Modelling astronomical instruments

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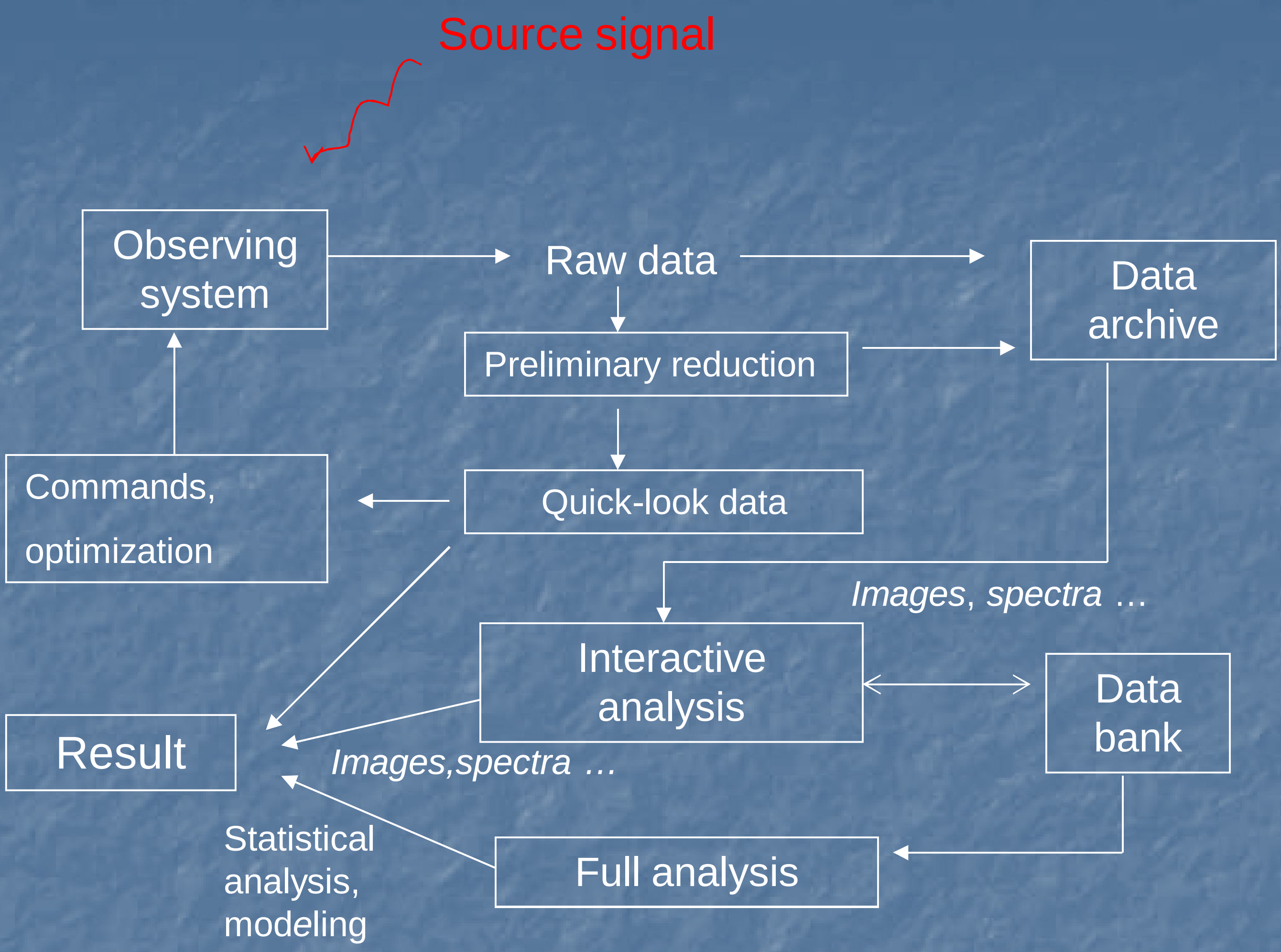
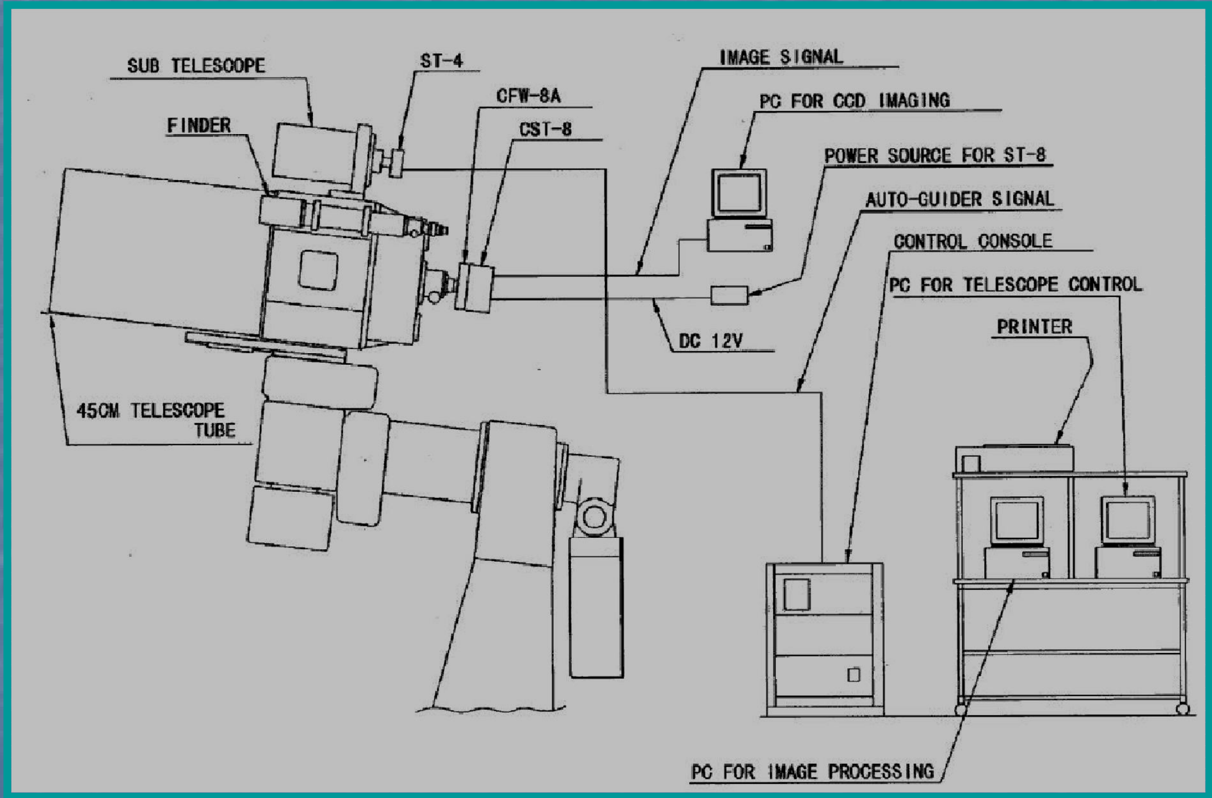


