Introduction to Optical Observations

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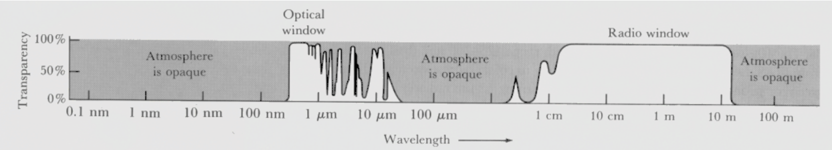
Acknowledge: 'Havaitseva Tähtitiede', URSA, Nilsson, Takalo & Piirola; lecture notes by Kari Nilsson (FINCA)

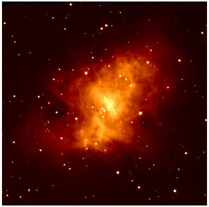
The optical regime

- $\lambda \sim 300 - 900$ nm.
- $\nu \sim 3 \times 10^{14} - 1 \times 10^{15}$ Hz.
- Photon energy ~ 1 eV.

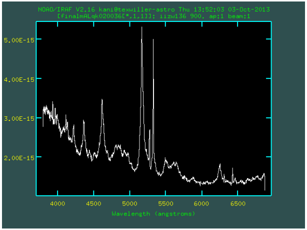


Optical techniques

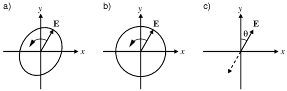
Imaging : Find out object structure, new objects (surveys), positions of objects (astrometry), target brightness (photometry), etc.



Spectroscopy : Find out the energy distribution of the object and/or brightness variations.

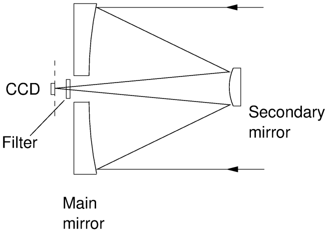


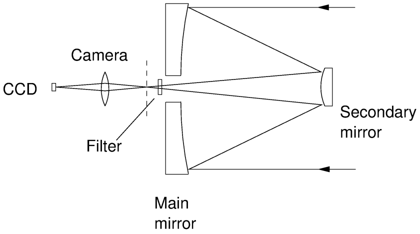
Polarimetry : Find out the polarization state of object light.



Imaging

Use the telescope to collect light and focus it onto the *focal plane* (dashed line below).



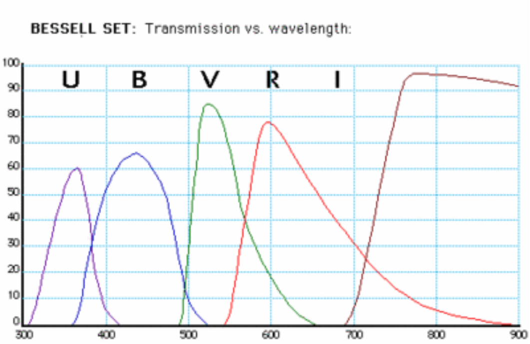


CCD directly at focal plane, e.g. StanCam @ NOT.

Re-imaging optics (camera), e.g. ALFOSC @ NOT.

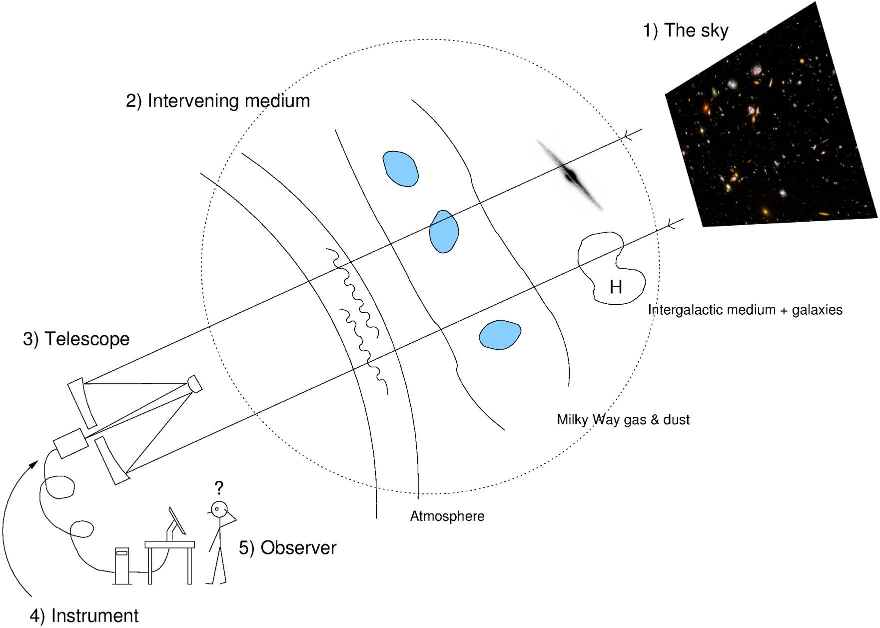
Optical imaging observations

- For astronomical imaging always use filters:
- Broad band: U, B, V, R
- Narrow band: e.g. Hα, Hβ etc.

