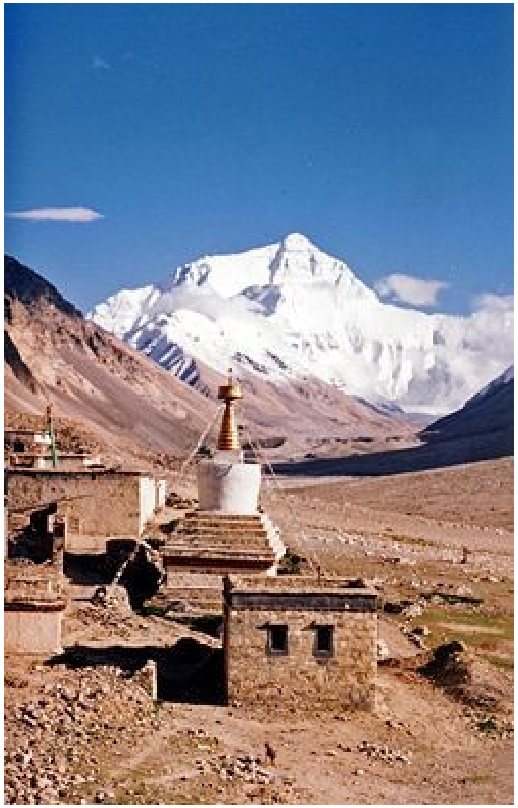
Mauna Kea and Siding Spring visible/NIR atmospheric transmission curves.
The plots are for zenith angles of 0, 15, 30, 45, 60, 75, 90 degrees

Sky counts against wavelength optical to infrared
ww.eso.org/observing/etc/skycalc



What two things stand out from this plot?

An interlude…. Which is the highest mountain in the world?



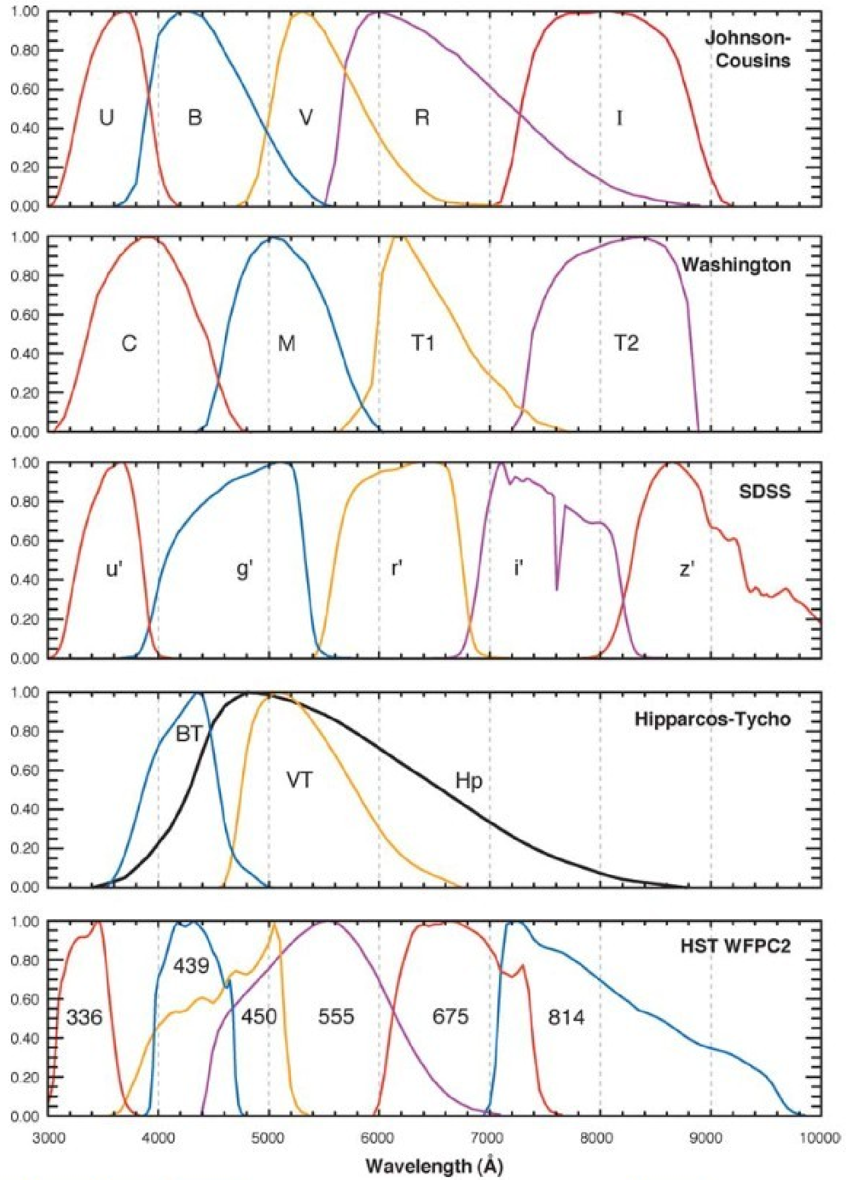
(a) Everest (Nepal; 8848m) (b) Chimborazo (Ecuador; 6263m) (c) Mauna Kea (Hawaii; 4207m) (d) Kilimanjaro Tanzania (5895m).

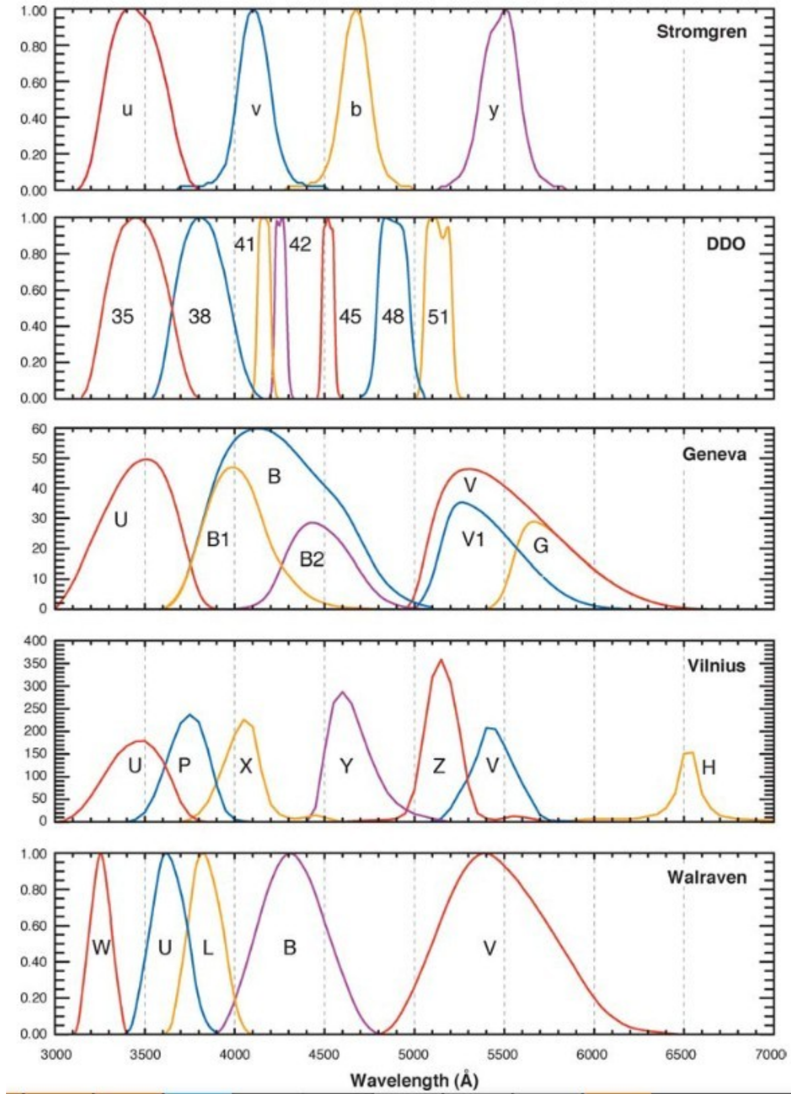
Imaging / Photometry:

What wavelength / filter do you want to observe and with what filter width?

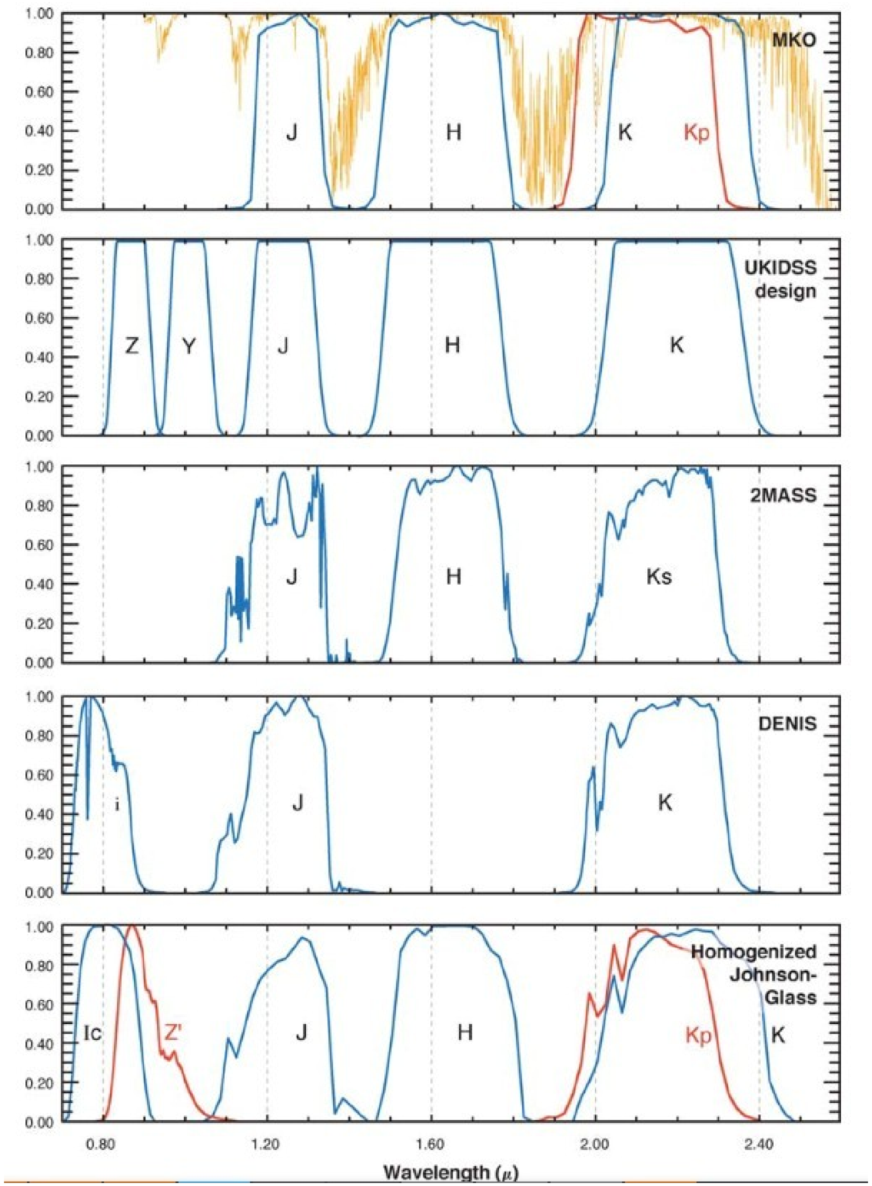
This brings us to photometric systems. These are a defined set of passbands (or filters) with a known sensitivity as a function of wavelength.

Photometric systems: optical (from Bessel 2005)
Can you see any issue with “U” ?





Photometric systems: near-Infrared (from Bessel 2005)



NIR infrared from about 800 to 2500 nm ZYJHK bands

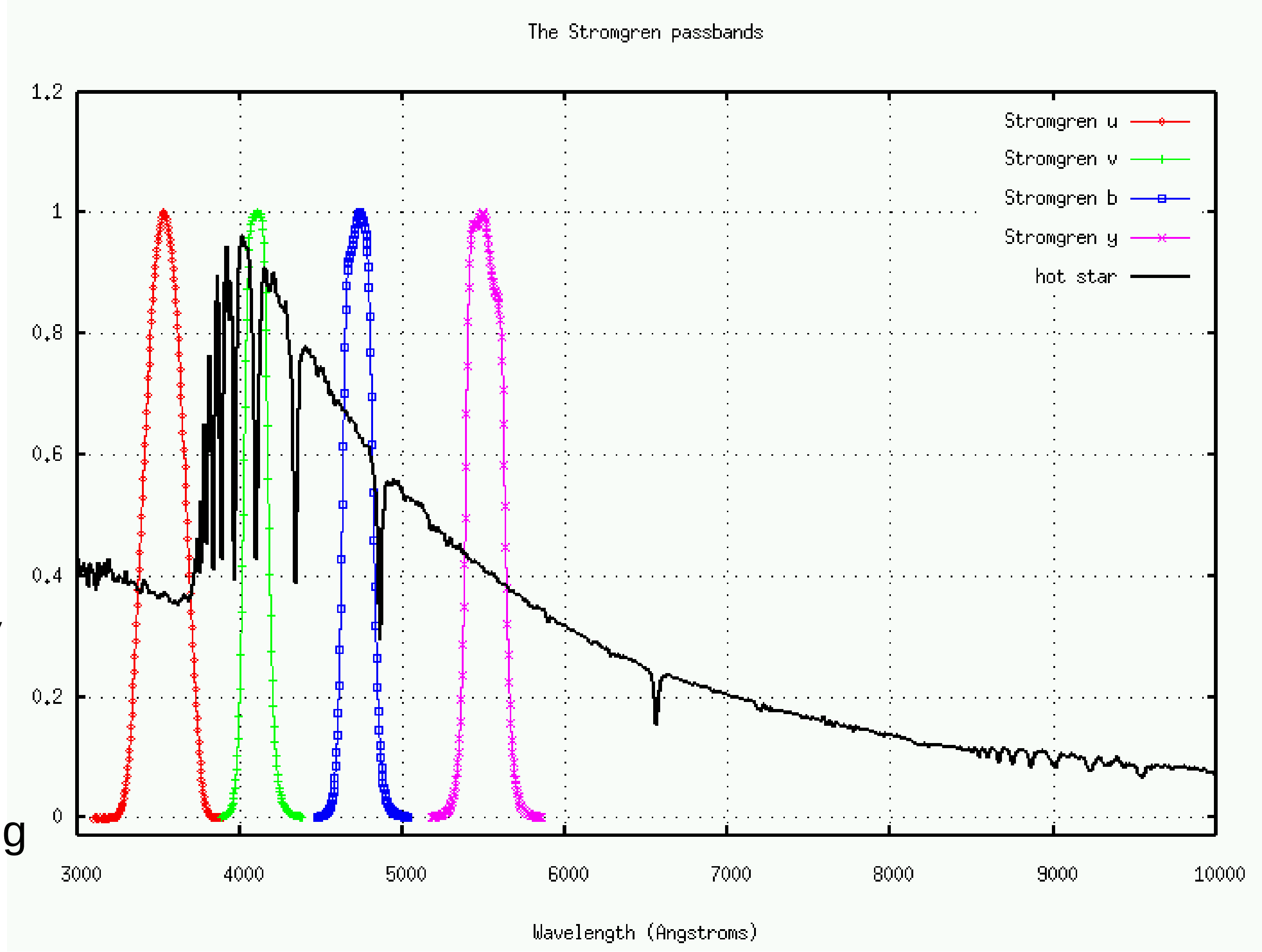
Then:

L → 3450 nm
M → 4700 nm
N → 10500 nm
Q → 21000 nm

Bands typically chosen to match atmospheric windows with less telluric absorption.

An example of a photometric system: Why were the Stromgren bands chosen to be as they are?

- u avoids the Earths atmospheric UV cutoff
- y measures magnitude (y = V)
- (b-y) colour gives an Idea of stellar temp hence spectral type
- c1 index that measures the balmer discontinuity
- m1 index to measure line blanketing as v is located where blanketing is strong
- reddening is also estimated.



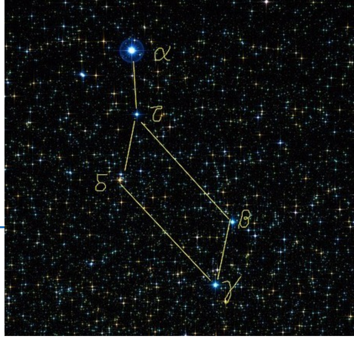
(Michael Richmond: phys.libretexts.org)

Imaging / Photometry:

The magnitude scale (or scales…) and “CCD equation”

(CCD = Charged Coupled Detector)

The magnitude scale (Pogson 1856) and differences between Vega and AB systems



$m - m0 = -2.5 * \log (I / I0)$ I1, I0 are the extracted counts

An object that has m=0 is 100 times brighter than one at m= 5
An object that has m=0 is 100,000,000 times brighter than one at m=20

The “0” subscript refers to a measurement relative to a “standard” star that is used to set the zero point of the system. This was historically chosen to be Vega i.e. in the equation above I0 is the flux of Vega in a given band.

Vega magnitudes:

These define: U_Vega = B_Vega = V_Vega = R_Vega = I_Vega = 0.0
Does **A**nybody know what spectral type of star has a flat spectrum? **0**h...
Unfortunately:
- The spectral energy distribution (SED) of Vega is not actually flat
- If you look at SIMBAD then Vega (alfa Lyr) is a delta Sct Variable

AB magnitudes:

In this system we define a zero point to be a source with a flat SED.

The zero point in every filter is defined to be 3631 Jy.

"The CCD equation" to determine S/N ratio

In most cases we want to maximise the S/N ratio in our observations.

To predict the expected S/N, we may use the following equation:

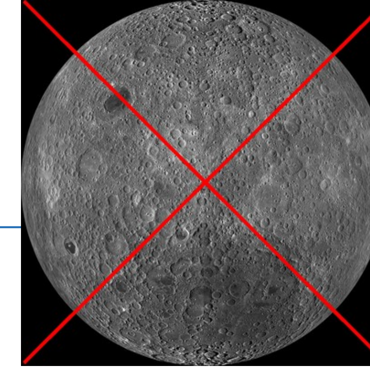
$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{pix}(N_{Sky} + N_{dark} + N_{RON}^2)}}$$

Maximise Numerator!