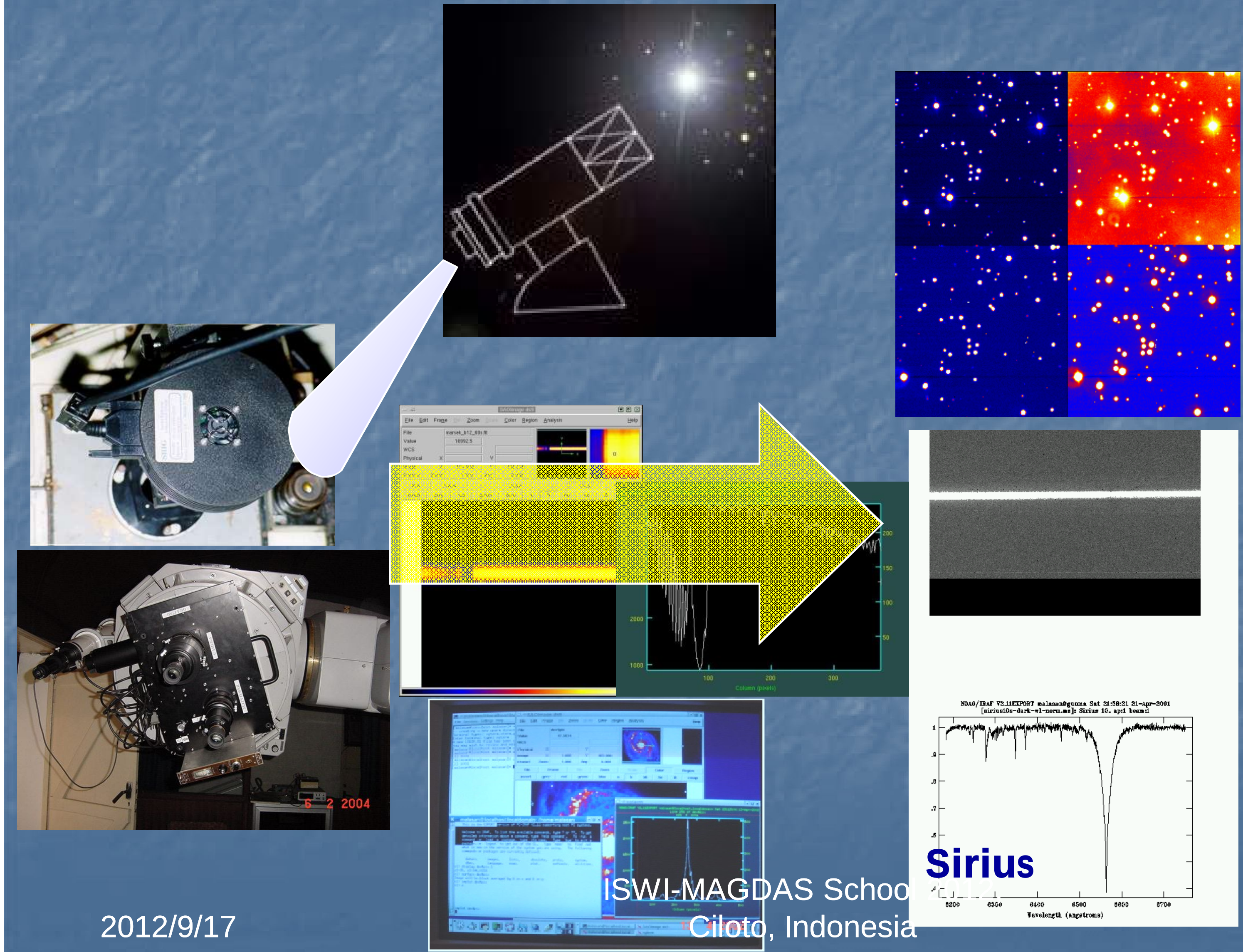
Acquisition system in astronomy

The case of common telescopes around us (small telescopes)

- ✓ Support of pointing & tracking for proper CCD imagery & spectroscopy
- ✓ Autoguider
- ✓ Control system based on common S/W → Remote
- ✓ Embedded acquistion system