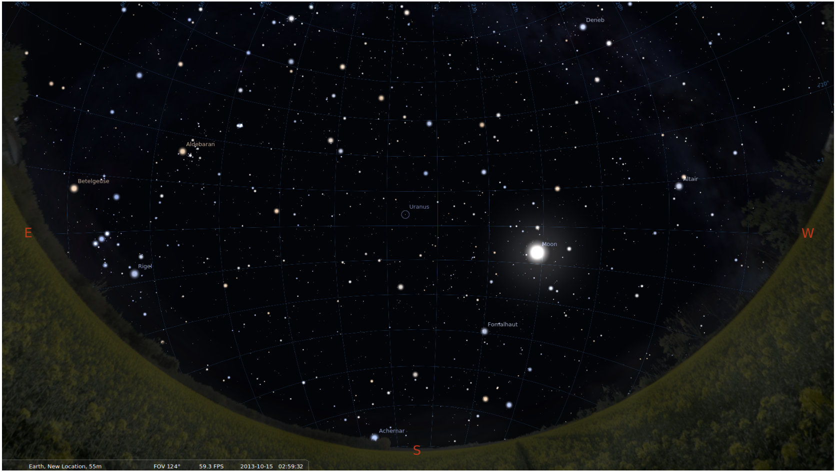


- Observer photometric standard stars to calibrate
- Can also use field stars to calibrate if not photometric

From target to observer



1) The sky



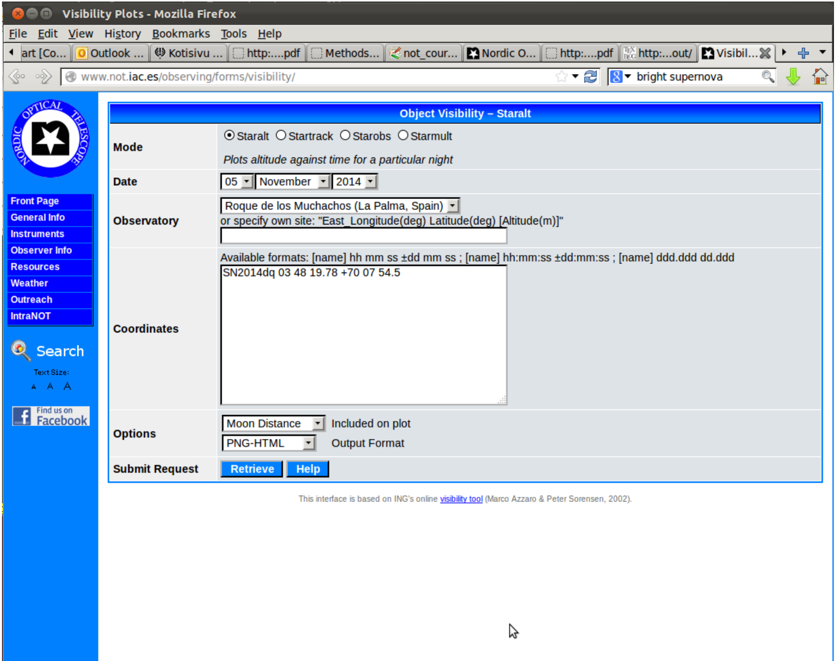
Deneb
Aldebaran
Betelgeuse
Altair
Uranus
E
W
Moon
Rigel
Fomalhaut
Achernar
S
Earth, New Location, 55m
FOV 124°
59.3 FPS
2013-10-15 02:59:32

- Targets rise form the East, reach the highest point in South and set to the West. Exception: circumpolar targets, which never set.
- As the night advances, progressively higher right ascensions become visible.
- Local Siderial Time (LST) gives the RA currently at meridian (South).
- During the year different RA ranges are visible during the night. This means that a given target is visible during part of the year only.