Minimise Denominator!

How do we maximise the numerator and minimise the denominator?

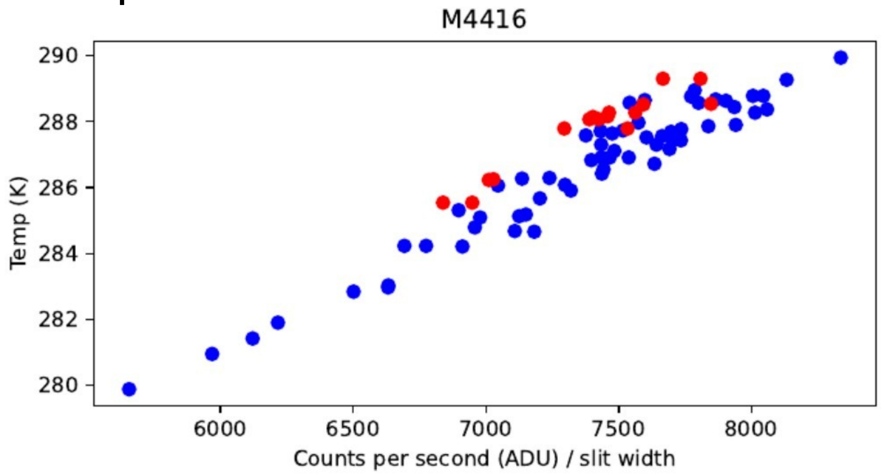
How to maximise the S/N ratio for point sources, especially faint targets



- Have a larger mirror (Diameter=D), or integrate for longer.
- Have a more sensitive detector.
- Observe as close to the zenith as you can to minimise atmospheric absorption.
- In the optical observe in “dark time” (little Moon)

- In the infrared (LM+) observe when the temperature is colder and/or when there is less water vapour in the atmosphere.

- Observe with **better seeing** / image quality (if readout noise an issue), or use adaptive optics. More light on fewer pixels!

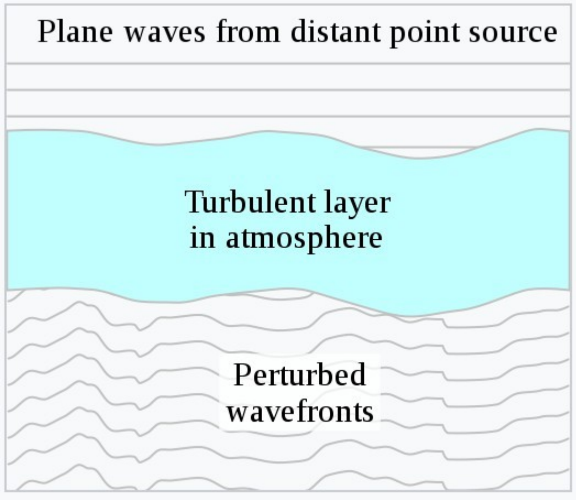


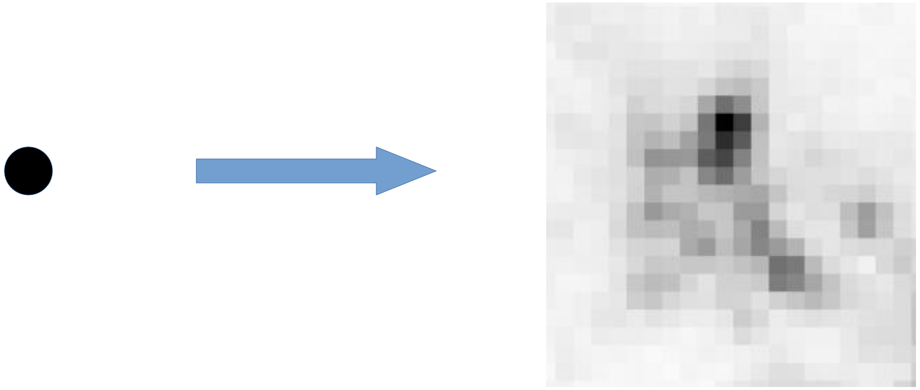
Bright source: S/N = sqrt(N*)

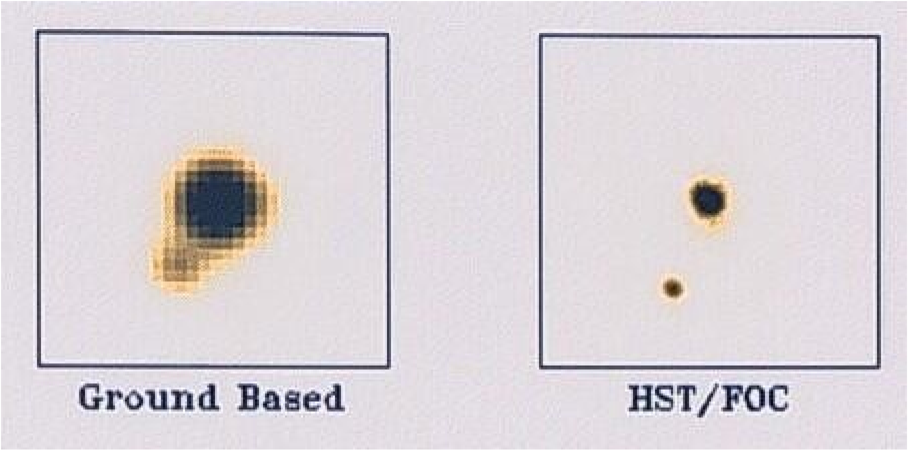
Sky dominated: S/N proportional to 1/npix → As npix is proportional to seeing squared then better seeing increases S/N a lot! For ELT we actually get D^4 improvement.

Readout noise dominated: If the sky and dark current are low then you need to readout less often (longer integration times) and / or bin the detector if possible as well as having a low readout noise detector.

Effect of the atmosphere on ground based stellar image and comparison between ground based (natural seeing) and space based

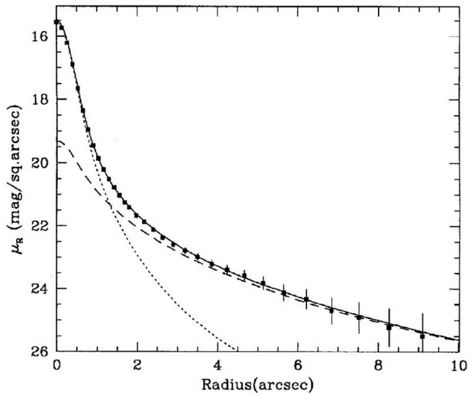






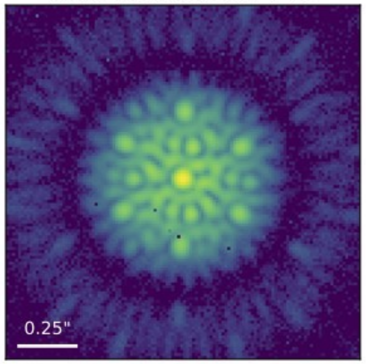
Effect of the instrument and telescope Point Spread Function (PSF) on the final image.

NTT (Falomo 1996)

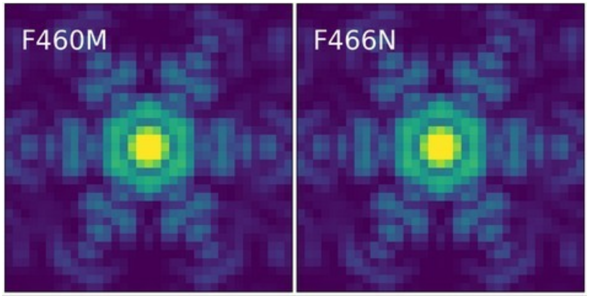


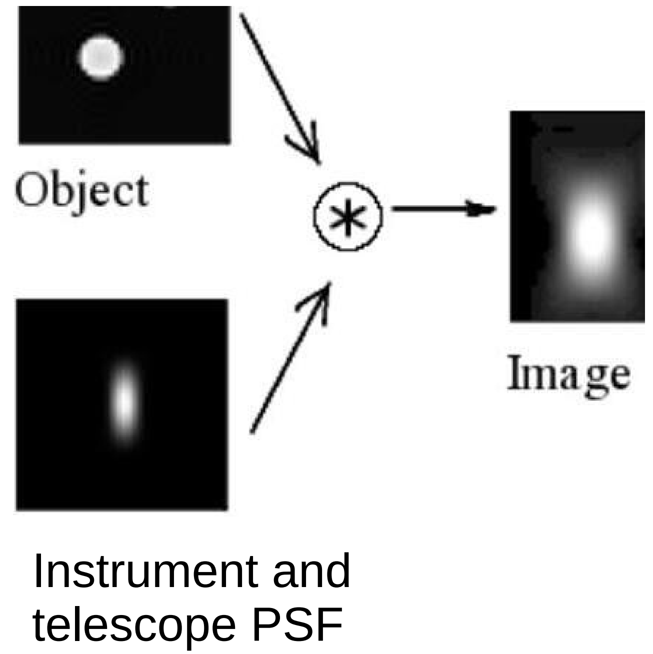
ERIS

HIP18714 with SAM-7 Ks

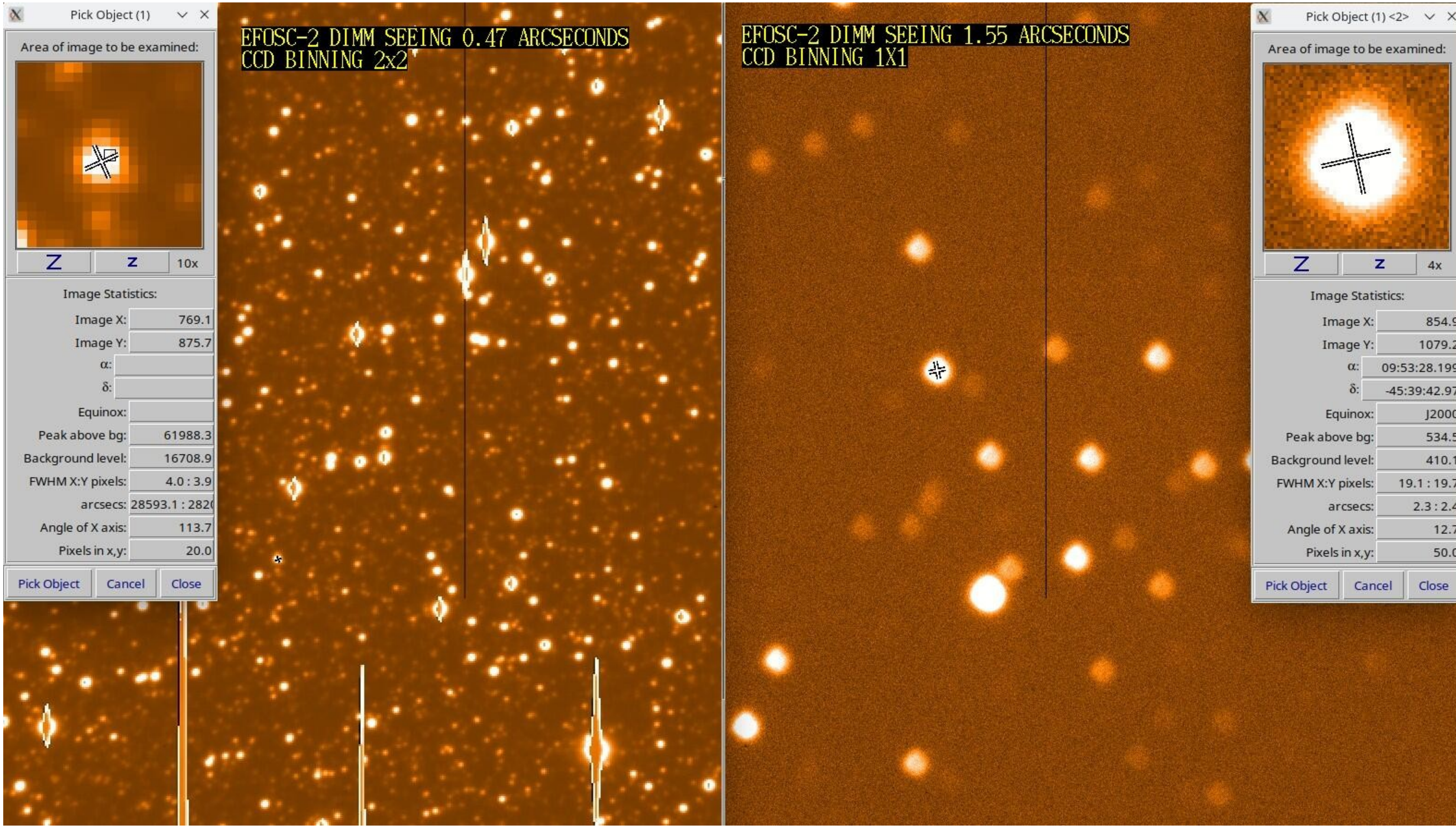


JWST



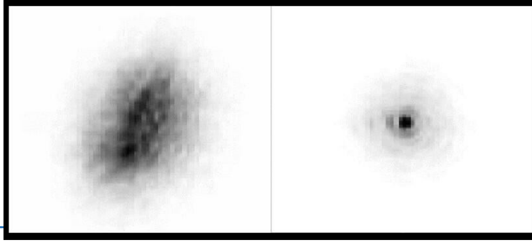


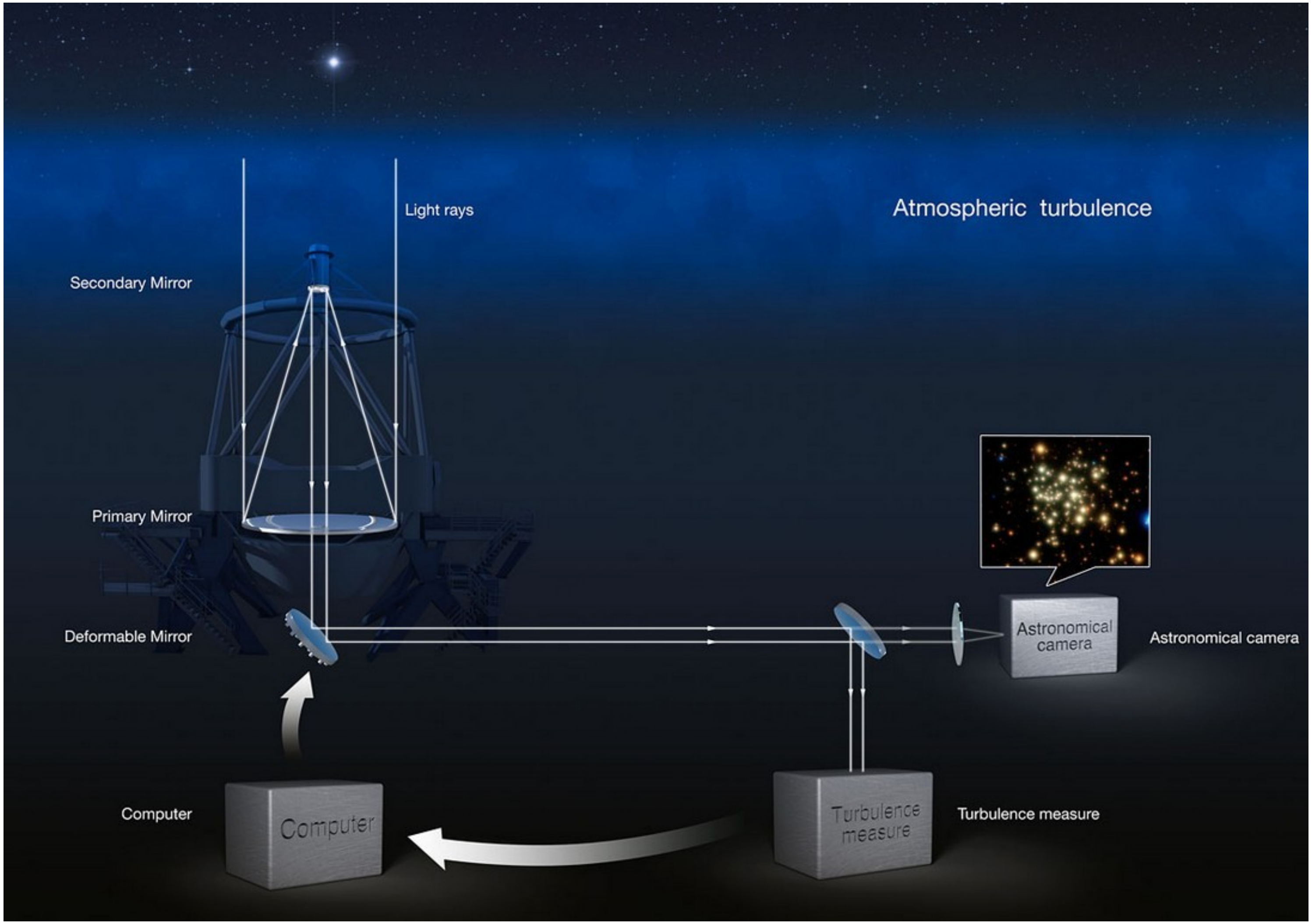
“Seeing”: Good (left) and bad (right) image quality EFOSC-2. We are at the mercy of the atmosphere!



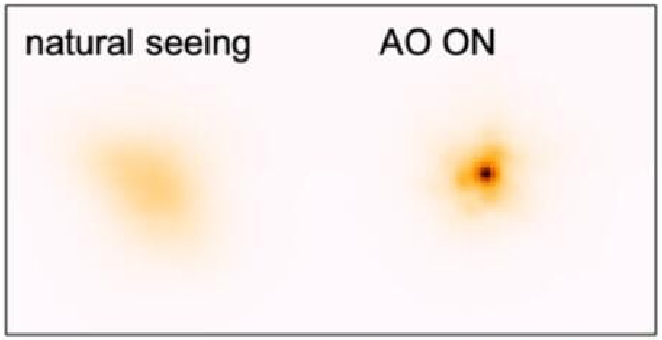
Note “IQ on a large telescope is always better than the seeing due to the finite outer scale of the turbulence” (Martinez 2010).

With adaptive optics we can drastically improve the image quality. However, only some instruments have AO.