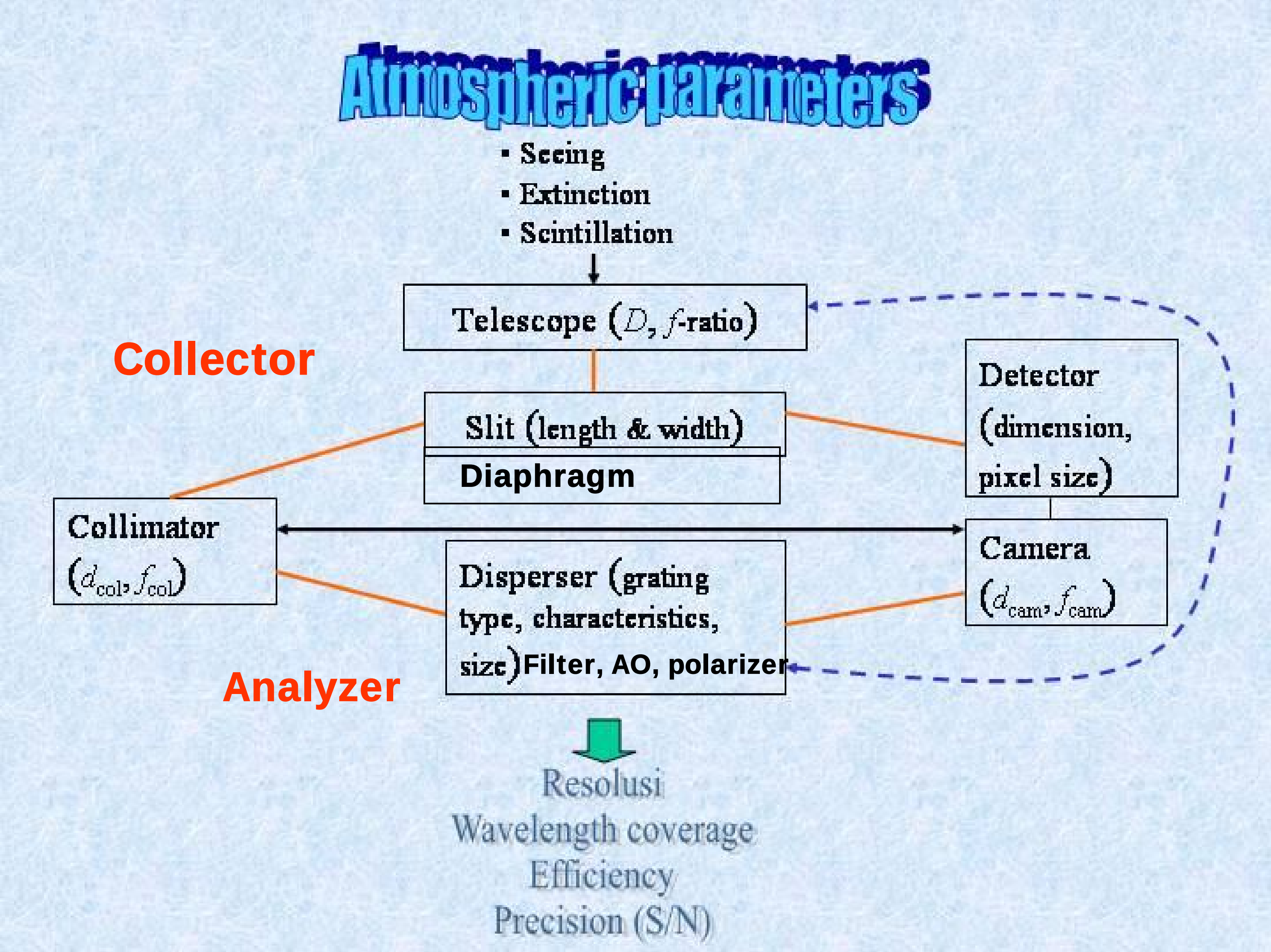
Astrophysical observation



Appearance in several wavelengths

Morphology, Temperature, density and variation

Modelling the instrument for optimum observation (case of optical)



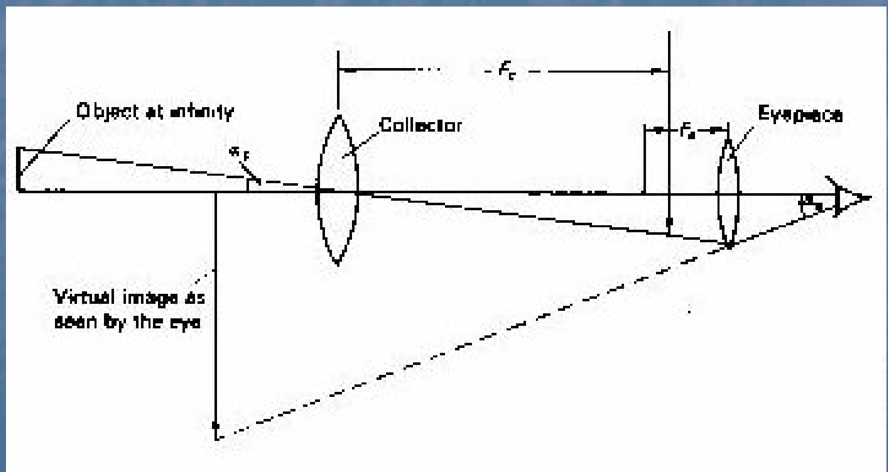
Basic parameters of Collector

Known parameter

- Aperture diameter (*D* in mm)
- Focal length (*f* in mm): Single lens, combination of mirror

$$\frac{f}{D}$$ Focal ratio

- *Power (magnification)*:



$$m = \frac{\alpha_e}{\alpha_c} = \frac{f}{f_{\text{eyepiece}}}$$

$$\frac{D}{2} \le m \le 28\sqrt{D} \text{ (Whittaker's law)}$$

- *Light gathering power*: Ability to collect energy compare to naked eye

$$\frac{D^2_{effective}}{d^2_{\text{pupil}}},\ d_{\text{pupil}} = 7-8\ mm,\quad D^2_{\text{effective}} = D^2_{\text{primary}} - D^2_{\text{secondary}}$$

- *Resolving power*: Abiltiy to resolve features on the object being observed

$$\alpha('') = \frac{140}{D(\text{mm})}\ (\text{Rayleigh})$$
$$= \frac{115}{D(\text{mm})}\ (\text{Dawes})$$