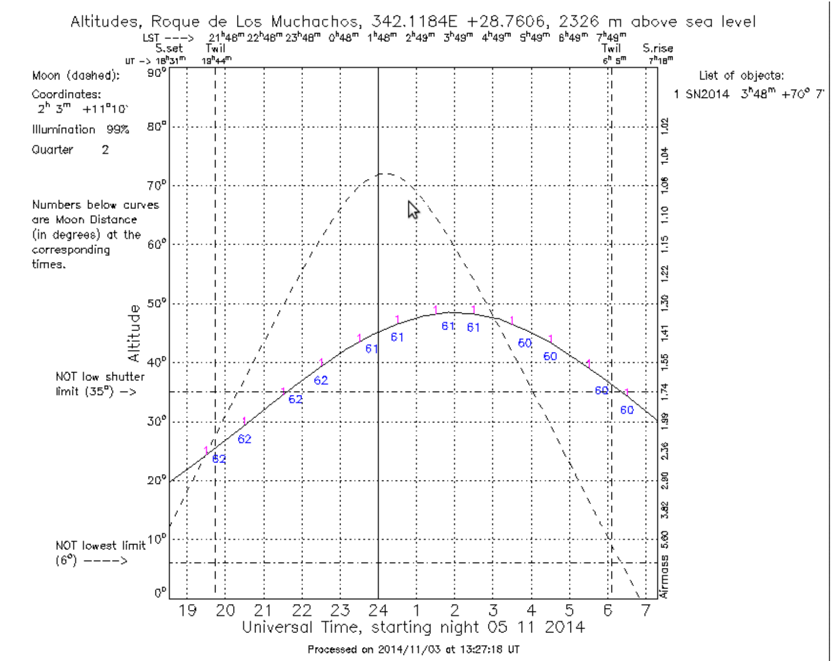
Preparations before observations (or even before applying)

- Make a list of target coordinates, selecting only targets which are visible during the time of year your observations are scheduled.
- Make a *visibility plot* of your targets.
- Check for possible Moon influence (e.g. Stellarium).
  - Dark time: $<$ 4 days from new moon.
  - Grey time: 4-10 days from new moon.
  - Bright time: close to full moon.

Visibility plot

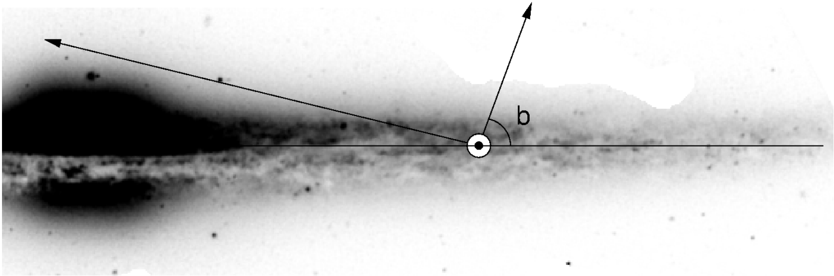


Visibility plot

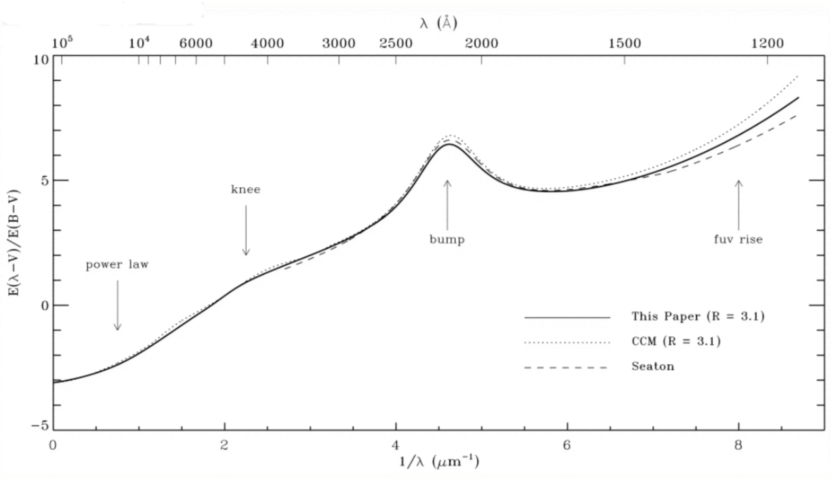


2) Intervening medium: The Galaxy

- The gas and dust in the Milky Way disk absorb light of extragalactic targets. This is called *galactic extinction*.
- The extinction is strongest at small galactic latitudes *b* and decreases towards the direction perpendicular to the plane (high *b*). The extinction is not smooth, but very patchy and irregular.