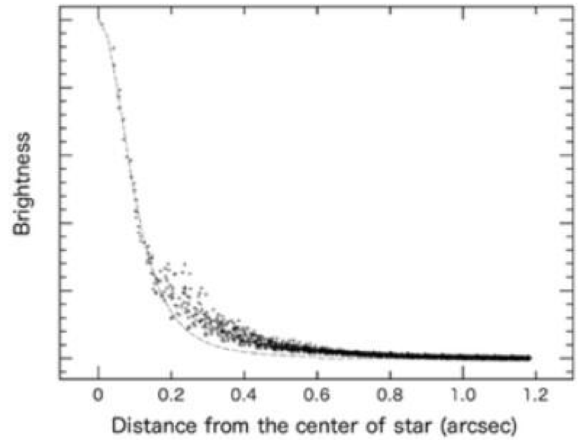


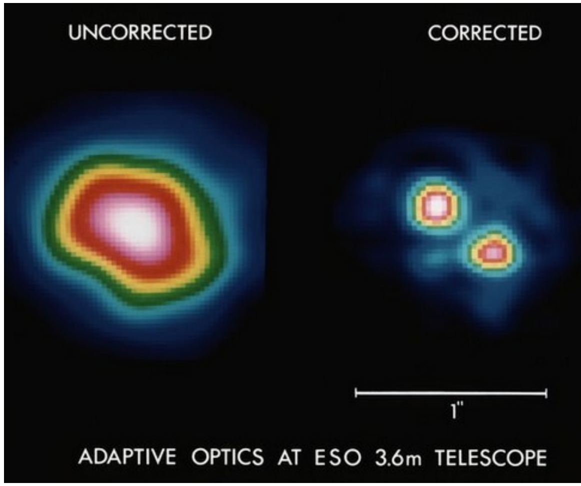


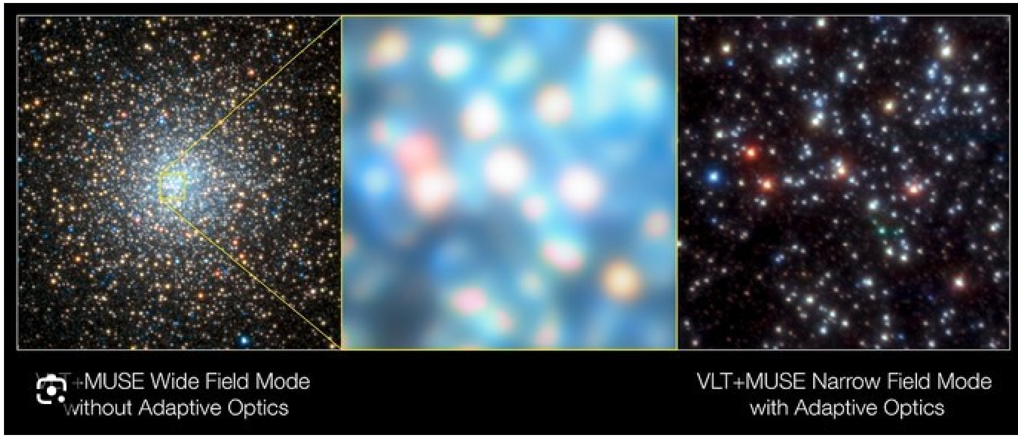
Images with and without adaptive optics (top: La Silla 1-m and 3.6-m, bottom: Paranal 8.2-m)



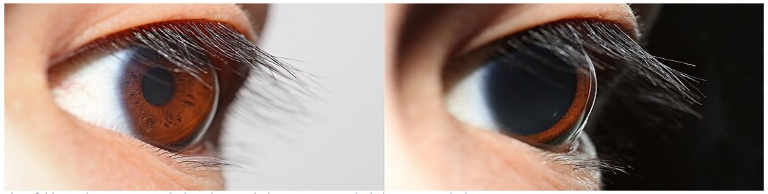
Minezaki et al. (2020) La Silla 1m tel.

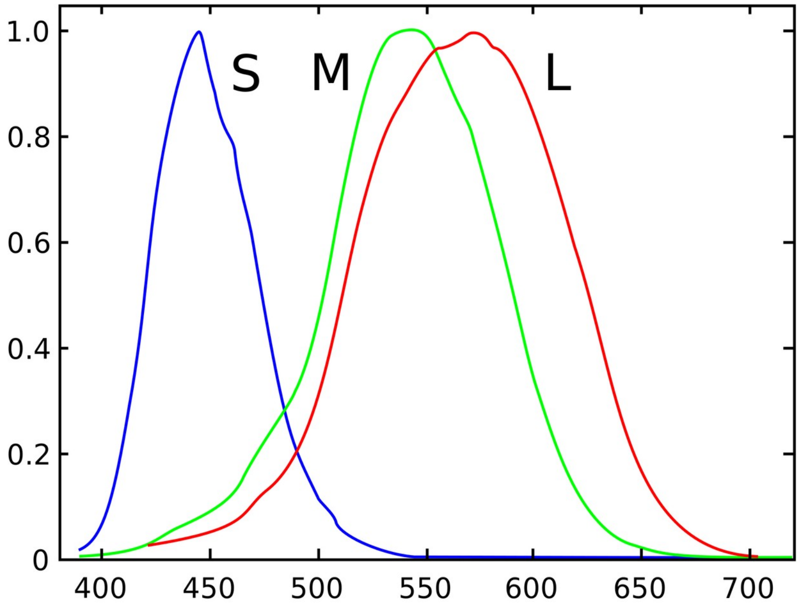


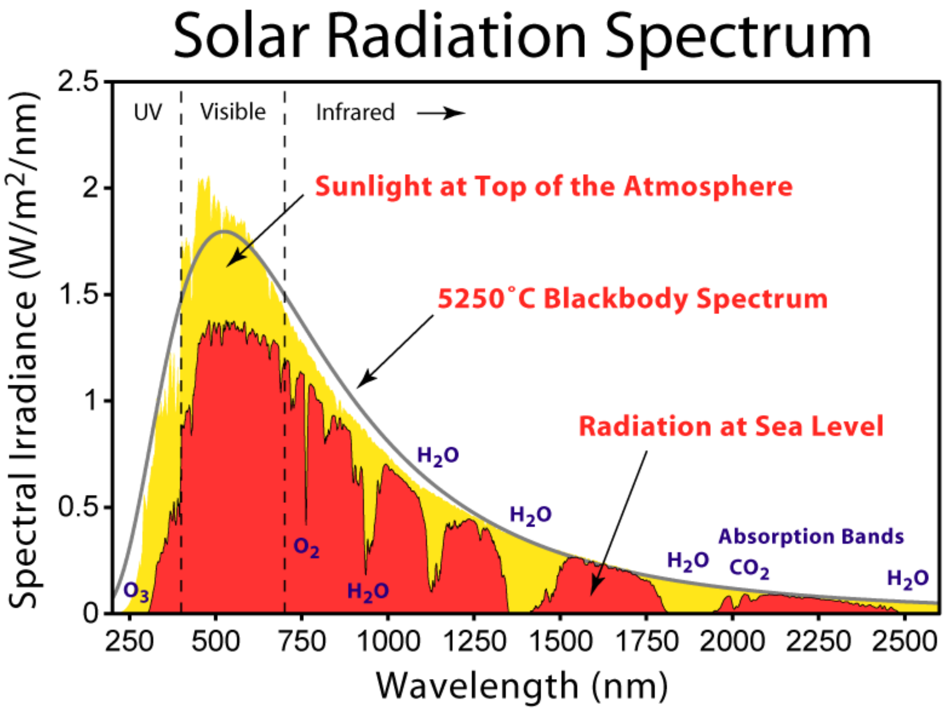




An interlude - the human eye







(V. Zekowitz)

Imaging / Photometry:

Prior to writing your proposal or to your observing run

- Check your targets are visible (!). Try and observe near to the meridian (Hour Angle = Local Siderial Time – Right Ascension = 0). **Why?**

- Decide how many **standard stars** you need to observe and at what airmass. Related to the previous point. Accuracy required?

- Decide if you should **split your exposures** (multiple exposures of the same source e.g. 3x600s instead of 1x1800s). Why? Why not?

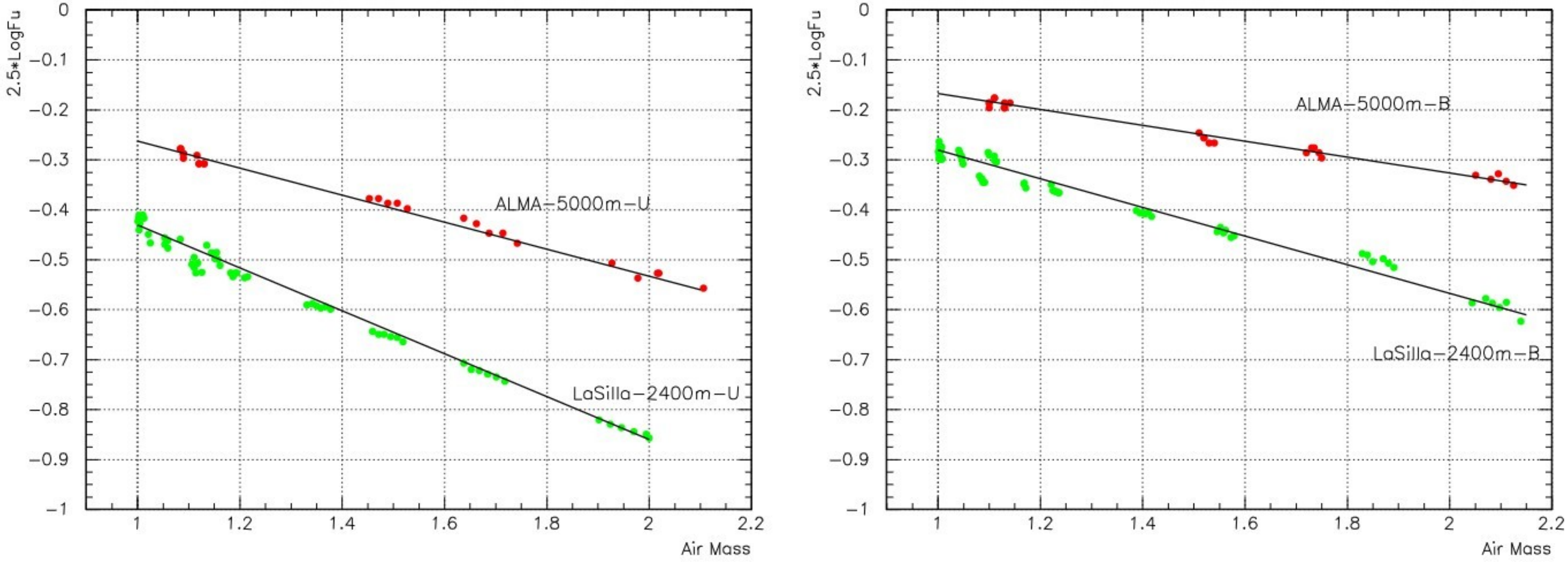
- Are chopping and/or nodding needed? Sky frames?

- Estimate the detected counts as a function of exposure time, Moon, sky conditions, airmass & seeing.

Often it is best to observe as near to the zenith as possible, especially in the bluer bands.

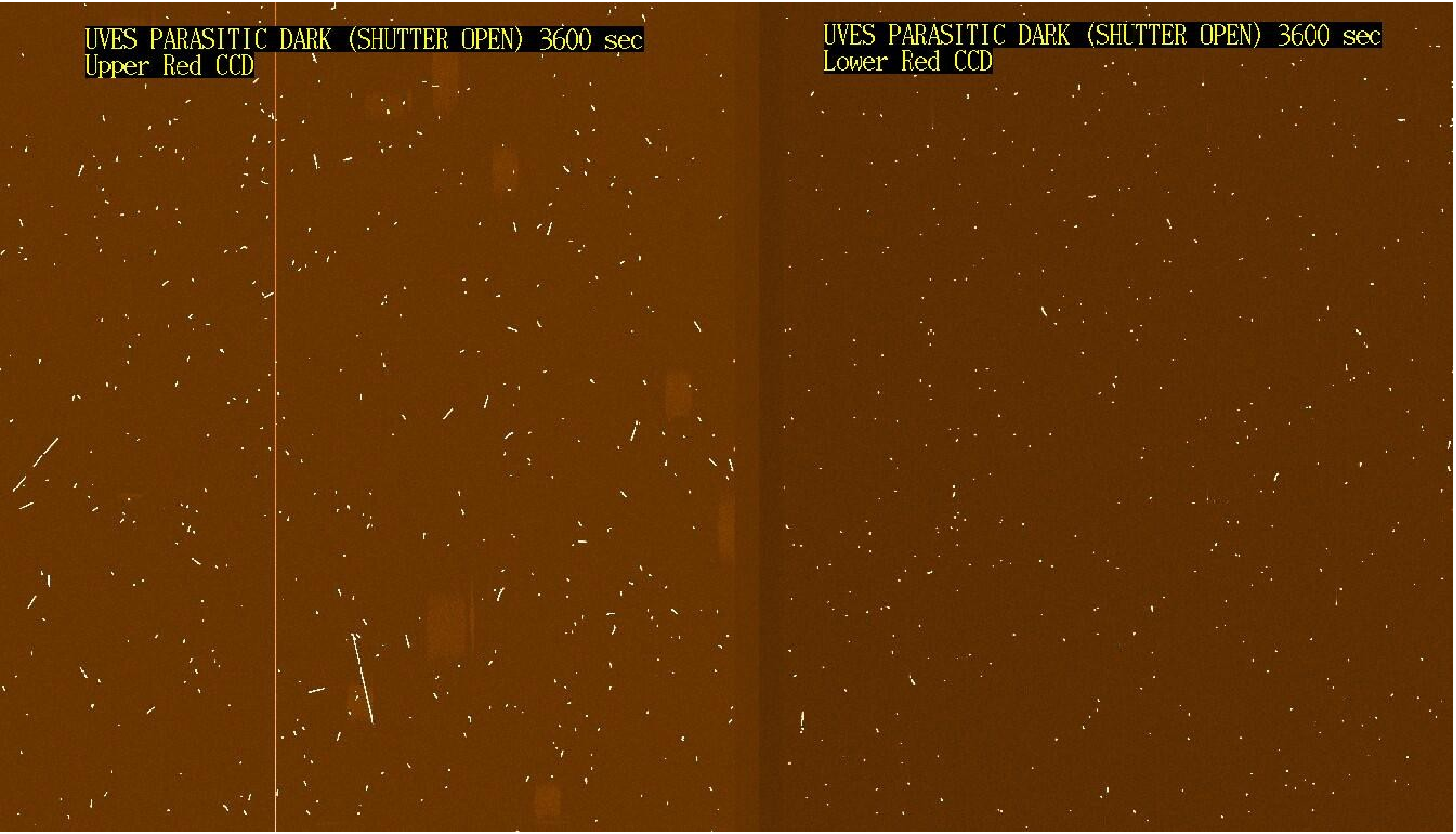
- Coefficients may change depending on the night. For very accurate photometry you might have to observe a standard star at many different airmasses over the night if observing several targets.

- On La Silla in the U-band, the apparent magnitude difference between observing at the zenith and airmass 2 is about -0.4, corresponding to a difference of 1.44 in flux (or observing time!). Seeing also gets worse at high airmass.

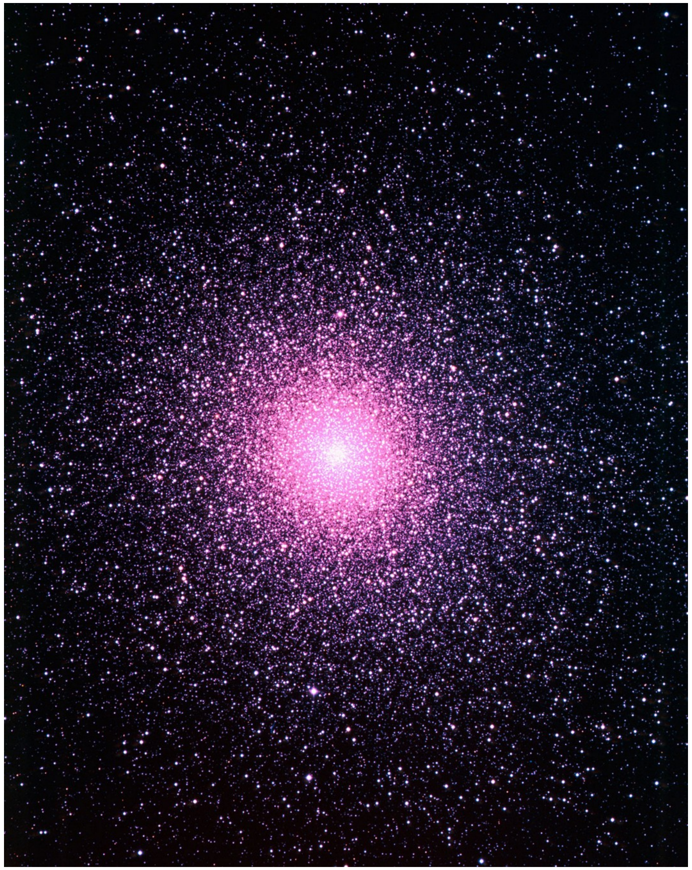


(Giraud et al.)