- *Limiting magnitude*:

$$m_{\text{limit}} = 6 + 5\log\frac{D_{\text{effective}}}{10}$$

Faintest object can be seen with naked eye

- *Field of view*:

$$FOV = \frac{\text{Apparent field of view}}{m}$$

Apparent field of view=45°-55°

- Image scale (*plate scale*): Relation between subtended angle and size of image on the focal plane

$$\text{Image scale} = \frac{206265''}{f\,(\text{mm})}$$

- *Exit pupil*: Diameter of beam exiting the eyepiece

$$\text{Pupil keluaran} = \frac{f_{\text{eyepiece}}(\text{mm})}{f/D}$$

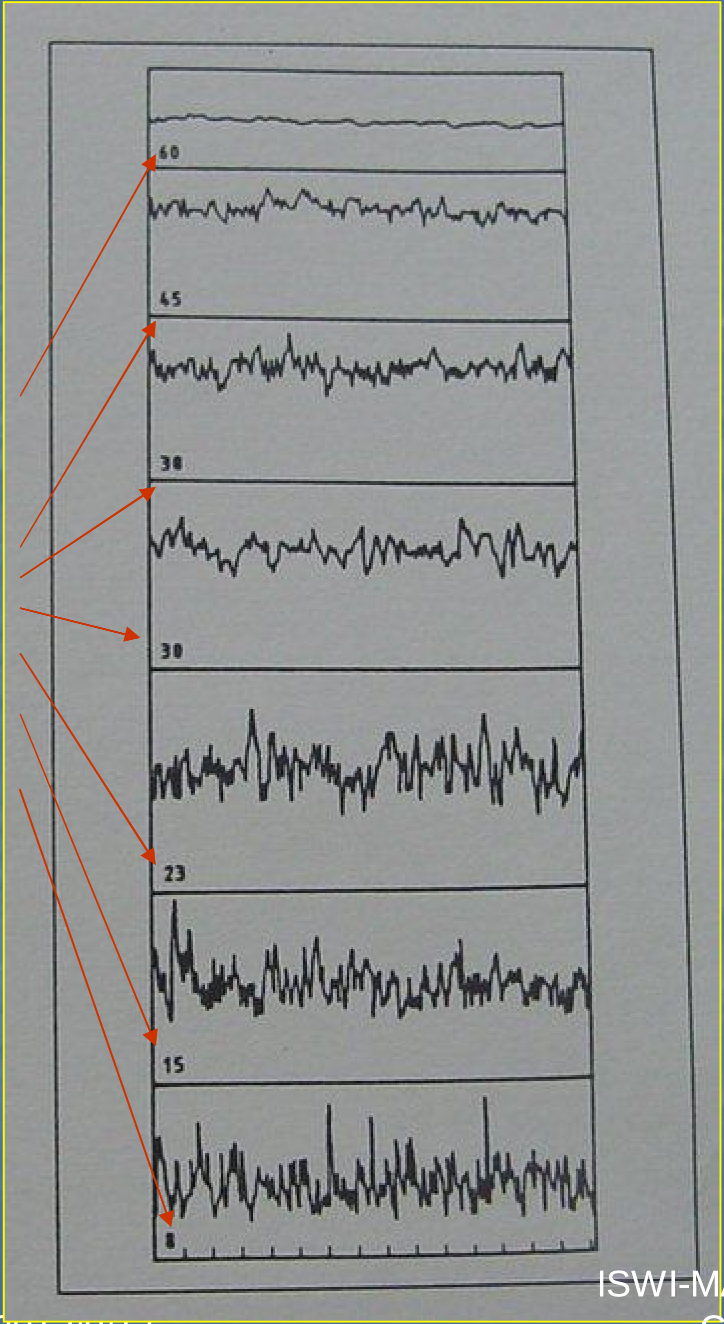
Atmospheric disturbance

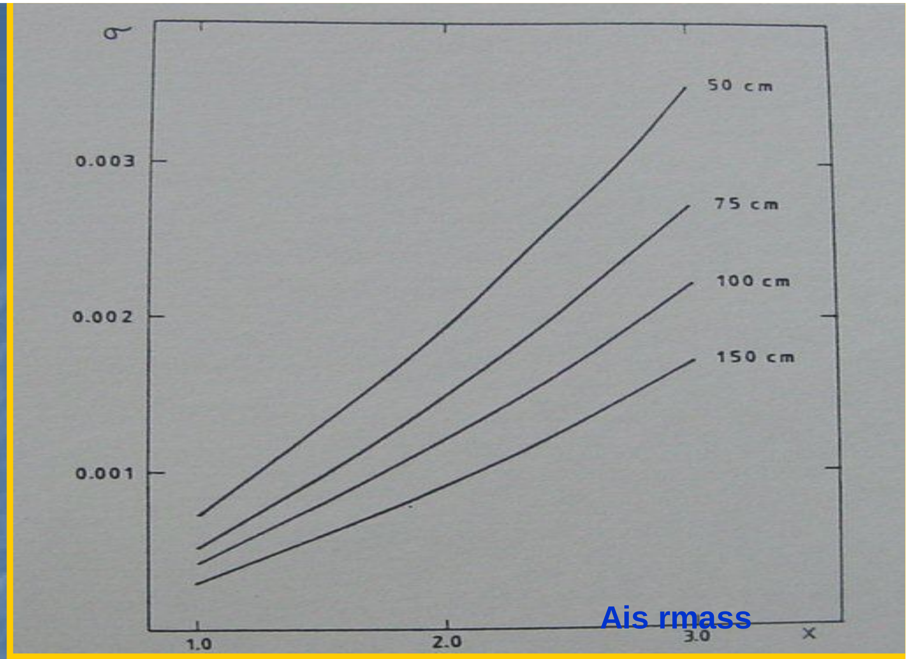
1. Local convergences and divergences of *wavefront*: increase/decrease in irradiation $\rightarrow$ *twinkling* of bright point sources: *Scintillation*

$$\sigma_{\text{scint}} = 0.09 D^{-2/3} F(z)^{3/2} \exp\left(\frac{-h}{8000}\right) t_{\text{int}}^{-1/2} \quad \text{(Fransen, 2000)}$$