- Galactic extinction is a very strong function of wavelength with blue wavelengths more strongly absorbed $\rightarrow$ targets appear fainter and "redder" than what they truly are.



Fitzpatrick et al. (1999) PASP 111, 755

2) Intervening medium: Atmosphere

The atmosphere

a) generates the unpredictable phenomenon called weather

b) absorbs and scatters light

c) refracts incoming light rays

d) increases the background due to emission and scattering

e) decreases resolution due to turbulence.

The strength of most effects depends on the zenith distance z and wavelength λ.

a) The weather

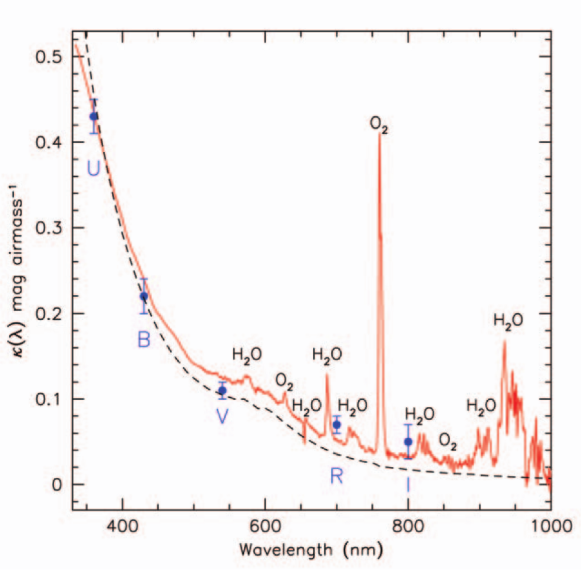
Ground-based astronomy is on the mercy of the weather, since observations are impossible e.g. through thick clouds.

Photometric weather = no clouds or dust in the air, i.e. the transparency of the atmosphere is stable.

Even on clear nights observations may be impossible due to limits set by the observatory for relative humidity, wind, dust and temperature.

<table>
<tr><th>Humidity</th><th>Wind</th><th>Dusty Wind</th><th>Temperature</th></tr>
<tr><td rowspan="3">> 90% - Close telescope
After 20min < 90% the telescope can be reopened.</td><td>12 m/s - Close sideports and lower hatch</td><td>10 m/s - Close sideports and lower hatch</td><td rowspan="3">If the humidity is > 90% and the temperature is < 0° C close telescope and do not open until all ice has melted on the outside of the dome.</td></tr>
<tr><td>15 m/s - Observe down wind</td><td rowspan="2">12 m/s - Close telescope</td></tr>
<tr><td>20 m/s - Close telescope</td></tr>
</table>

b) Absorption and scattering: λ-dependence



ESO Messenger 118, 11

Absorption and scattering: z-dependence

The absorption and scattering by the atmosphere causes the target to appear fainter, which is called *atmospheric extinction*.

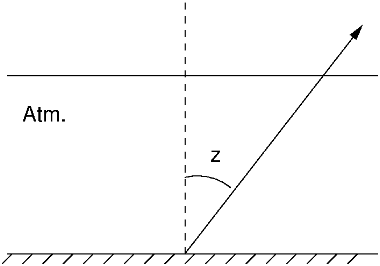
When expressed in magnitudes the extinction is

$$A_\lambda = k_\lambda * X,$$

where k_λ is the *extinction coefficient* and X is the *airmass*, which can be computed from

$$X = 1/\cos z$$

in the plane parallel atmosphere approximation.



- Airmass $X = 1.0$ corresponds to the airmass at zenith. Therefore, k_λ gives the extinction at zenith in magnitudes.

- Typical values for UBVRI filters at high altitude observatories: $k_U = 0.45$, $K_B = 0.22$, $k_V = 0.10$, $k_R = 0.07$, $k_I = 0.05$ mag/airmass.

- At airmass $X = 2.0\,(z = 60^\circ)$ there is twice as much atmosphere between the target and the observer than at zenith. Observations should generally be done above $X = 2$, if possible.

c) Background due to emission and scattering

The atmosphere

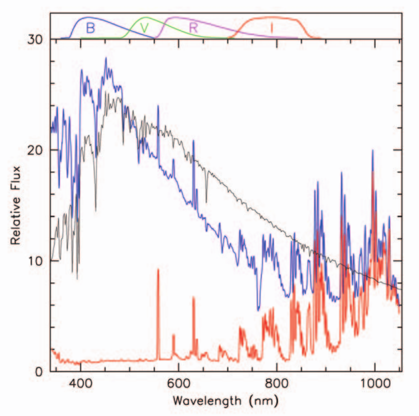
- emits light (airglow) and
- scatters terrestrial lights (light pollution) and moonlight,

increasing the background and producing spectral artifacts.