Why split images? UVES parasitic dark images (shutter open) showing cosmic rays and something else



Are sky frames needed? (Optical)



47-Tuc image taken with La Silla 1.0-m Schmidt telescope

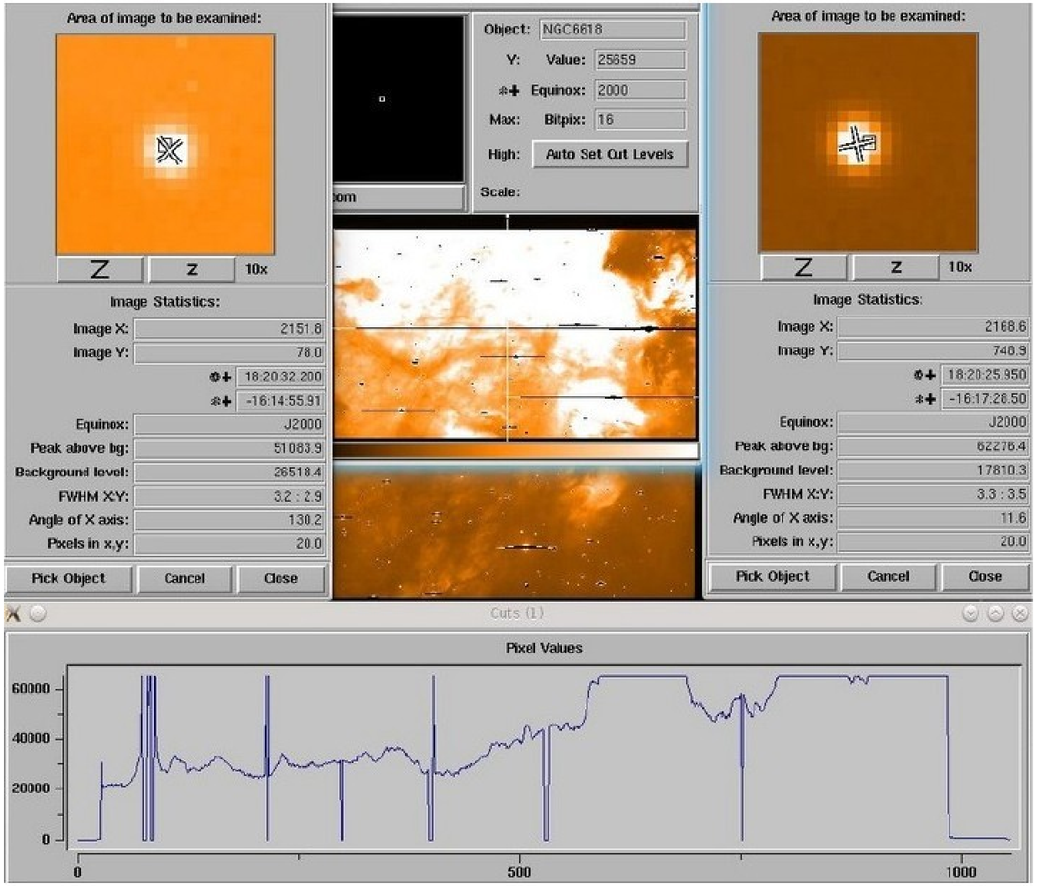
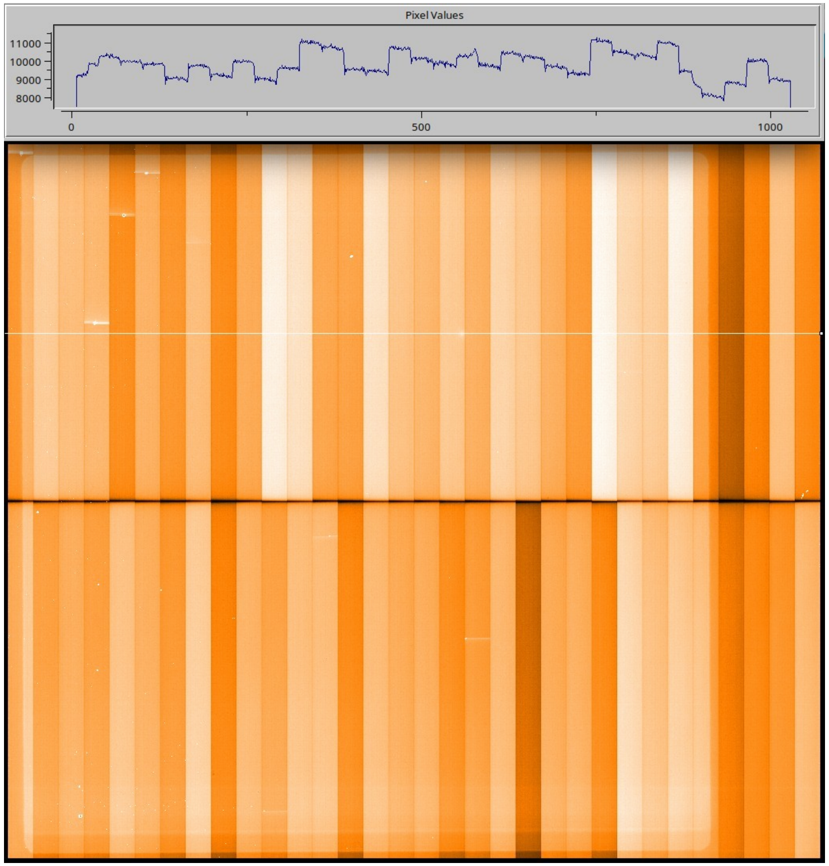
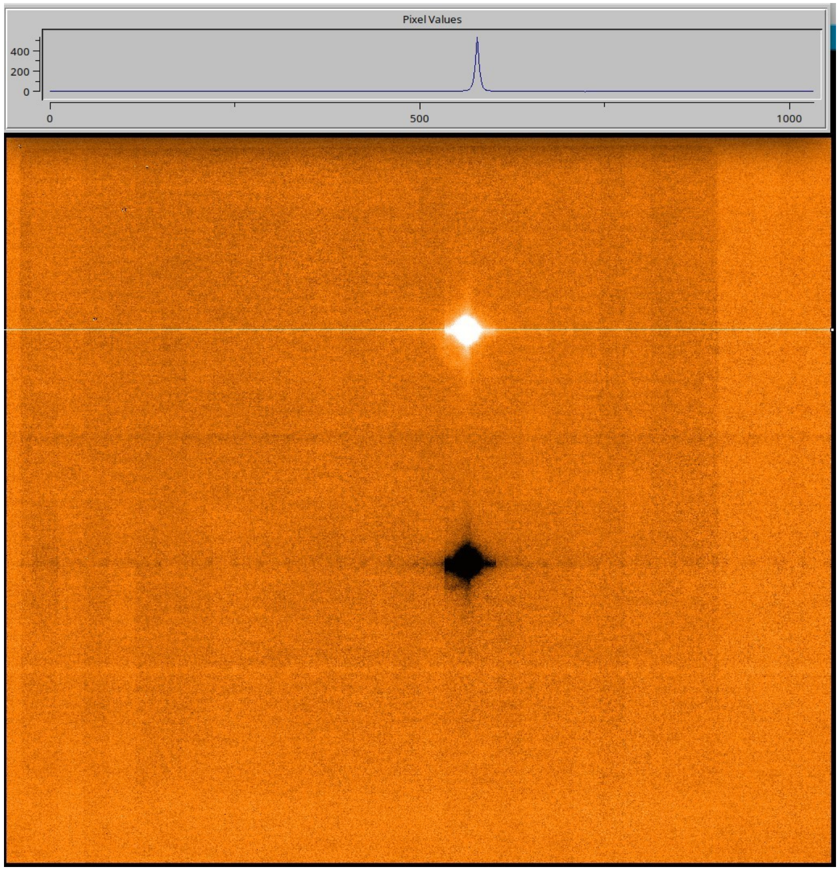


Image of a nebula taken with the FORS2 instrument

Are sky frames needed? Nearly always in the far infrared (> 5 microns) as the sky level is so high. VISIR image below of mK=2 star with DIT=0.01 seconds!

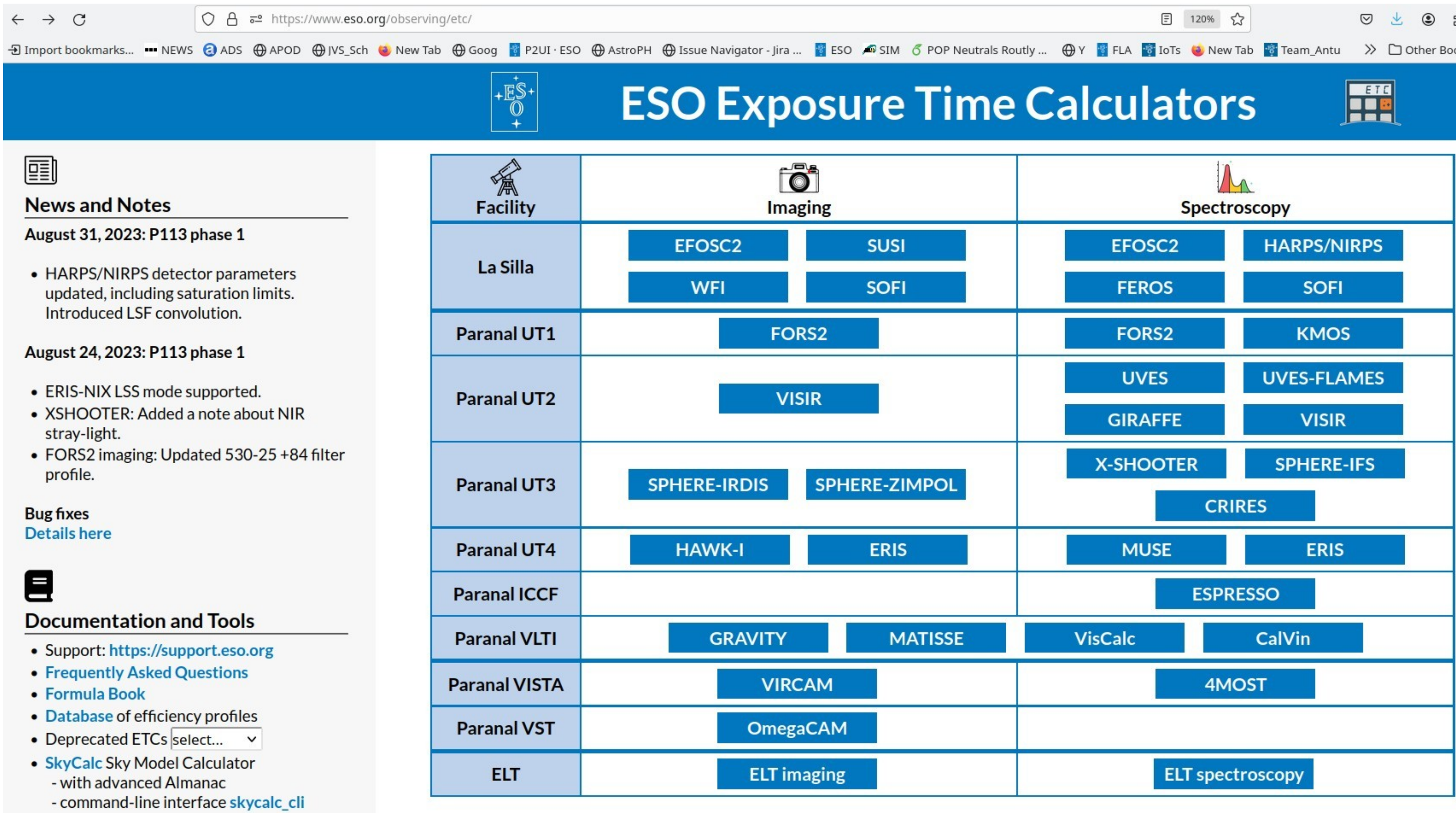


Individual VISIR M-band image. Star only just visible as sky level is so high.



Combined VISIR M-band image with multiple chopping positions subtracted.

Estimate the expected counts, for example using the ESO exposure time calculators (ETCs): https://www.eso.org/observing/etc



https://www.eso.org/observing/etc/

Import bookmarks... NEWS ADS APOD JVS_Sch New Tab Goog P2UI · ESO AstroPH Issue Navigator - Jira ... ESO SIM POP Neutrals Routly ... Y FLA IoTs New Tab Team_Antu Other Book

ESO Exposure Time Calculators

News and Notes

August 31, 2023: P113 phase 1

- HARPS/NIRPS detector parameters updated, including saturation limits. Introduced LSF convolution.

August 24, 2023: P113 phase 1

- ERIS-NIX LSS mode supported.
- XSHOOTER: Added a note about NIR stray-light.
- FORS2 imaging: Updated 530-25 +84 filter profile.

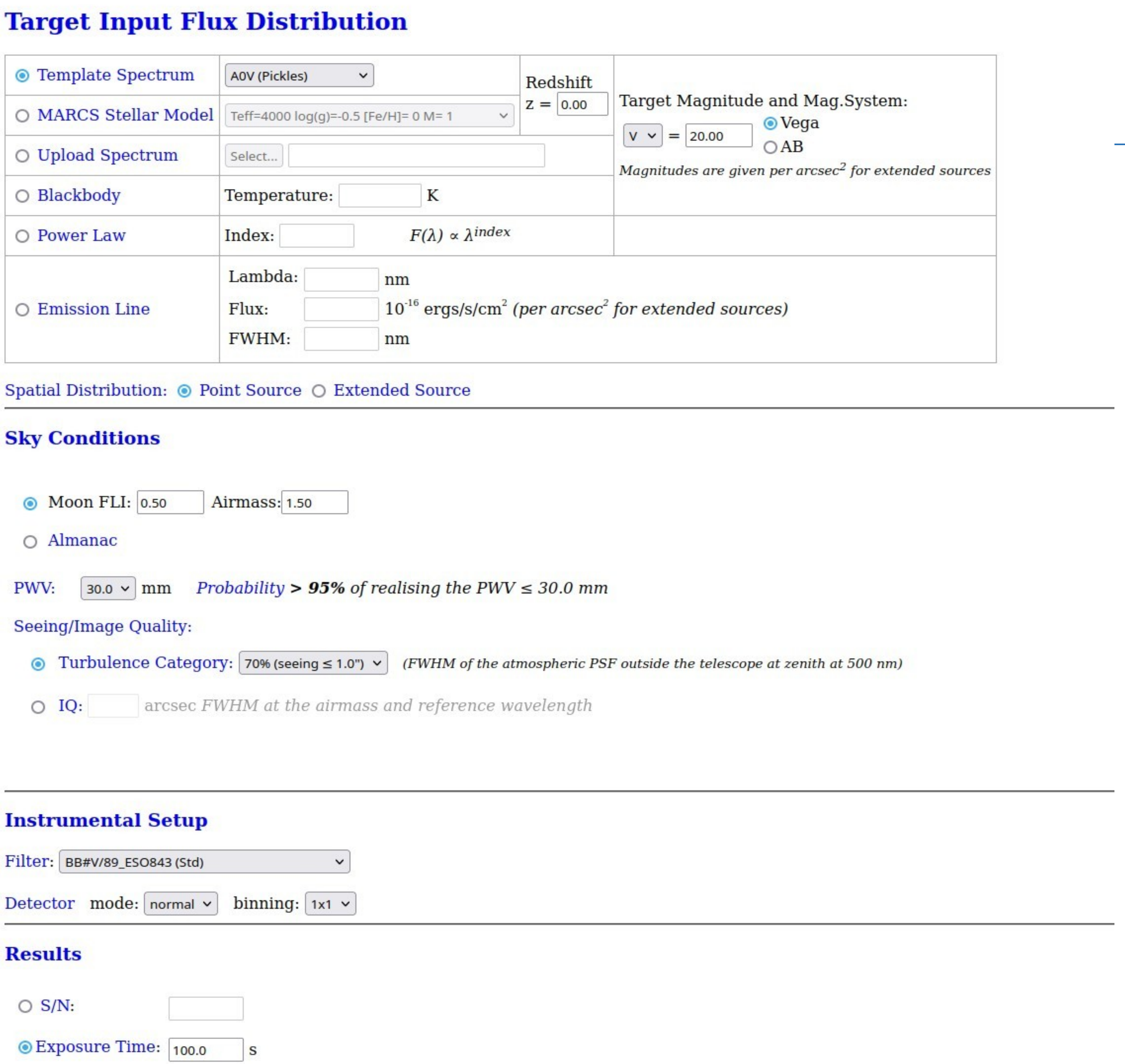
Bug fixes
Details here

Documentation and Tools

- Support: https://support.eso.org
- Frequently Asked Questions
- Formula Book
- Database of efficiency profiles
- Deprecated ETCs select...
- SkyCalc Sky Model Calculator
  - with advanced Almanac
  - command-line interface skycalc_cli

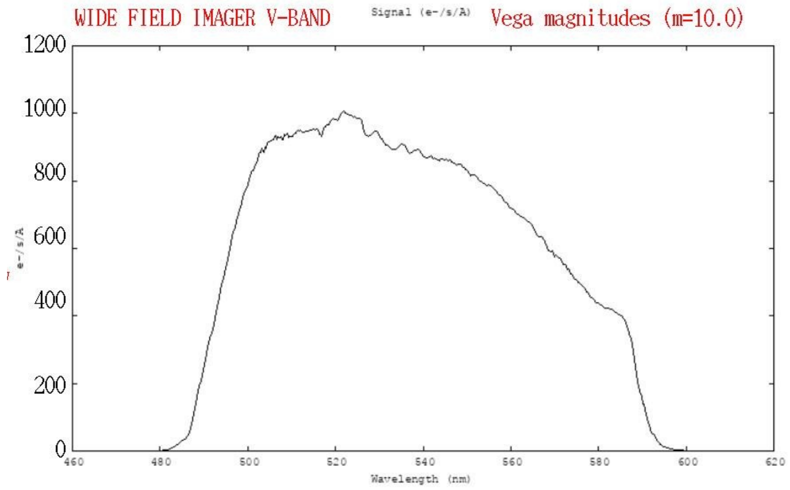
Facility	Imaging	Spectroscopy
La Silla	EFOSC2, SUSI, WFI, SOFI	EFOSC2, HARPS/NIRPS, FEROS, SOFI
Paranal UT1	FORS2	FORS2, KMOS
Paranal UT2	VISIR	UVES, UVES-FLAMES, GIRAFFE, VISIR
Paranal UT3	SPHERE-IRDIS, SPHERE-ZIMPOL	X-SHOOTER, SPHERE-IFS, CRIRES
Paranal UT4	HAWK-I, ERIS	MUSE, ERIS
Paranal ICCF		ESPRESSO
Paranal VLTI	GRAVITY, MATISSE	VisCalc, CalVin
Paranal VISTA	VIRCAM	4MOST
Paranal VST	OmegaCAM	
ELT	ELT imaging	ELT spectroscopy