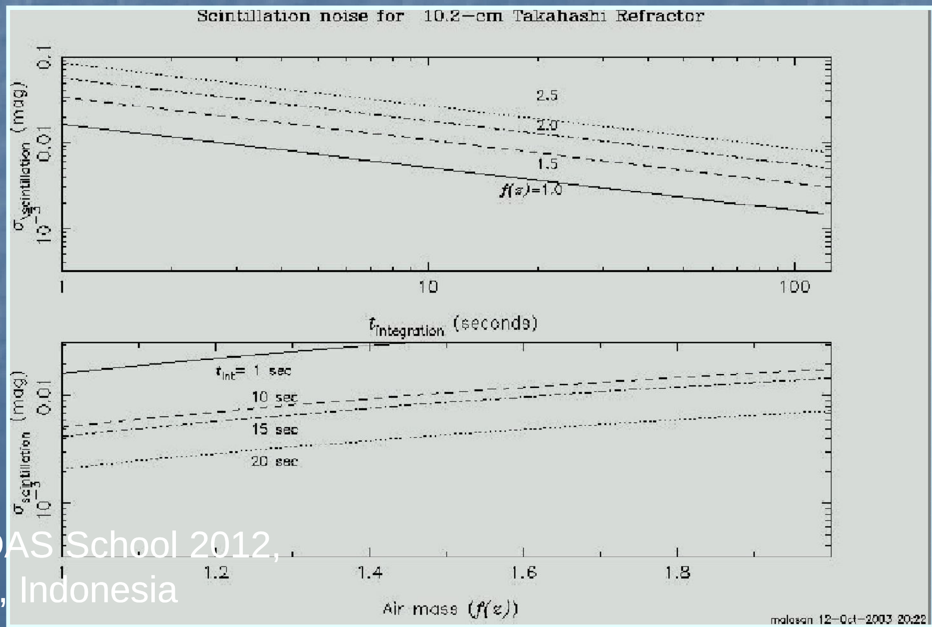
D: diameter of telescope (cm), *h*: altitude (dlm m), t_{int}: integration time (seconds).

Ref. Young, A.T. 1974 in *Methods in Experimental Physics*, vol 12A, Academic Press, NY





Case of 10.2 cm diameter telescope

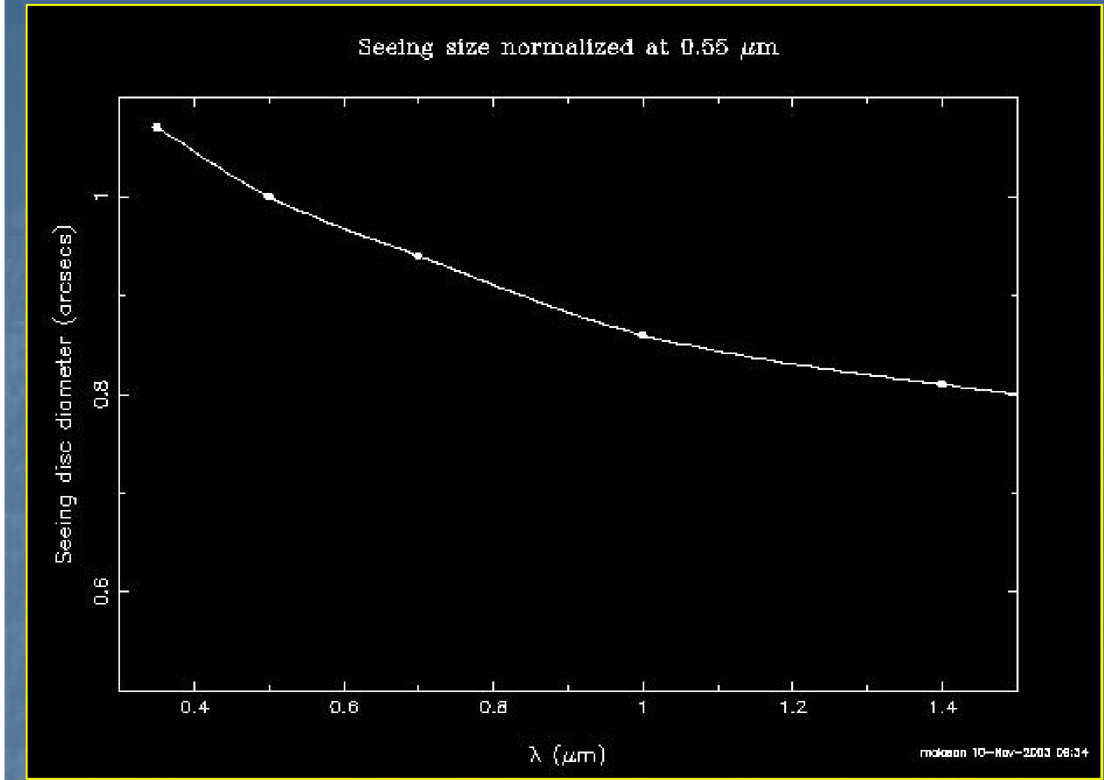


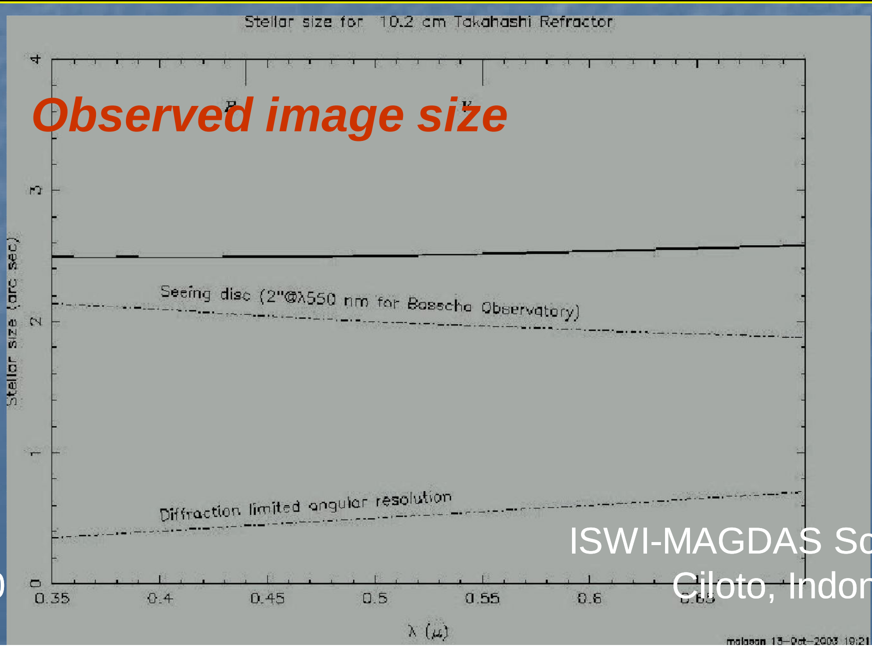
2. Random variation in local direction of beam (relative to the normal of wavefront) random motion of image: *Seeing*