Red: night sky spectrum in dark conditions (no Moon).

Blue: night sky spectrum with full Moon on the sky.

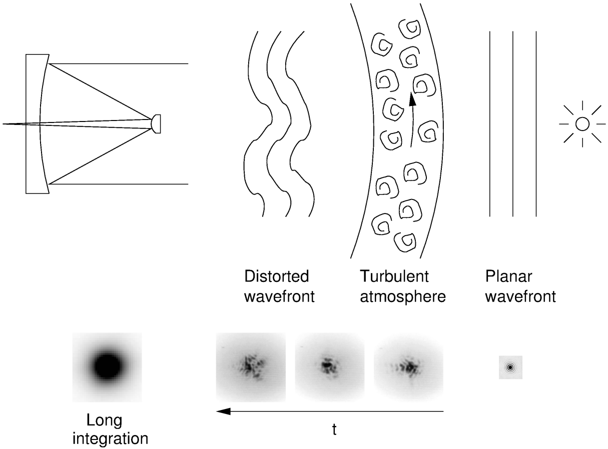
Black : spectrum of a Solar type star.



ESO Messenger 118, 11

d) Atmospheric turbulence

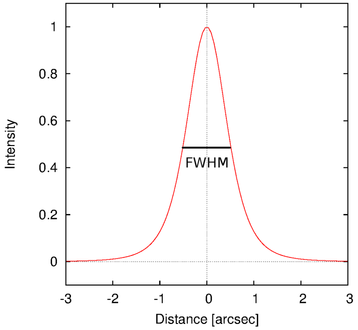
Turbulence in the atmosphere creates phase errors into the incoming wavefront → object image is distorted.



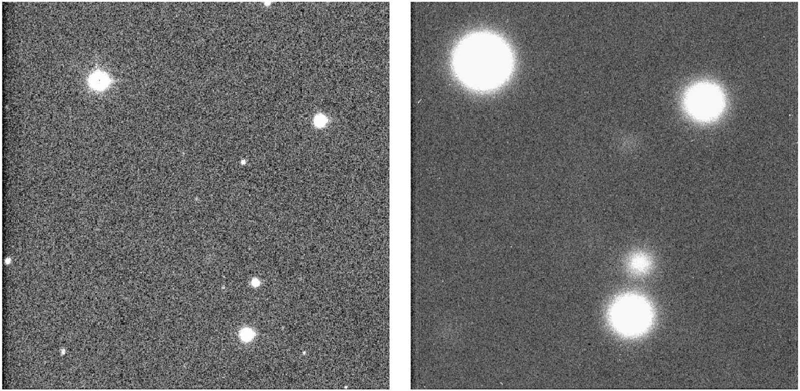
Seeing

- A long integration (long wrt the turbulence time scale) results in a broadened light distribution.
- This broadening is measured from the apparent width (FWHM) of point sources (e.g. stars) in the image (=*seeing*).
- Seeing depends on the airmass: FWHM $\propto$ FWHM(zenith) $X^{3/5}$.
- Typical seeing values:

HST:	0.05”
NOT:	0.4”-0.9”
Tuorla:	2.5” - 5”



Seeing matters!



The PSF

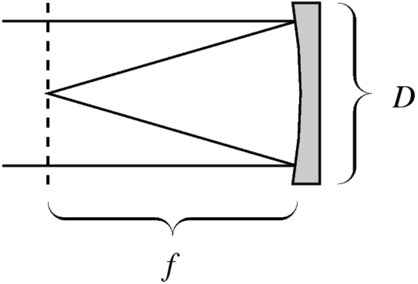
- The 2-dimensional shape of a point source in an image is called the *point spread function* (PSF).

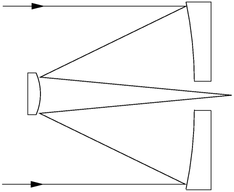
- The PSF tells how a point source looks through the telescope.