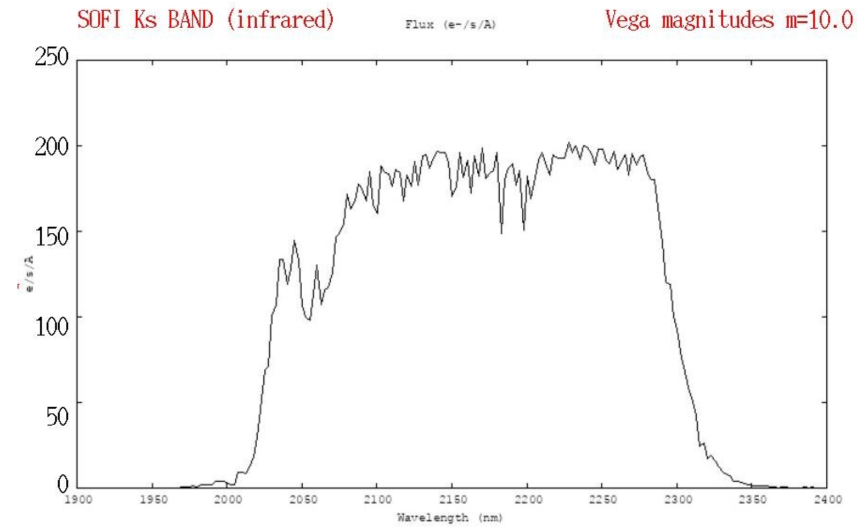
Wide field imager ETC

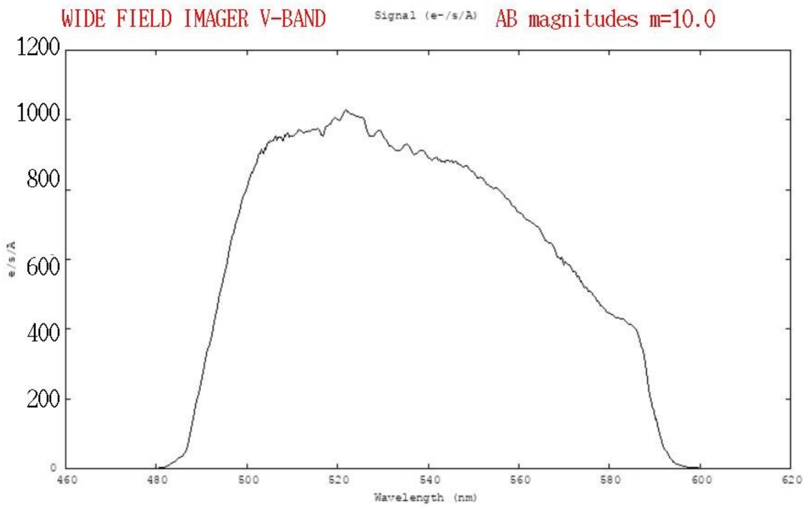


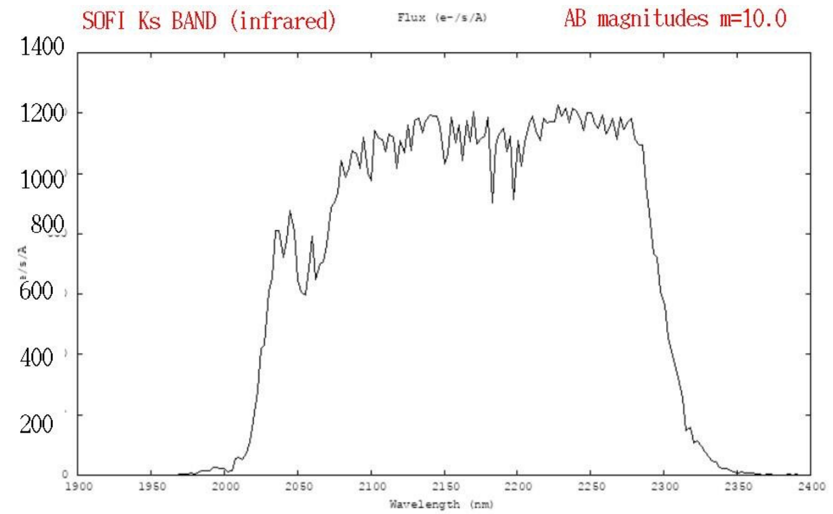
ESOs exposure time calculators basically use the CCD equation plus a sky model.

Expected counts in the optical (left) and infrared (right) using Vega magnitudes (top) and AB mags (bottom)

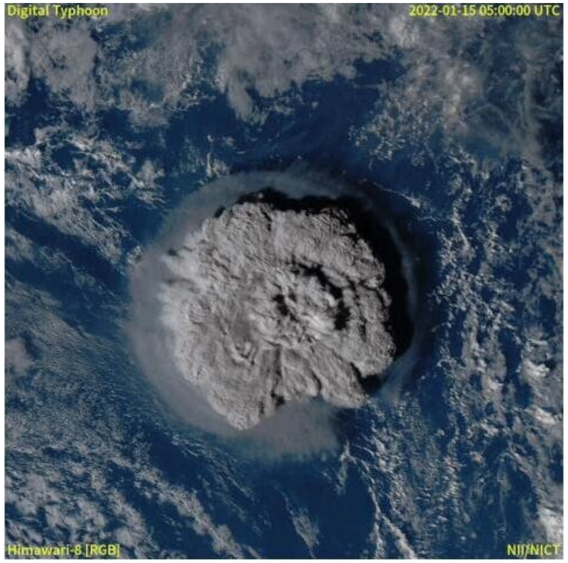


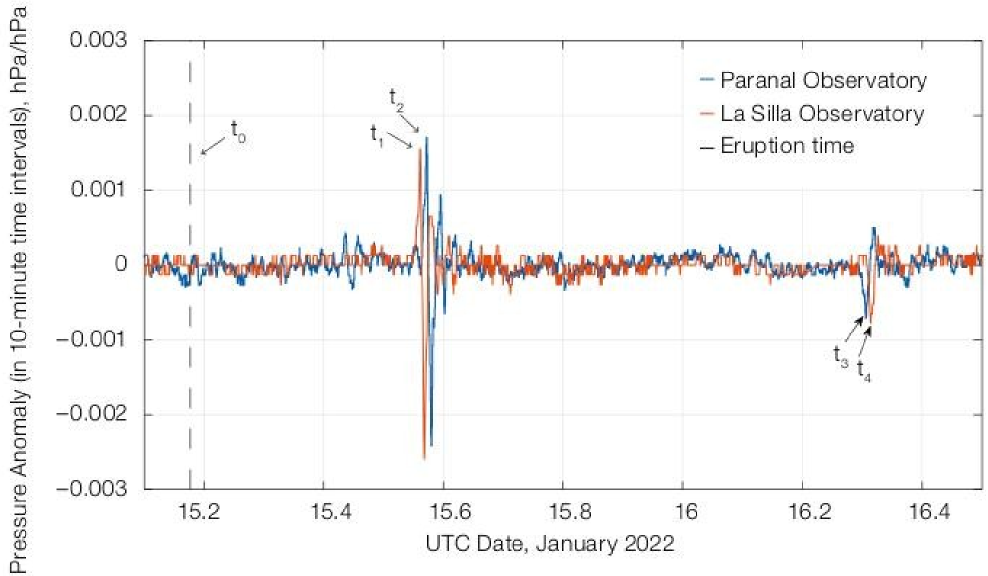


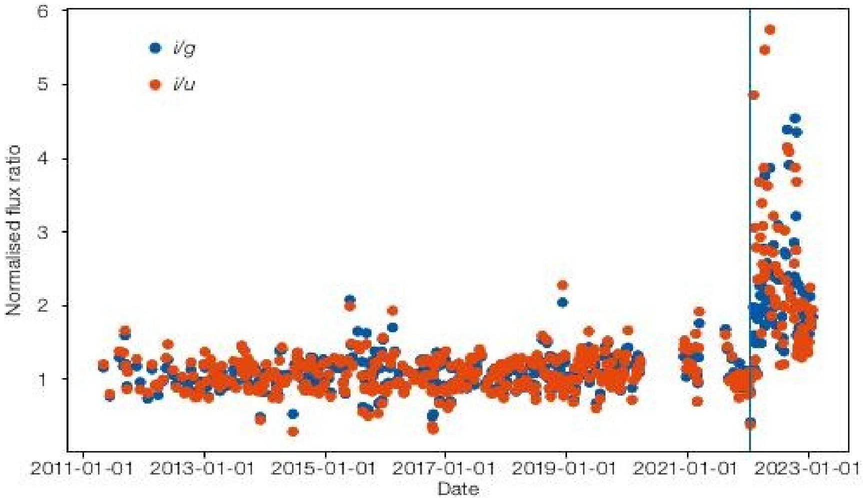




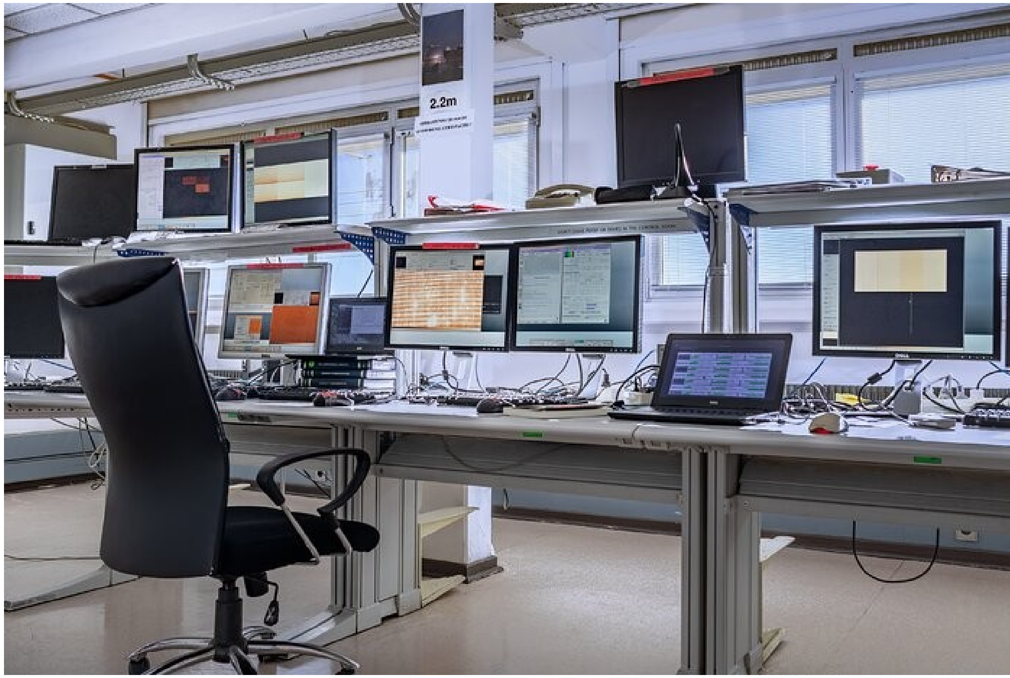
An interlude: Effects of the Hunga-Tonga Volcanic eruption on observations at La Silla and Paranal

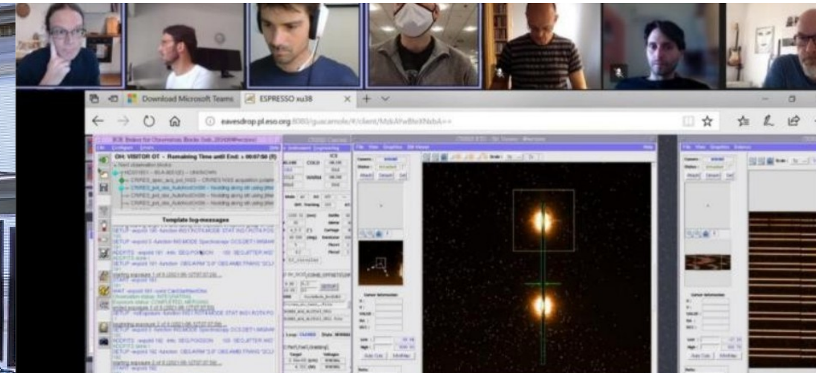




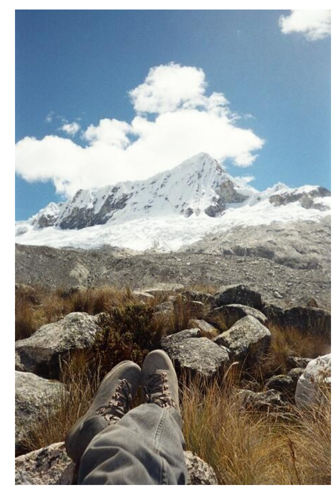


You take your observations….





..or remotely...



Either in person….

Then back home to finish reducing your data!

Interlude – whats the largest desert in the world?

The Atacama?

The Sahara?

The Gobi?

(credit: Doron)

Somewhere else?

Interlude – whats the largest desert in the world?

We have our data! Steps in the calibration / reduction of imaging observations

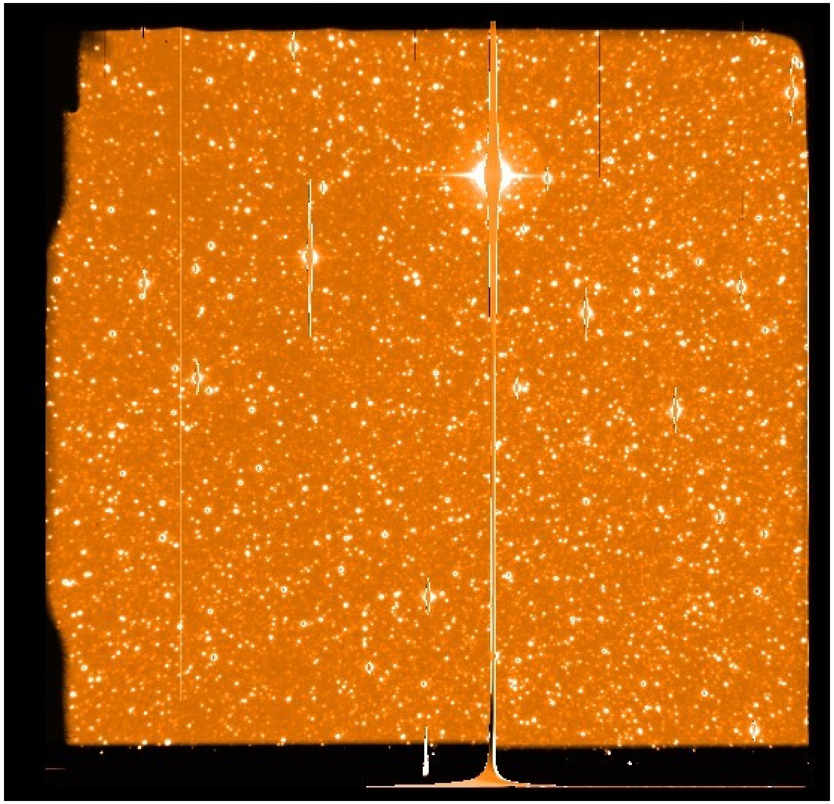
Depending on the detector used, calibration of imaging observations uses some or all of the following steps:

- **Look at your images (both calibration and science)!**
- Bias and dark subtraction
- Non linearity correction
- Flatfielding
- Fringe removal
- Subtraction of sky image (especially in the infrared)
- Correction of persistance
- Cosmic ray removal
- Illumination correction
- Correction for airmass

There is a lot of information available in FITS headers (200+ lines in this case for EFOSC)

FITS headers often have information such as ambient conditions, instrument state, airmass etc etc etc.

These headers are often read by data reduction pipelines.



dfits EFOSC.2007-07-02T05:33:34.709.fits | fitsort ra dec tel.ambi.temp exptime ins.filt1.name tel.ambi.fwhm.start

FILE	RA	DEC	TEL.AMBI.TEMP	EXPTIME	INS.FILT1.NAME	FWHM.START
EFOSC.2007-07-02T05:33:34.709.fits	262.157304	-29.15728	15.90	300.0005	R#642	0.48

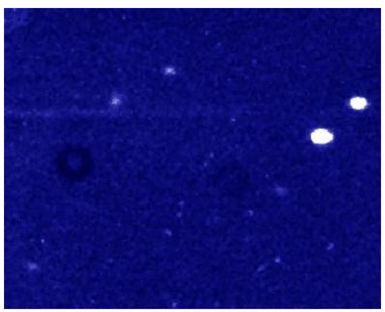
First, visually inspect your data and calibrations

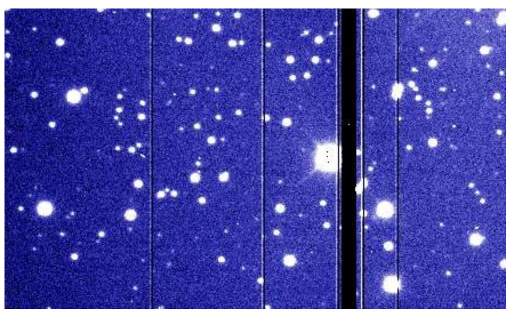
See: https://www.eso.org/~ohainaut/ccd/CCD_artifacts.html

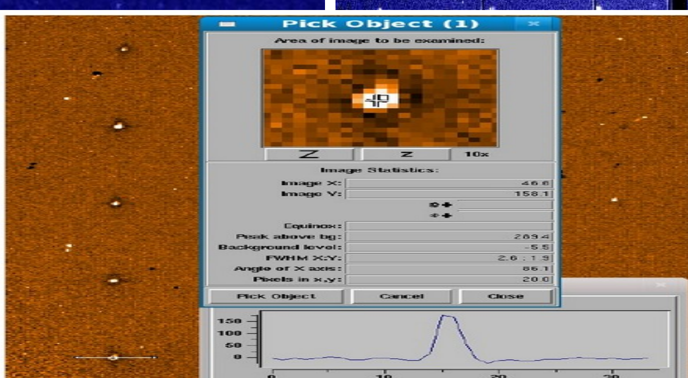
If you are using a data reduction pipeline, rubbish in → rubbish out

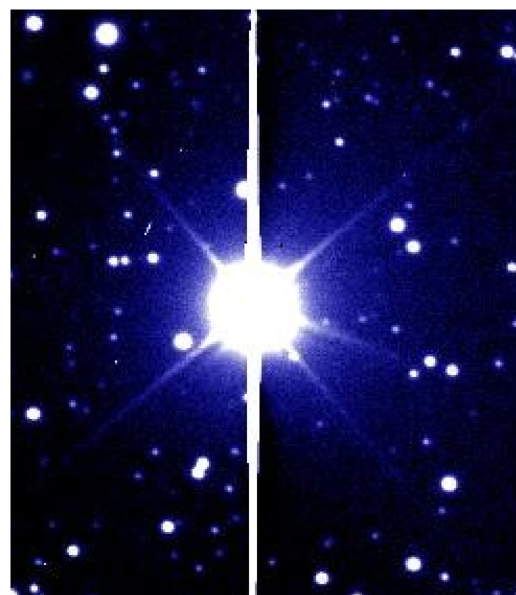
Things to check:

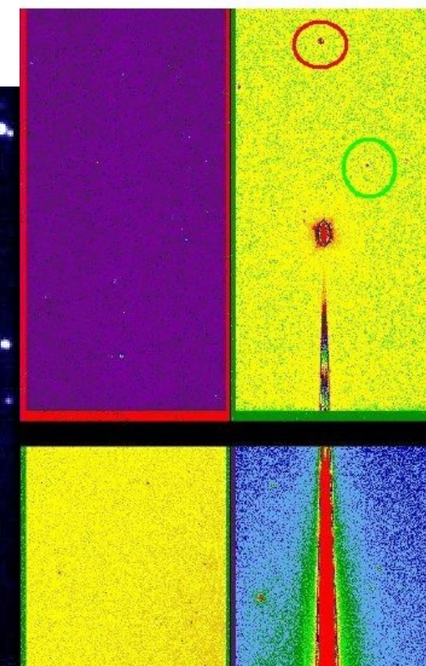
- Vignetting (dome not tracking with telescope, wrong component in light path)
- Features caused by condensation on the dewer entrance window. Bad columns.
- Stray light (nearby bright planet when you observed)
- Saturation trails & diffraction spikes, satellite trails or lasers
- Persistance due to previous observaions of bright objects. Dust on filters etc etc etc



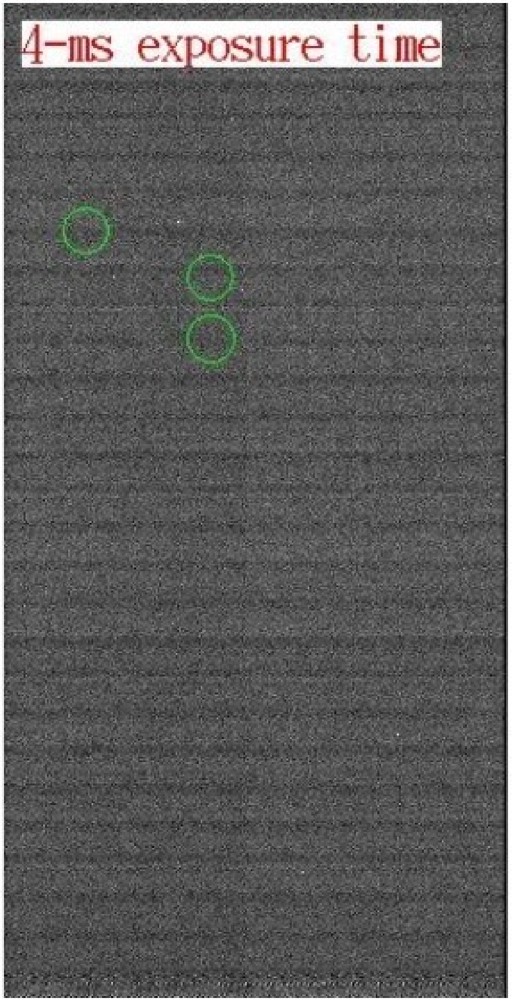


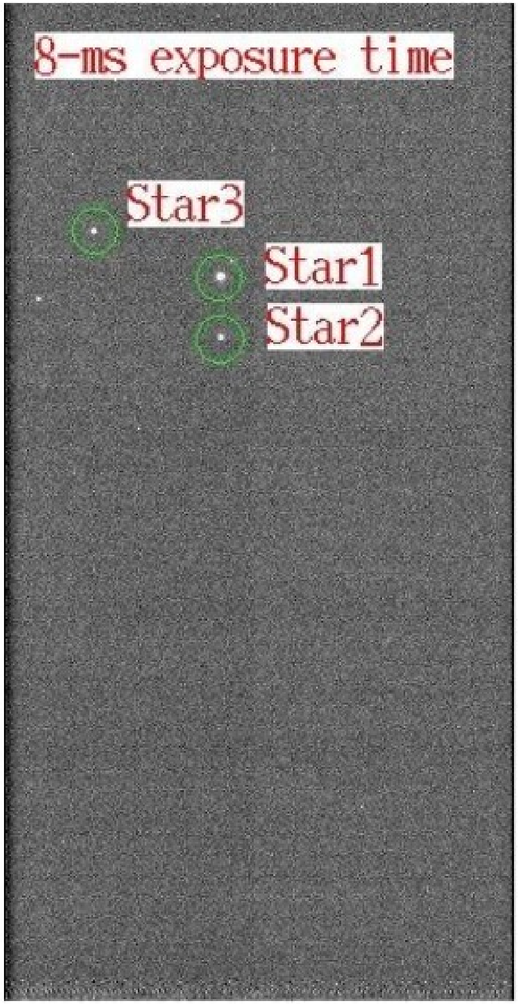






Visually check data: Instrument and camera shutters have a non-infinite speed! (OmegaCAM)





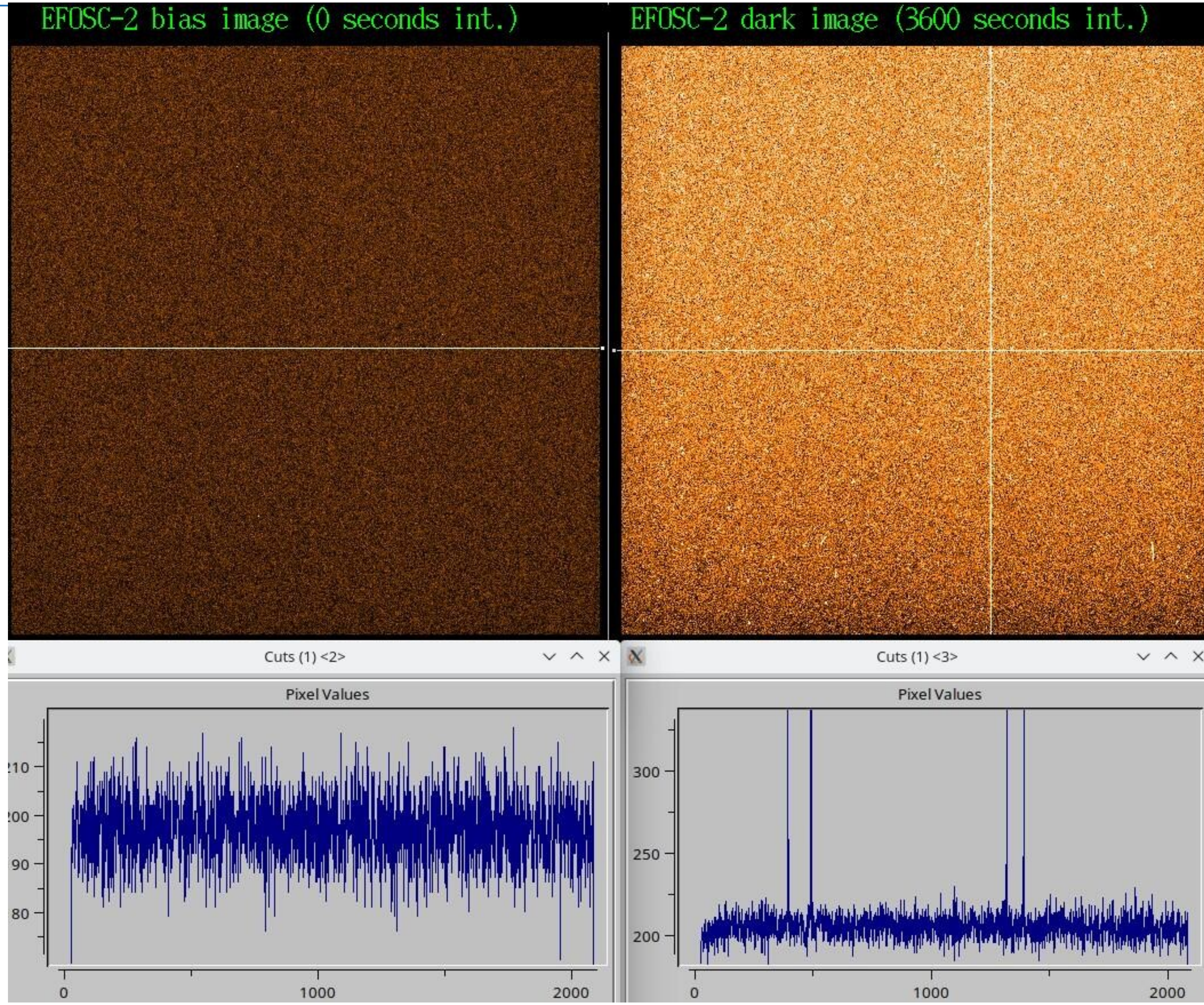
The general point is if you are taking data close to the performance limit of an instrument you have to be on the lookout for unforeseen effects.

Bias and dark removal: EFOSC-2 bias and darks

Left image: EFOSC-2 bias frame (exposure time 0-s) with horizontal cut of counts.

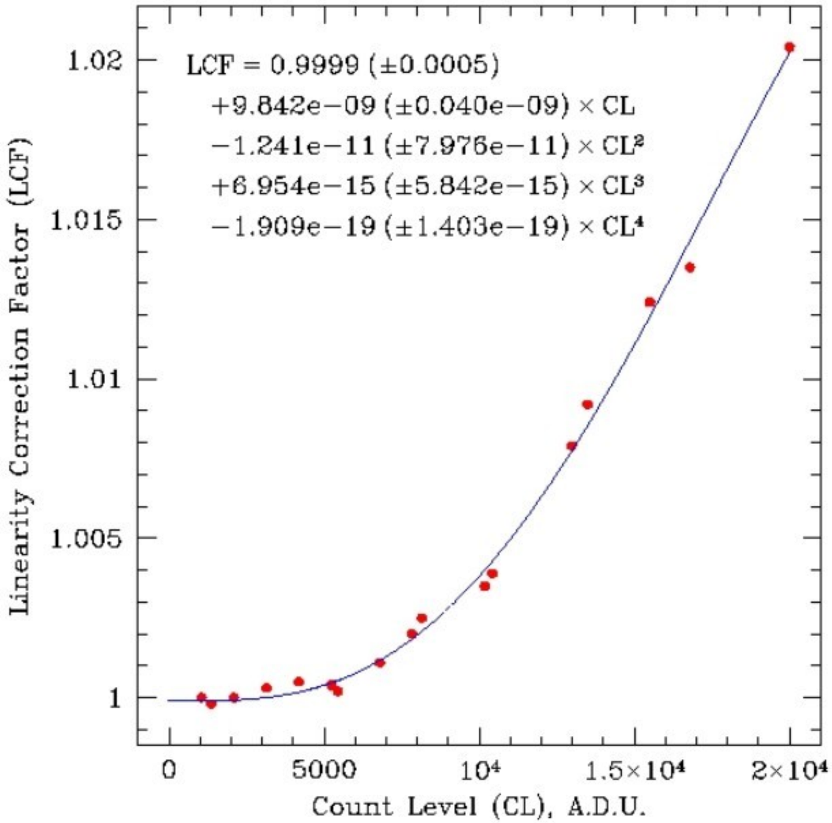
Right image: EFOSC-2 dark frame (3600-s integration time) with horizontal cut of counts.

Normally you average or median many bias or dark frames before subtracting from science / calibs



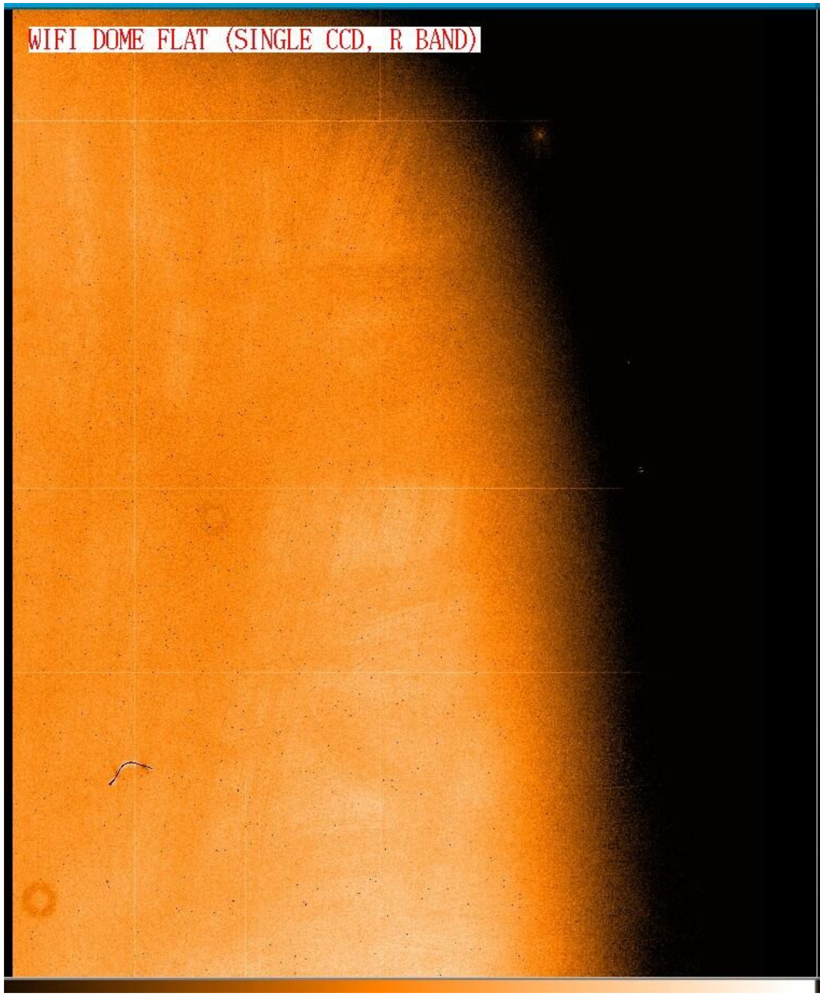
Detector responses are not linear – SOFI non linearity curve. You may need to correct for this.

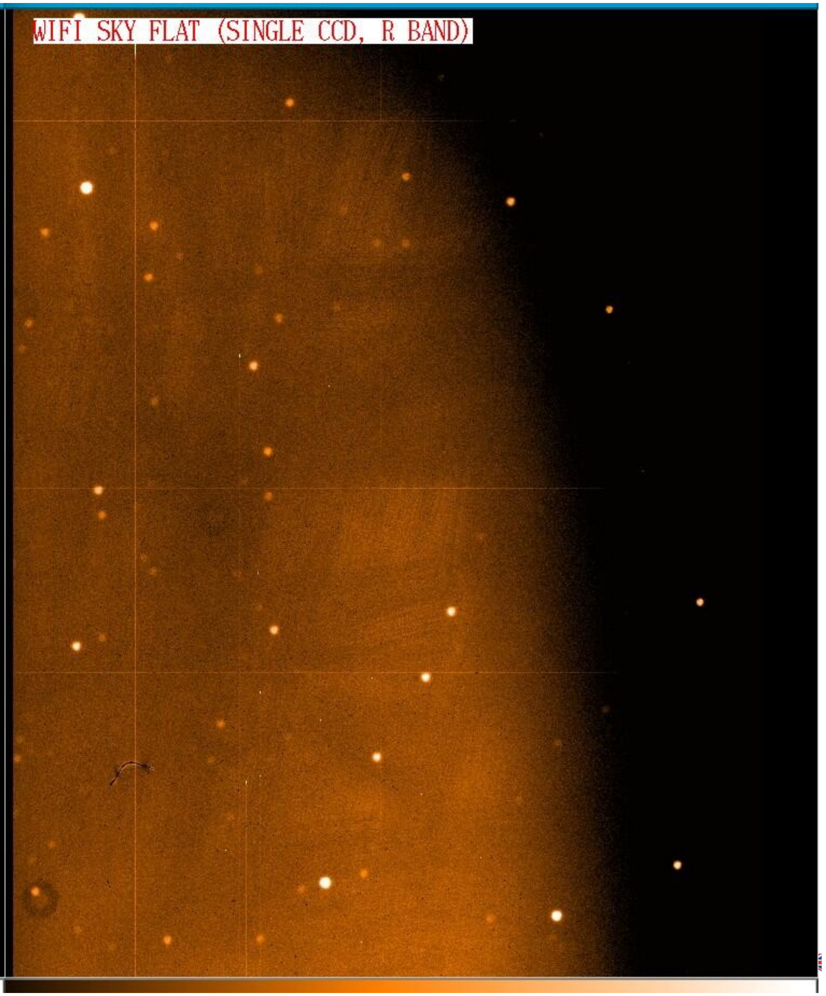
As you get closer and closer to the saturation limit of the detector, the same number of input photons produce fewer output electrons. This effect has to be corrected, ideally on a pixel-to-pixel basis. Often there will be a static calibration file to do this as part of a pipeline release.