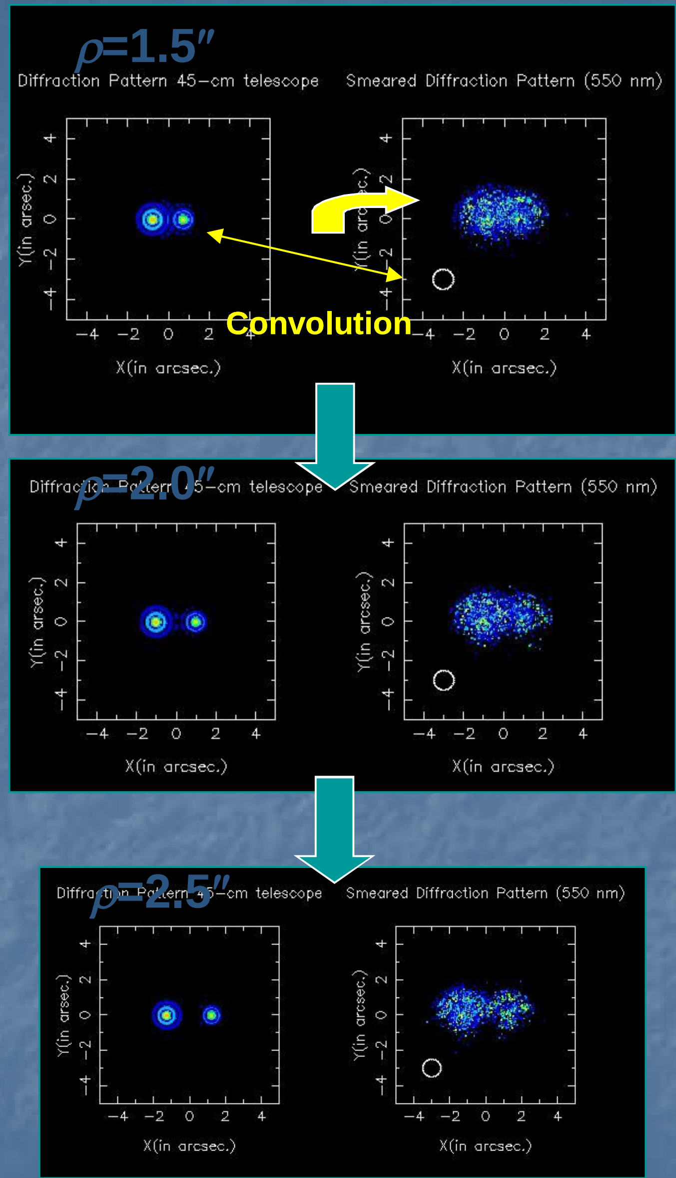
Dancing of point-source image with amplitude ≈ arc seconds around mean position.

- Increases with greater aperture
- Area of seeing disk proportion to the airmass.

Ref.: Young, A.T. 1974, ApJ, 189, p. 587





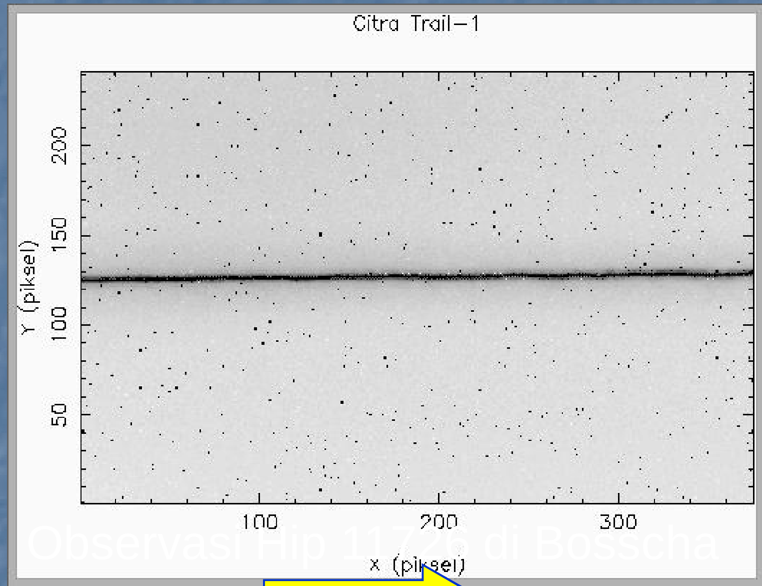


Double star observed at the *seeing* of 1.0″

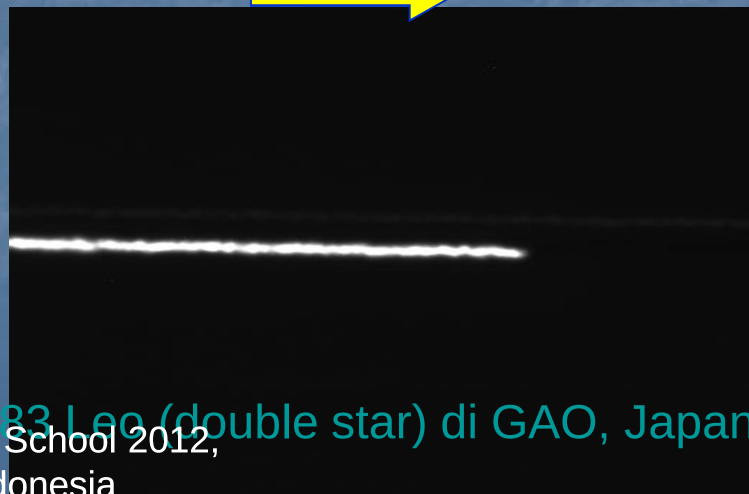
The technique of star trail

- Technique: Imaging the trail of point source (with or without filter) by turning off telescope tracking
- *Critical sampling* CCD =2-3 pixels

$$d_{\text{pixel}}^{\text{optimum}} = \frac{1000\ f\,(\text{mm})}{206265} P('')$$