- Observed image is a result of *convolution* of the “true” image by the PSF:

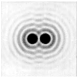
$$Obs(x, y) = True(x, y) * PSF(x, y)$$

3) The telescope





- Light gathering power $\propto D^2$



- Resolution = $1.22\lambda/D$, set by diffraction
  NOT, V-band (550 nm): 0.054" but atmosphere limits to $>$ 0.4"
- Focal ratio = f/D (e.g f/11)
- Pixel scale ("/pix.) = $205265 * \frac{d_{pix}}{f}$, d_{pix} = pixel size.

4) The instrument

- Processes and records the incoming light, but also adds random variations, i.e. *noise*, to the images.
- In addition to instrumental noise, the image always contains *photon noise*, which cannot be avoided.
- A fundamental rule of observational astronomy:

Plan the observations in such a way that the noise is dominated by photon noise, not by instrumental noise.

In the first case the data are said to be *photon noise limited* (=good) contrary to e.g. *read noise limited* data (=bad).

Photon noise

Imagine a perfect detector, which records every photon hitting it and adds no noise to the signal.

If the detector records n photons, then for “large” n ($>$a few tens) the standard deviation of n is $\sqrt{n}$.

Thus the true photon rate is with 68% probability in the interval $(n - \sqrt{n}, n + \sqrt{n})$.

Photon noise gives the fundamental lower limit of noise in any image.

Signal to noise

The *signal to noise* (S/N) is a measure of data quality.

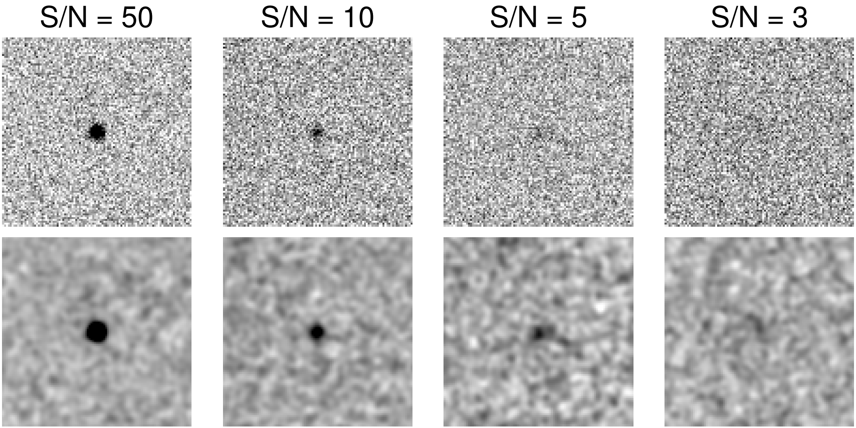
$$\frac{S}{N} = \frac{\text{observed signal}}{\text{noise}}$$

$S/N > 3$ is generally required to claim detection, but $S/N > 5$ is a safer limit.

In the case of perfect detector $S/N = \frac{n}{\sqrt{n}} = \sqrt{n}$.

Before observations there should be an idea of required S/N and the observations should be planned so that this S/N is reached.

S/N examples



Computing S/N

Computing S/N depends on the situation, but if

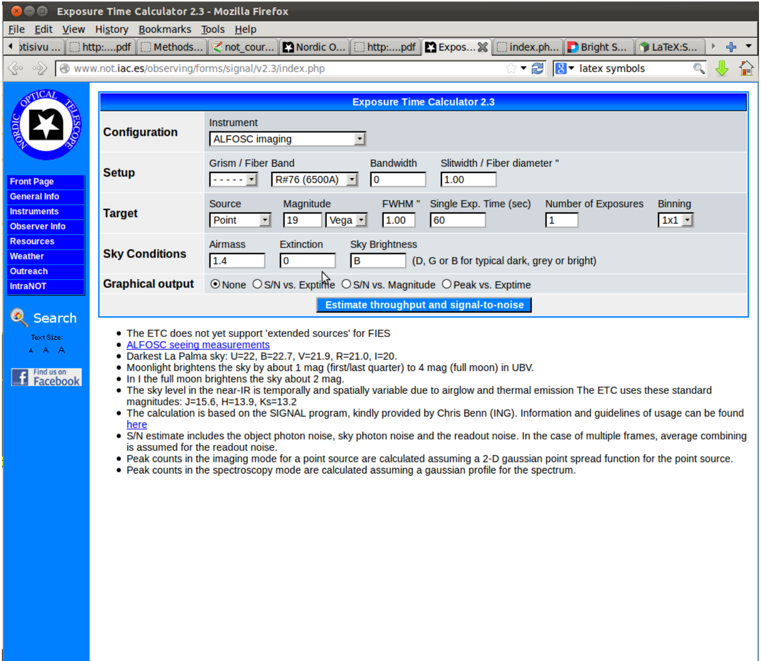
- the signal is obtained by summing the signal of M pixels with n_i photons in pixel i and
- the standard deviation of n_i in pixel i is σ_i