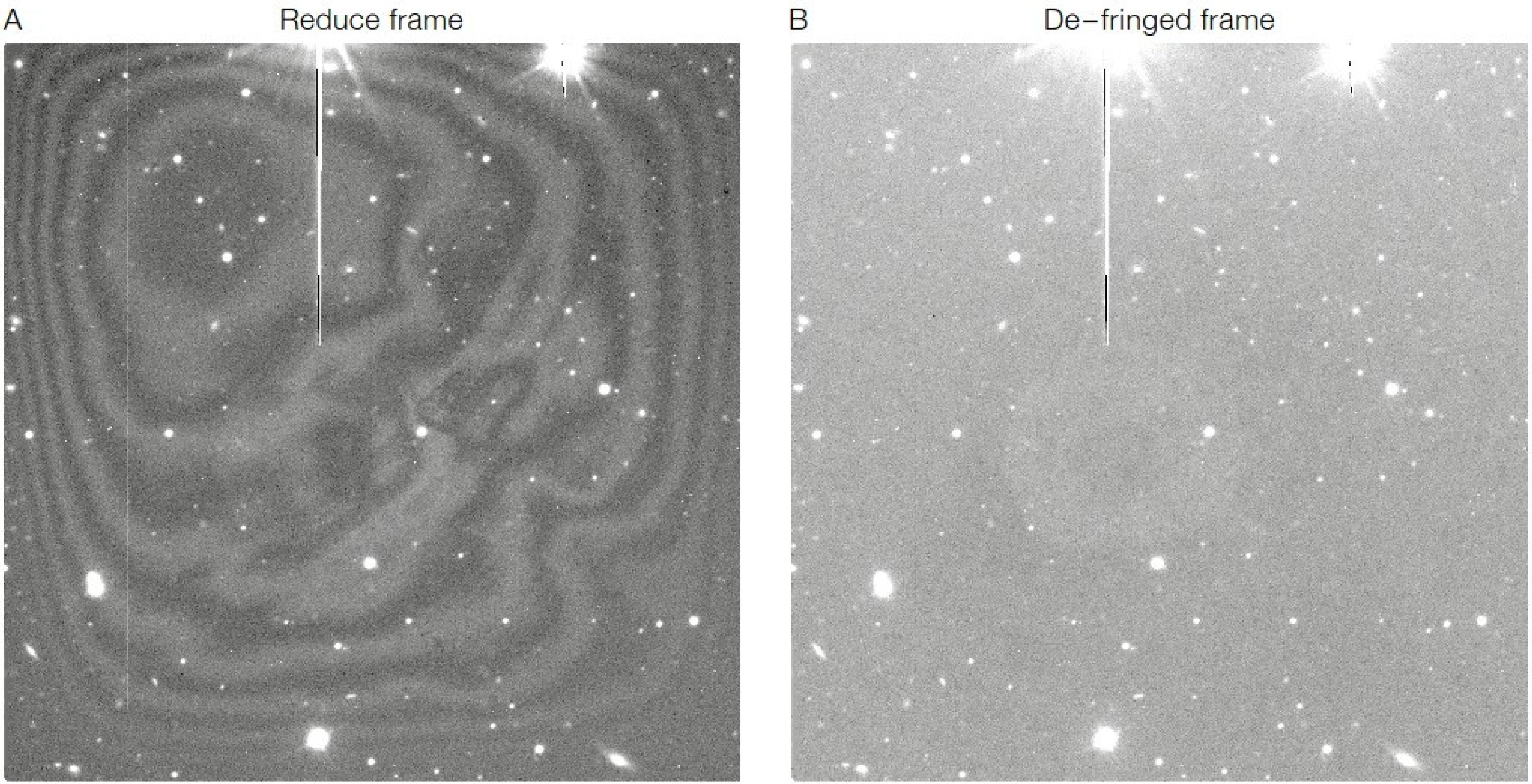
Flatfielding: WIFI dome and sky flatfield images

- Median filter jittered sky flats to get rid of stellar features
- Divide data by normalised flats to reduce pixel-to-pixel variations
- Both dome and sky flats have their advantages and disadvantages



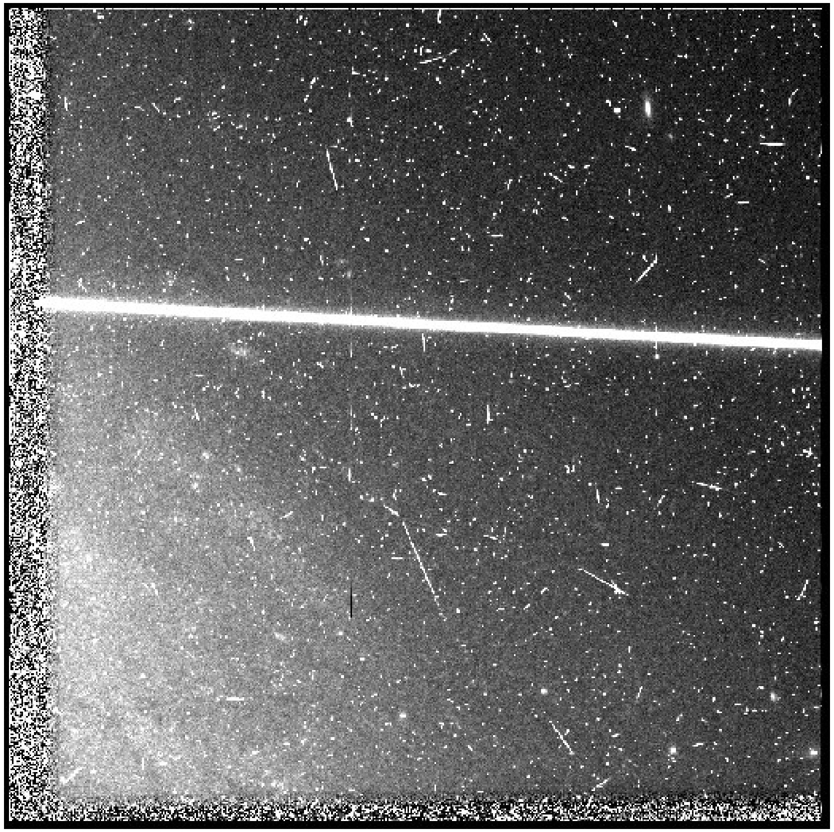


Fringes: Effects of fringing on EFOSC-2 images (La Silla) and their removal



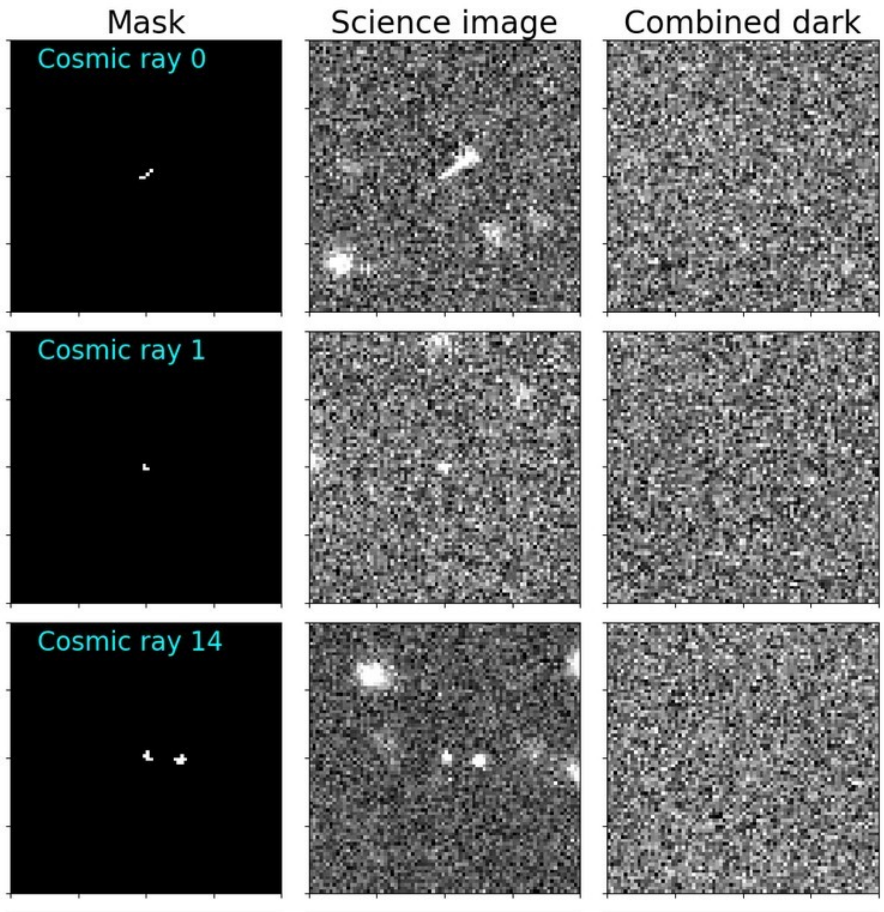
EFOSC-2 image (left) and de-fringed frame (Snodgrass & Carry 2013)

Cosmic rays: removal by taking the median of several images. Needs two or more images.



(Michael Richmond http://spiff.rit.edu/classes/phys445/lectures/median/median.html)

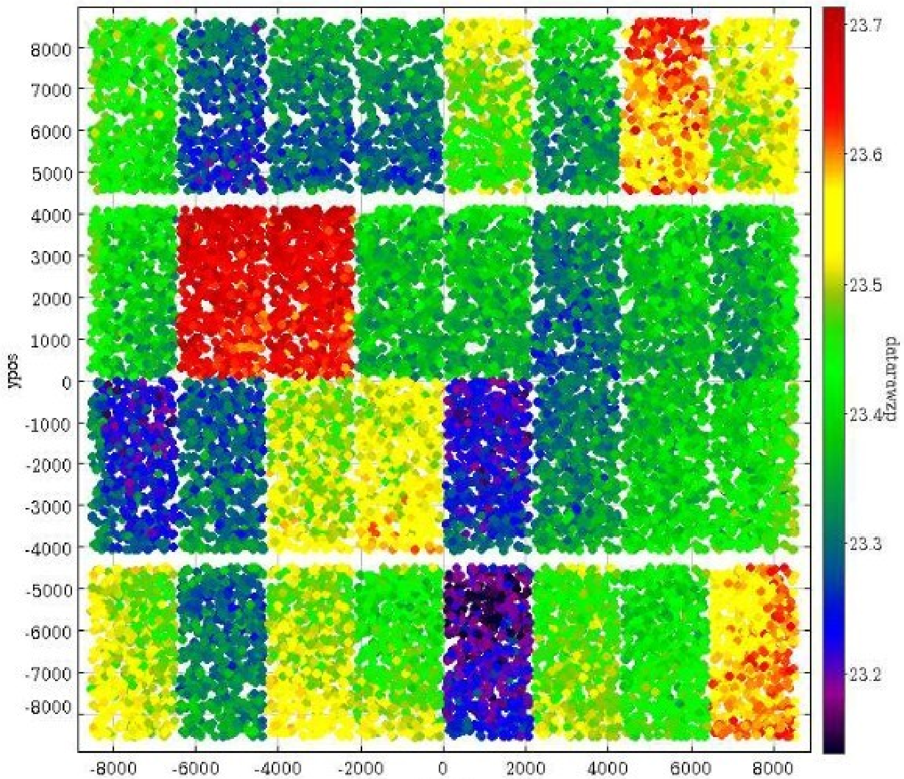
Cosmic rays: detection by sigma clipping. Then mask the affected region or interpolate using nearby pixels.

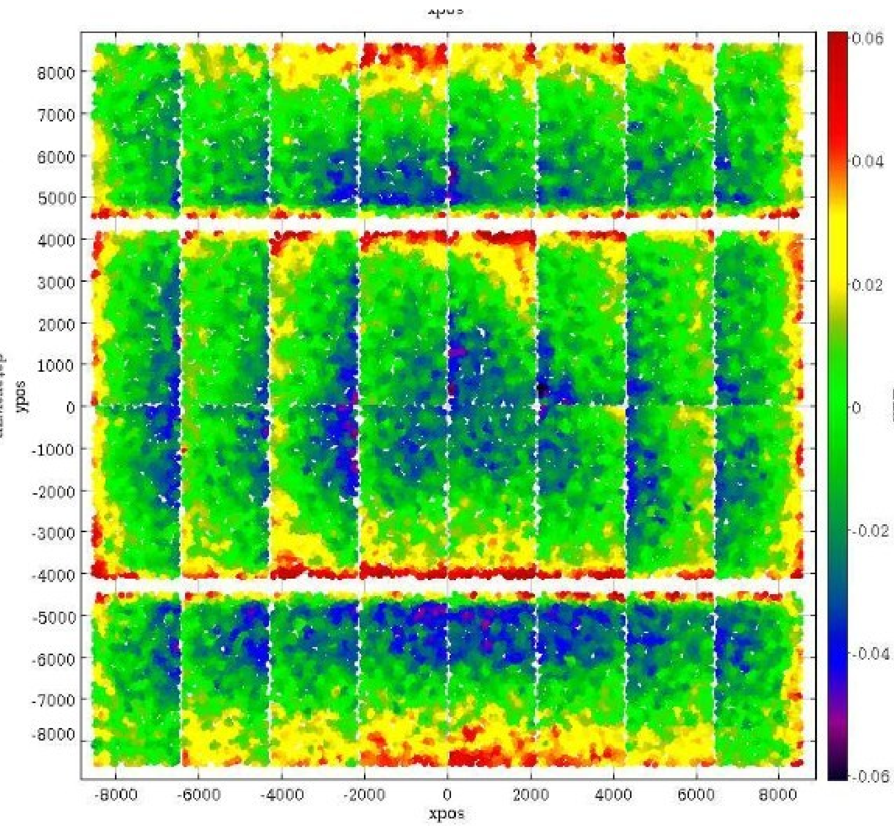


(AstroPy LACosmic: https://www.astropy.org/ccd-reduction-and-photometry-guide/v/dev/notebooks/08-03-Cosmic-ray-removal.html)

Illumination correction – not all parts of the focal plane have the same response!

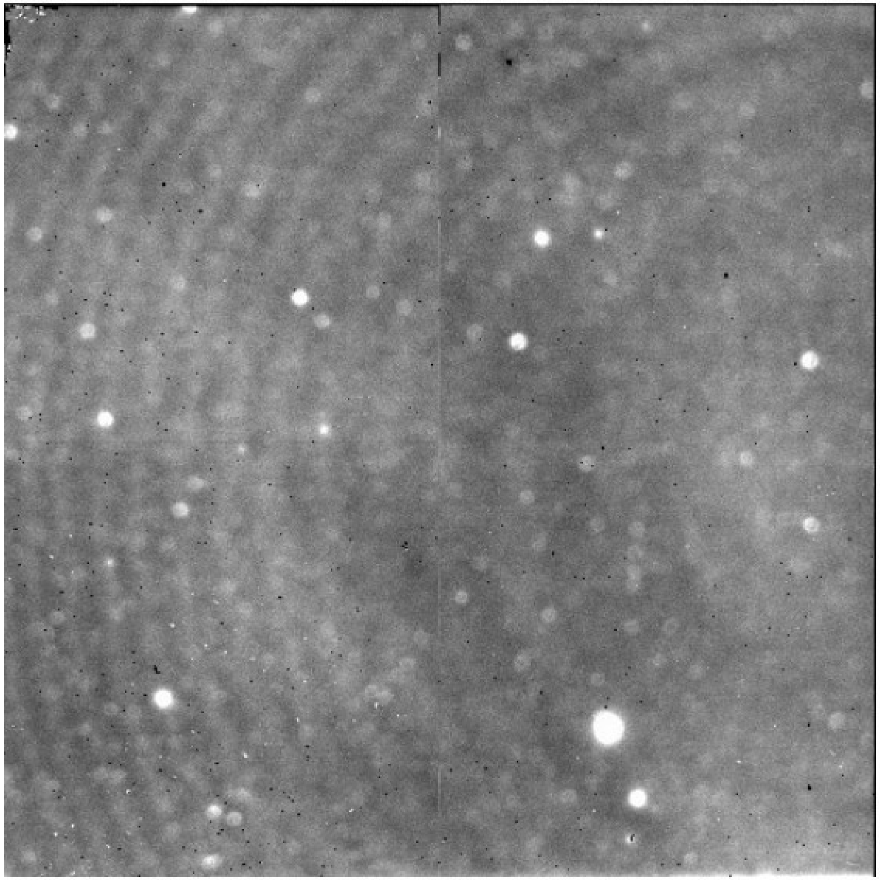
The illumination correction map is derived from observations of the same star (or stars) with a jitter pattern covering the entire array and measuring the stellar magnitude at each position.

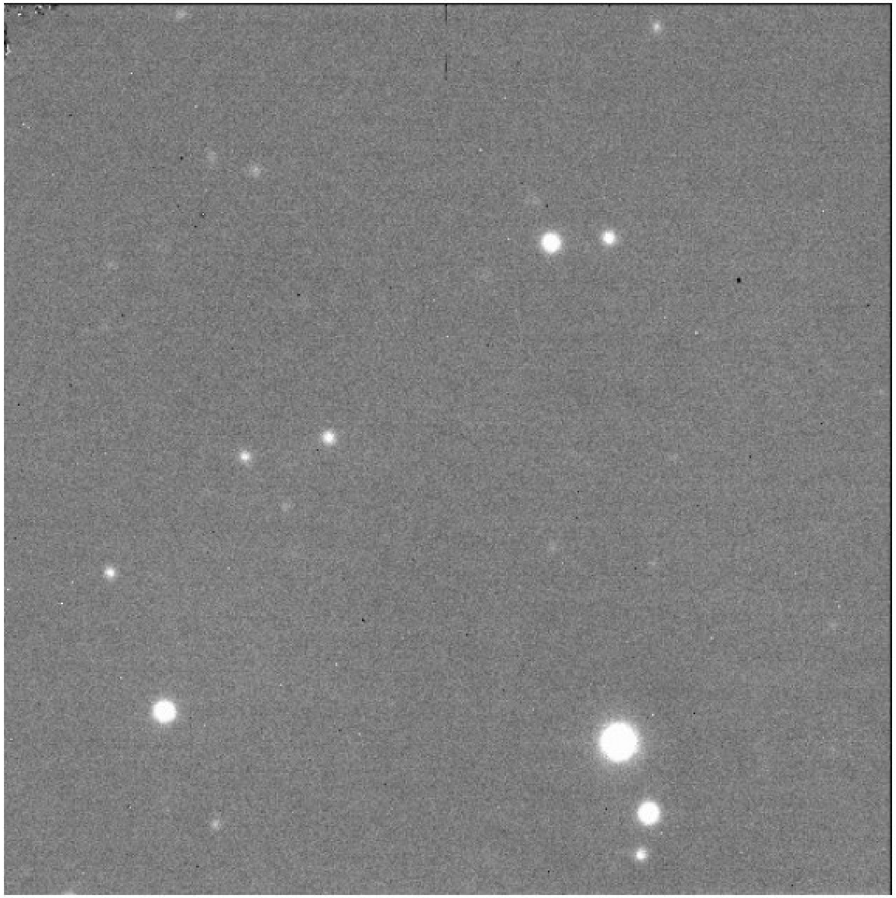




(OmegaCAM instrument consortium)

OK, we have reduced our data!
Infrared image before and after data reduction





An interlude: Anything strange here?

(Boris Haeussler)

An interlude: Anything strange here as well?