Observasi Hip 11726 di Bosscha


83 Leo (double star) di GAO, Japan

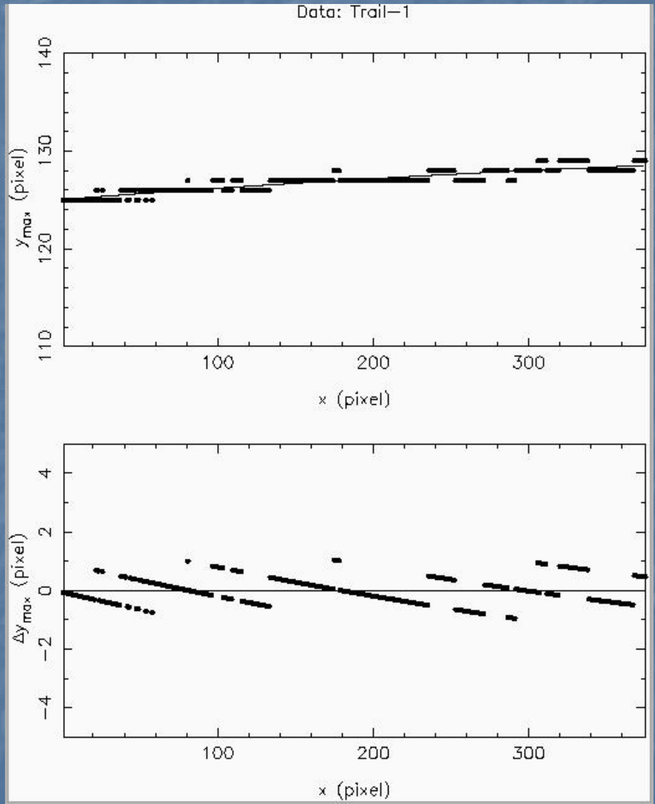
Seeing determination

The algorithm of Gochermann et al 1999, Experimental Astron.,9,15

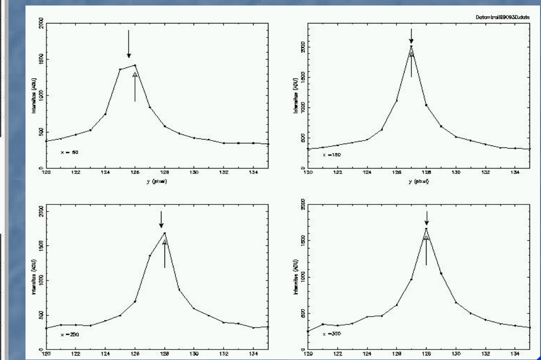
a. For each pixel along the trail direction (*x*)
a.1. Find peak intensity in the prependicular direction (*y*)
a.2. Locate pixel in y-direction which coincides with the peak intensity.
a.3. Do quadratic fitting using three points: two neighbouring pixels before and after pixel that associates with peak intensity. The result of quadratic fitting is y_{max}
b. Store (x,y_{max}) in a table
c. Make polynomial (parabolic) fitting to the relation between x and y_{max}. The standard deviation of fitting, sigma, should be used later for deriving seeing and FWHM parameters