then

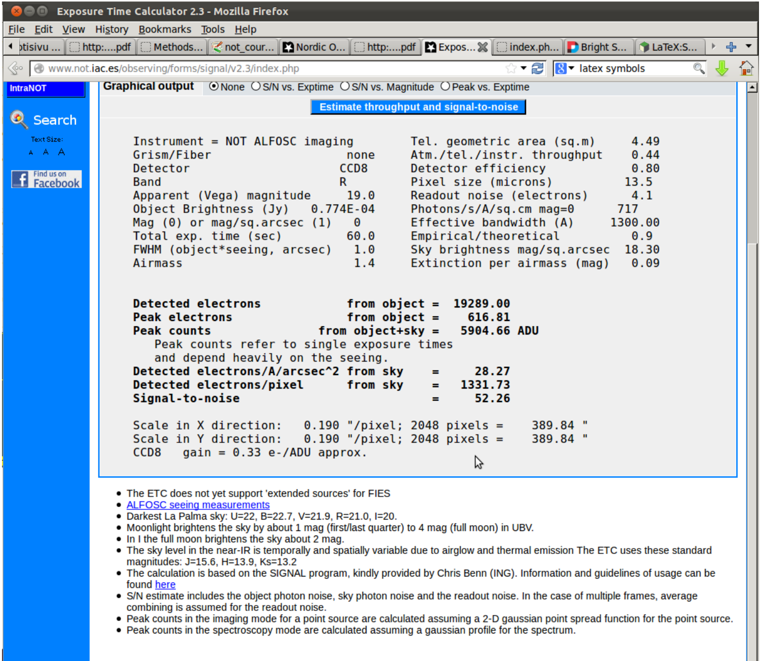
$$\frac{S}{N} = \frac{\sum_{i=1}^{M} n_i}{\sqrt{\sum_{i=1}^{M} \sigma_i^2}}$$

Note that in the case of perfect pixels ($\sigma_i = \sqrt{n_i}$) we get $S/N = \sqrt{\sum n_i}$.

S/N example: observe an object with R = 19



S/N of ∼50 sufficient for precise photometry



Exposure Time Calculator 2.3 - Mozilla Firefox

File Edit View History Bookmarks Tools Help

www.not.iac.es/observing/forms/signal/v2.3/index.php

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Graphical output ◉ None ○ S/N vs. Exptime ○ S/N vs. Magnitude ○ Peak vs. Exptime

Estimate throughput and signal-to-noise

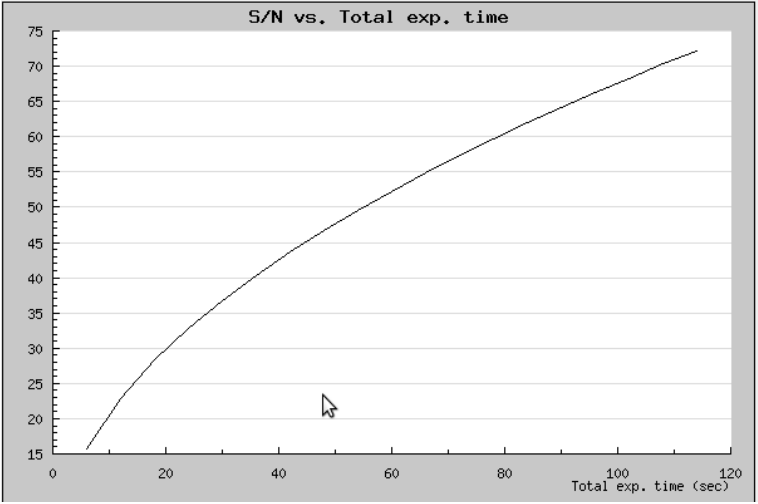
```
Instrument = NOT ALFOSC imaging        Tel. geometric area (sq.m)      4.49
Grism/Fiber                     none   Atm./tel./instr. throughput     0.44
Detector                        CCD8   Detector efficiency             0.80
Band                            R      Pixel size (microns)           13.5
Apparent (Vega) magnitude       19.0   Readout noise (electrons)       4.1
Object Brightness (Jy)    0.774E-04    Photons/s/A/sq.cm mag=0       717
Mag (0) or mag/sq.arcsec (1)    0      Effective bandwidth (A)     1300.00
Total exp. time (sec)           60.0   Empirical/theoretical           0.9
FWHM (object*seeing, arcsec)    1.0    Sky brightness mag/sq.arcsec  18.30
Airmass                         1.4    Extinction per airmass (mag)    0.09


Detected electrons              from object =  19289.00
Peak electrons                  from object =    616.81
Peak counts                 from object+sky =   5904.66 ADU
   Peak counts refer to single exposure times
   and depend heavily on the seeing.
Detected electrons/A/arcsec^2 from sky     =     28.27
Detected electrons/pixel      from sky     =   1331.73
Signal-to-noise                            =     52.26

Scale in X direction:   0.190 "/pixel; 2048 pixels =    389.84 "
Scale in Y direction:   0.190 "/pixel; 2048 pixels =    389.84 "
CCD8   gain = 0.33 e-/ADU approx.
```