(Boris Haeussler)

Post data-reduction

- Photometry

- Narrow band imaging

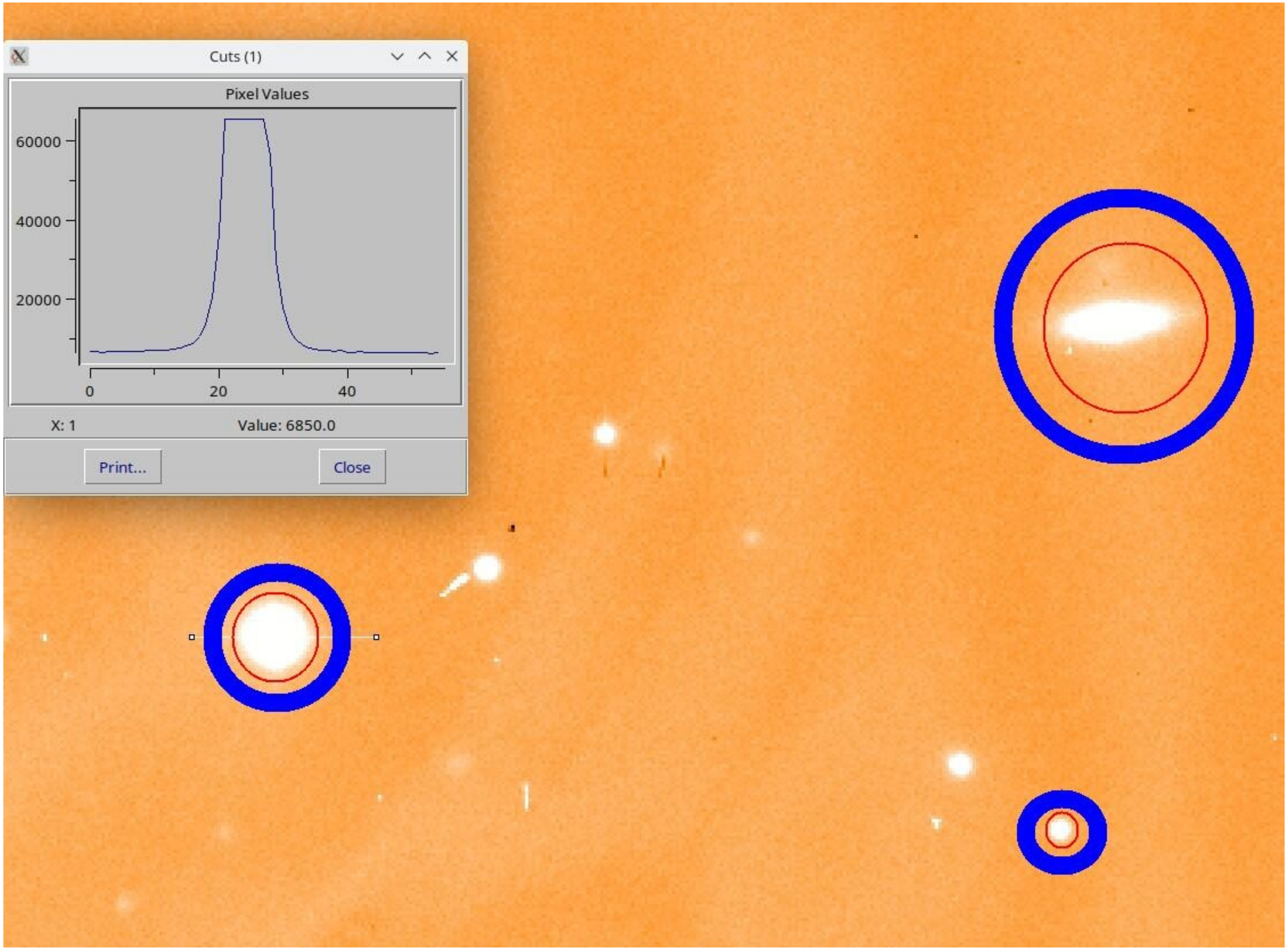
- Differential photometry

Aperture photometry (EFOSC-2 data) – we find the stars, sum the light within a defined radius per star and subtract the sky level per pixel derived in another aperture from the total object count (per pixel). Quick and simple!

Only one of the three objects is really applicable for circular aperture photometry.

Why?

What other limitations does this technique have?

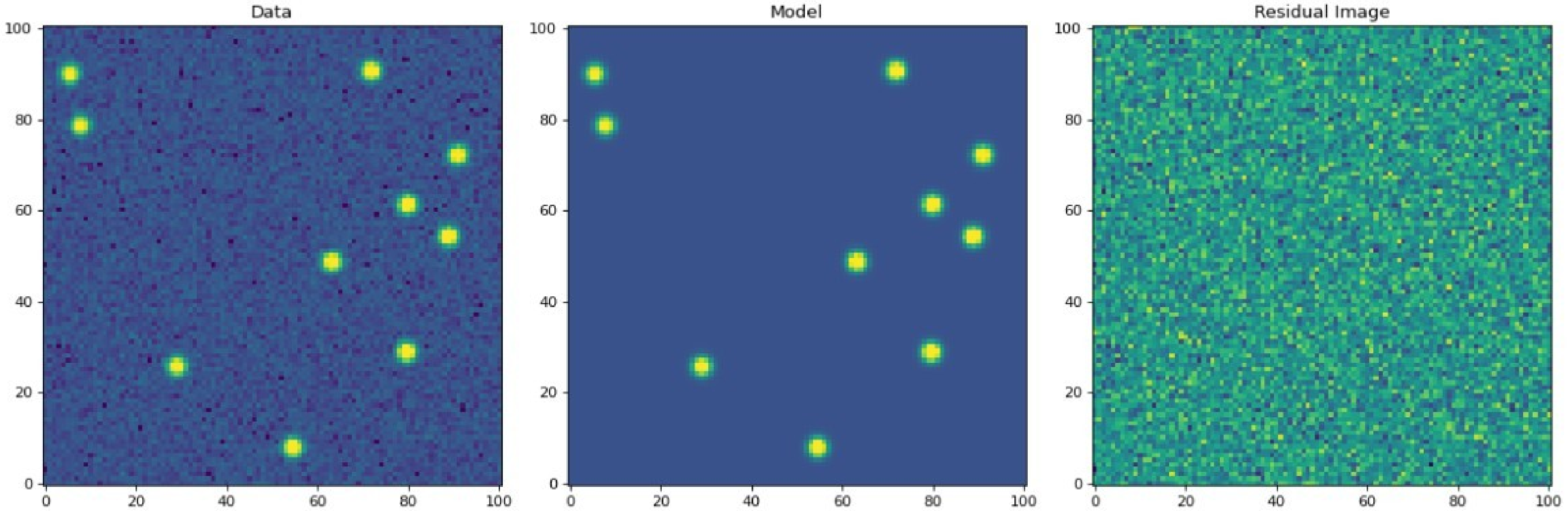


Point spread fitting photometry

- Often more accurate than aperture photometry in crowded fields. As in aperture photometry we first search for objects such as stars and galaxies.

- We use isolated stars to create the point spread function. This can be an analytical function, or using the data, or a combination of the two. It may change depending on the position on the image plane and almost certainly changes from exposure to exposure for ground based images (why?).

- A scaled version of the PSF is then subtracted at each stellar position and the magnitude estimated.



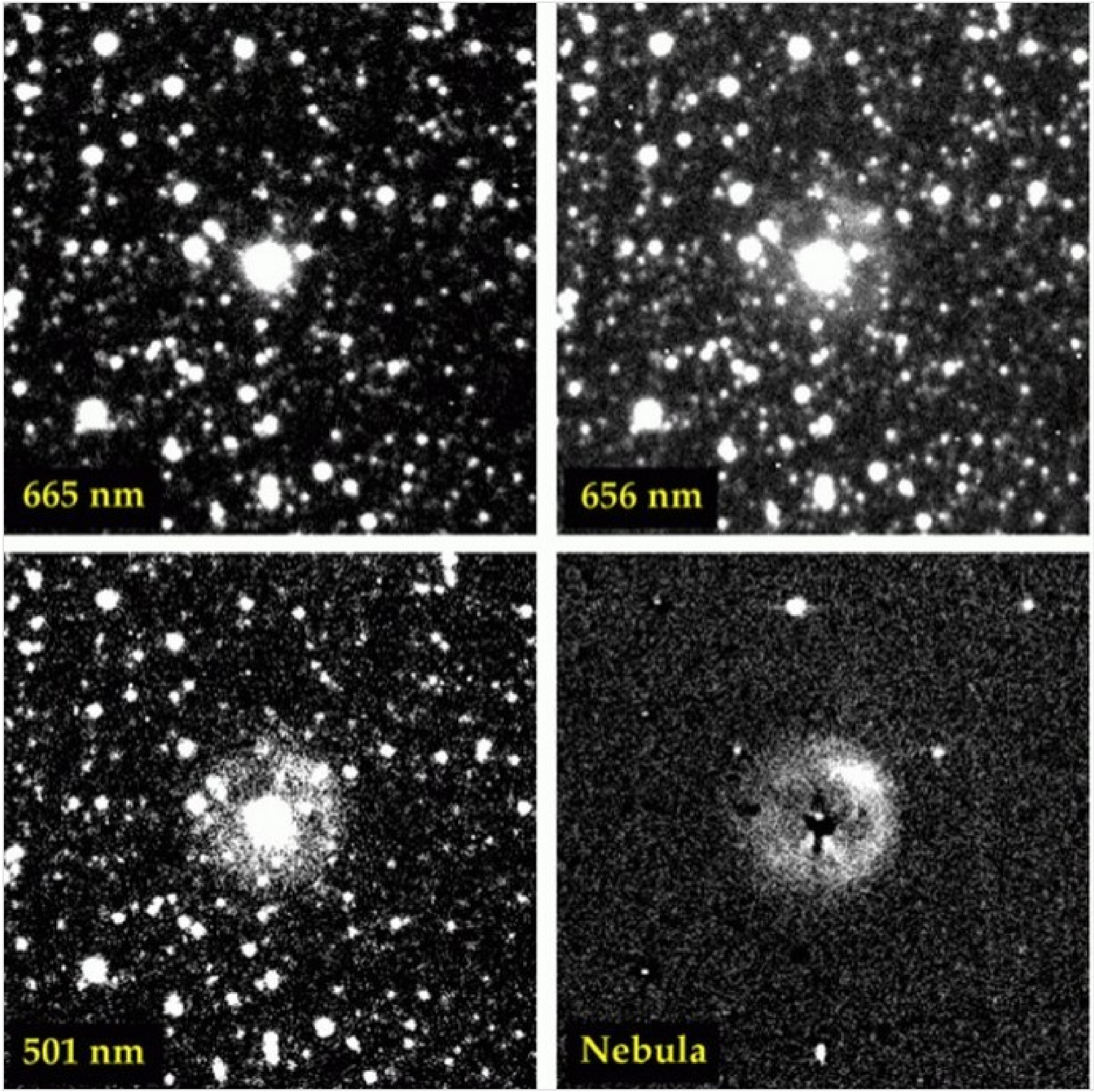
https://photutils.readthedocs.io/en/stable/psf.html

Narrow band photometry

Narrow band filters can be used to study a particular line, in this case [0III] (bottom left) and H alpha (top right with bottom right showing continuum subtracted image).

Advantage of using a narrow band filter is that you can see structure otherwise washed out in the broad band image.

What are the disadvantages? (at least two...)



(La Silla Danish 1.5m)

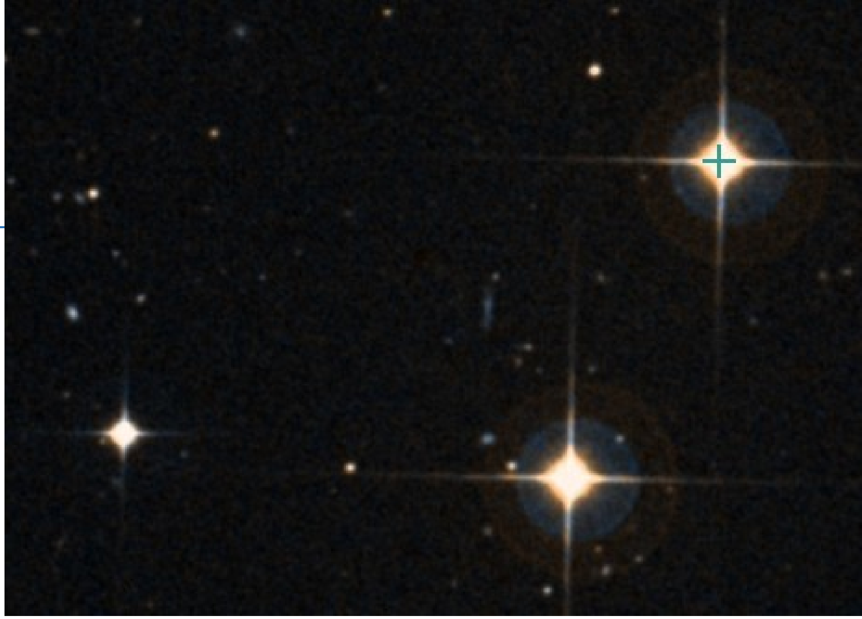
Other examples of narrow band photometry

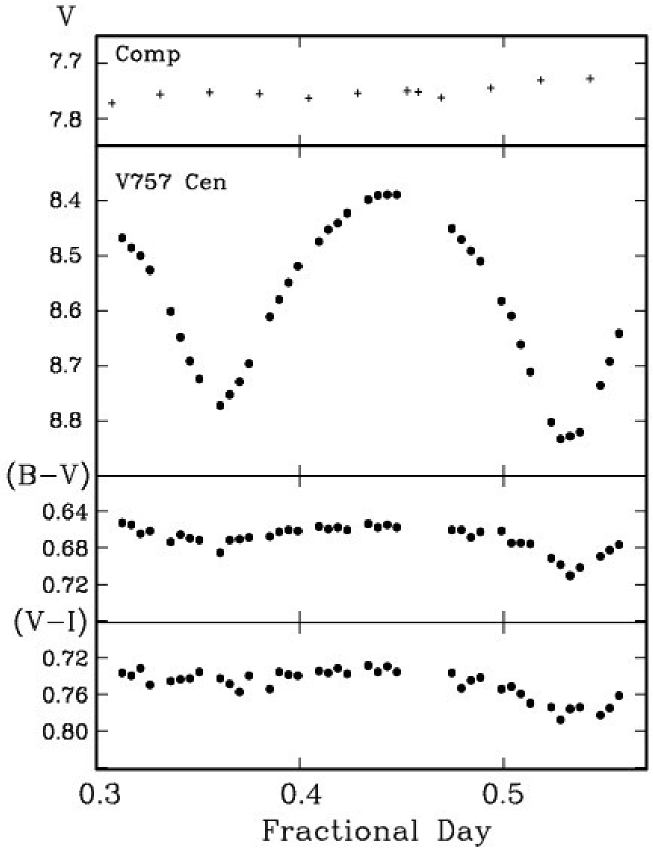
(GOODS south field, H-alpha and Lyman alpha combination)

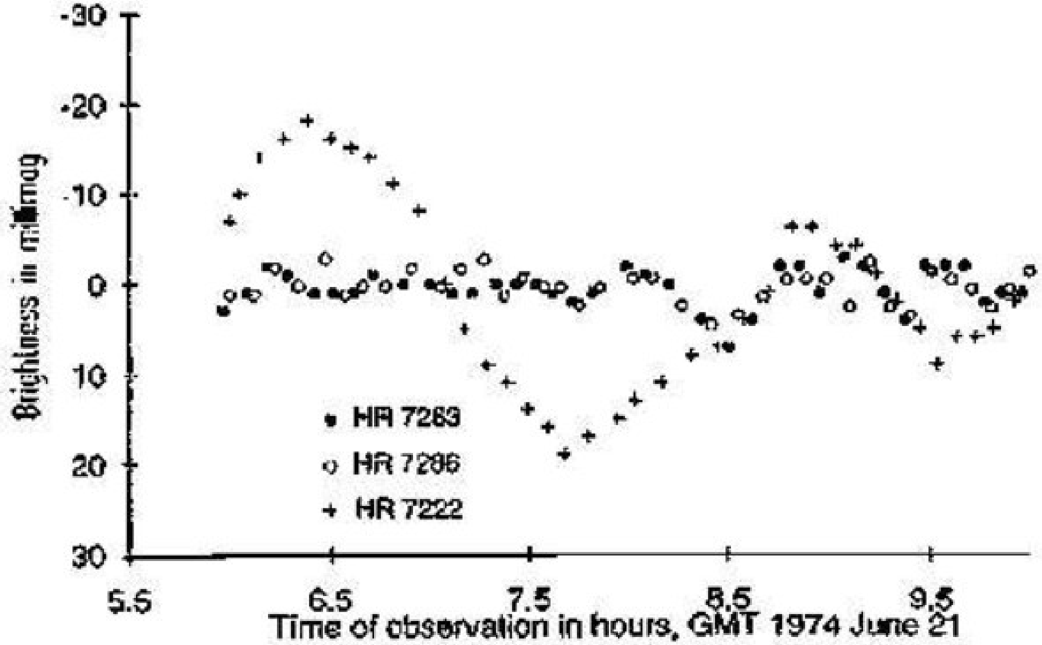
Differential photometry

- Observe multiple stars simultaneously, the target and one or more comparison stars.

- Changes in the Earths atmosphere (for example due to thin cirrus) affect all stars, hence can be calibrated out.







(Kilkenny 1974)

The End! Thanks for attending :)

Acknowledgements

- Images are from ESOs website www.eso.org or wikipedia if not otherwise noted.

- Free distribution of this talk is allowed for non commercial use as long as the original source attribution is kept as well as attribution to www.eso.org and wikipedia.

Image Quality vs seeing (Martinez et al. ESO Msgr)

Seeing and image quality are two quantities that are frequently confused in the field of astronomical instrumentation.

The first is an inherent property of the atmospheric turbulence, which is independent of the telescope that is observing through the atmosphere. The second, defined as the full width at half maximum (FWHM) of long exposure stellar images, is a property of the images obtained in the focal plane of an instrument mounted on a telescope observing through the atmosphere.

Without considering instrumental aberrations, one remaining property of the turbulence that affects the image quality is the outer scale: the size of the largest turbulent eddies present in the atmosphere. It has been observed that the image quality in a large telescope is always lower than the seeing, owing to the finite outer scale of the turbulence, as opposed to the commonly used Kolmogorov theory that considers an infinite outer scale.