- The ETC does not yet support 'extended sources' for FIES
- ALFOSC seeing measurements
- Darkest La Palma sky: U=22, B=22.7, V=21.9, R=21.0, I=20.
- Moonlight brightens the sky by about 1 mag (first/last quarter) to 4 mag (full moon) in UBV.
- In I the full moon brightens the sky about 2 mag.
- The sky level in the near-IR is temporally and spatially variable due to airglow and thermal emission The ETC uses these standard magnitudes: J=15.6, H=13.9, Ks=13.2
- The calculation is based on the SIGNAL program, kindly provided by Chris Benn (ING). Information and guidelines of usage can be found here
- S/N estimate includes the object photon noise, sky photon noise and the readout noise. In the case of multiple frames, average combining is assumed for the readout noise.
- Peak counts in the imaging mode for a point source are calculated assuming a 2-D gaussian point spread function for the point source.
- Peak counts in the spectroscopy mode are calculated assuming a gaussian profile for the spectrum.

Increasing the exposure time by $\times 1.5$ will only increase the S/N by $\times\sqrt{1.5} \sim 1.2$



Watch out for detector saturation for bright sources! ALFOSC is linear up to ∼350 000 ADU/pixel.

Exposure Time Calculator 2.3

Configuration	Instrument: ALFOSC imaging
Setup	Grism / Fiber: - - - - - ; Band: R#76 (6500A); Bandwidth: 0; Slitwidth / Fiber diameter ": 1.00
Target	Source: Point; Magnitude: 13.5 Vega; FWHM ": 1.00; Single Exp. Time (sec): 60; Number of Exposures: 1; Binning: 1x1
Sky Conditions	Airmass: 1.4; Extinction: 0; Sky Brightness: B (D, G or B for typical dark, grey or bright)
Graphical output	(•) None ( ) S/N vs. Exptime ( ) S/N vs. Magnitude ( ) Peak vs. Exptime

Estimate throughput and signal-to-noise

Instrument = NOT ALFOSC imaging		Tel. geometric area (sq.m)	4.49
Grism/Fiber	none	Atm./tel./instr. throughput	0.44
Detector	CCD8	Detector efficiency	0.80
Band	R	Pixel size (microns)	13.5
Apparent (Vega) magnitude	13.5	Readout noise (electrons)	4.1
Object Brightness (Jy)	0.123E-01	Photons/s/A/sq.cm mag=0	717
Mag (0) or mag/sq.arcsec (1)	0	Effective bandwidth (A)	1300.00
Total exp. time (sec)	60.0	Empirical/theoretical	0.9
FWHM (object*seeing, arcsec)	1.0	Sky brightness mag/sq.arcsec	18.30
Airmass	1.4	Extinction per airmass (mag)	0.09

Detected electrons from object = 0.306E+07
Peak electrons from object = 97757.77
Peak counts from object+sky = 300271.19 ADU
Be careful, the source might be saturating the detector
Peak counts refer to single exposure times
and depend heavily on the seeing.
Detected electrons/A/arcsec^2 from sky = 28.27
Detected electrons/pixel from sky = 1331.73
Signal-to-noise = 1715.95

Scale in X direction: 0.190 "/pixel; 2048 pixels = 389.84 "
Scale in Y direction: 0.190 "/pixel; 2048 pixels = 389.84 "

General guidelines

Observation planning phase:

- Estimate the required S/N and determine the required exposure time to reach that with given telescope and instrument.
- Make a visibility plot of your targets and plan the observations so that targets are observed high in the sky.

When observing:

- The weather is unpredictable. Be ready to change the plan during the night.
- Expose long enough for the data to be photon noise dominated.