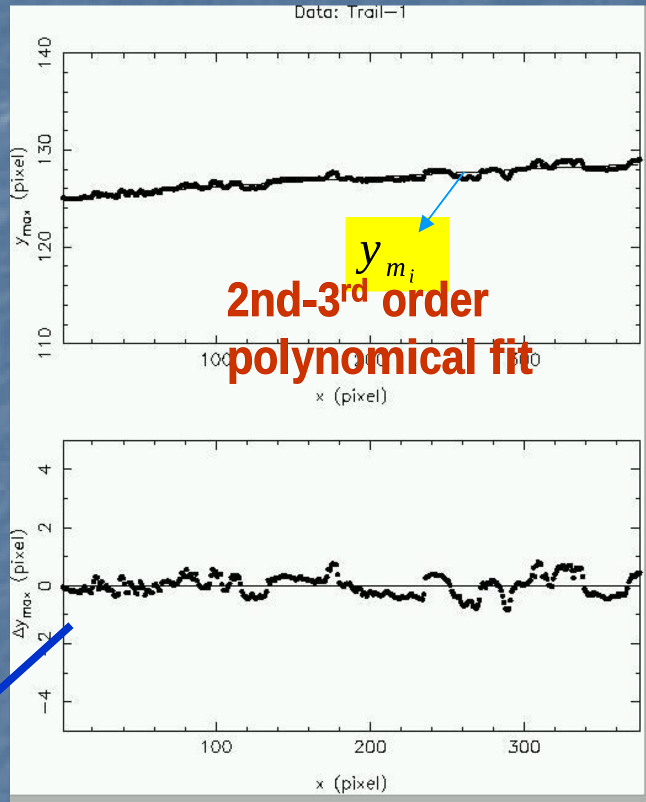
Analysis with peak finding

Discrete effect in peak finding



Quadratic fitting





y_{m_i}

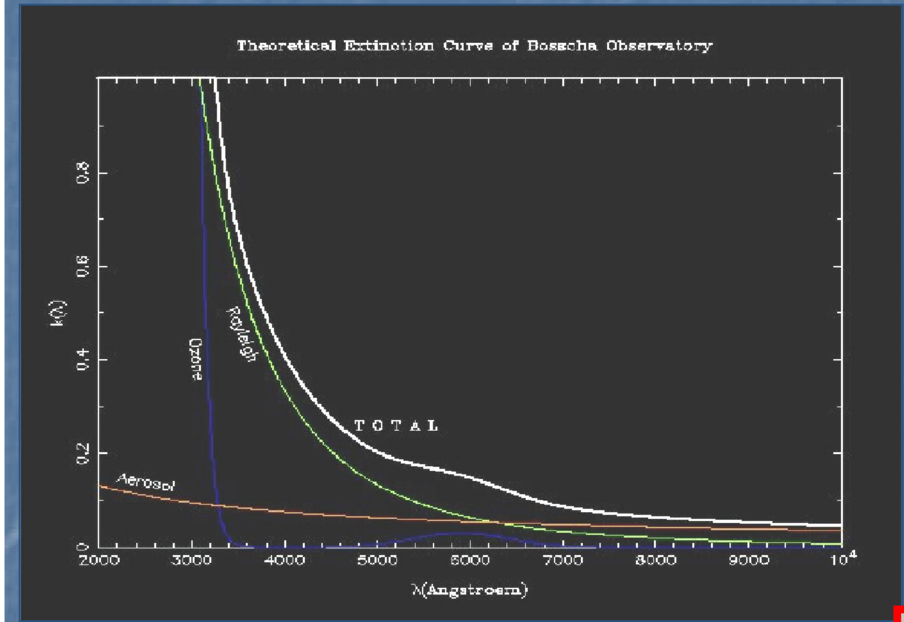
2nd-3rd order polynomical fit

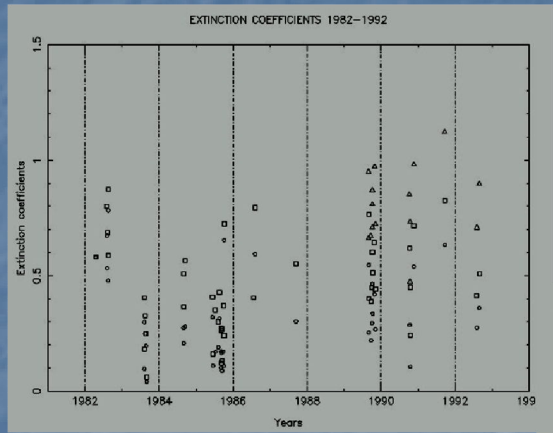
$$\sigma_\lambda = \sqrt{\frac{1}{n-2}\sum_{i=1}^{n}\left(y_{m_i} - y_{p_i}\right)^2}$$

$$d = 2\sigma_\lambda\sqrt{-2\ln(1-q)} = 4.895\,\sigma_\lambda \; (q = 95\%)$$

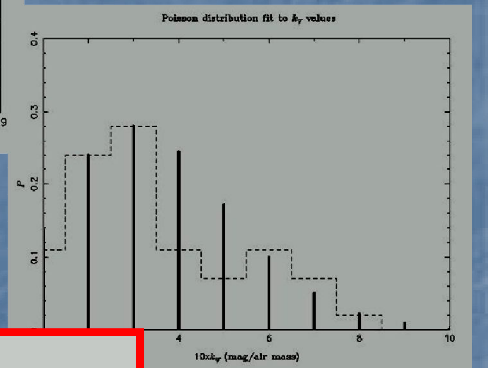
$$FWHM = 2.355\,\sigma_\lambda$$

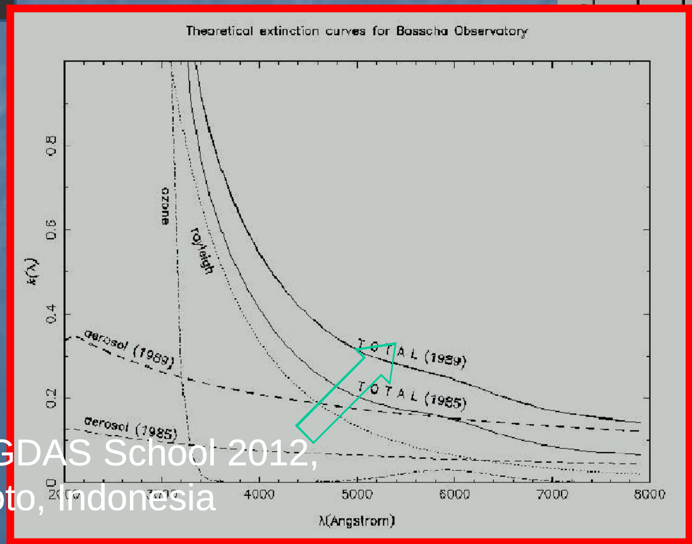
Transparency & Atmospheric extinction





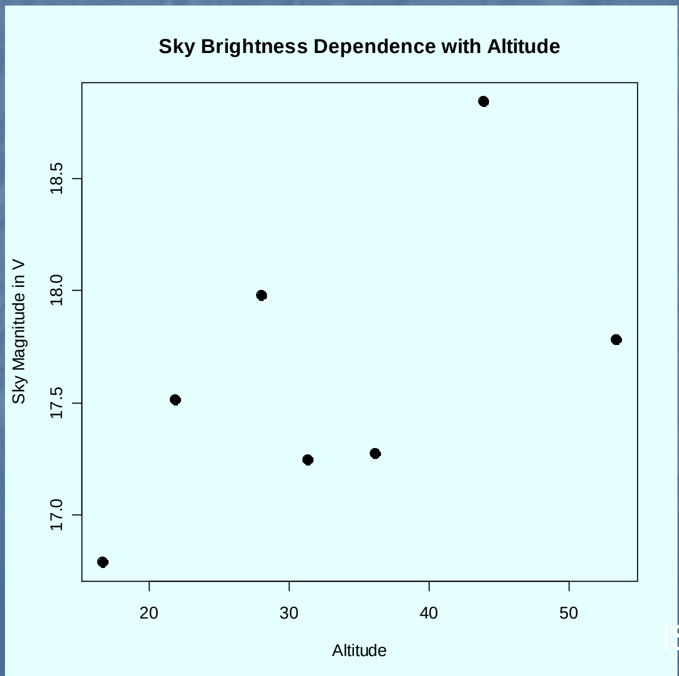
The use of long-term database of photometry

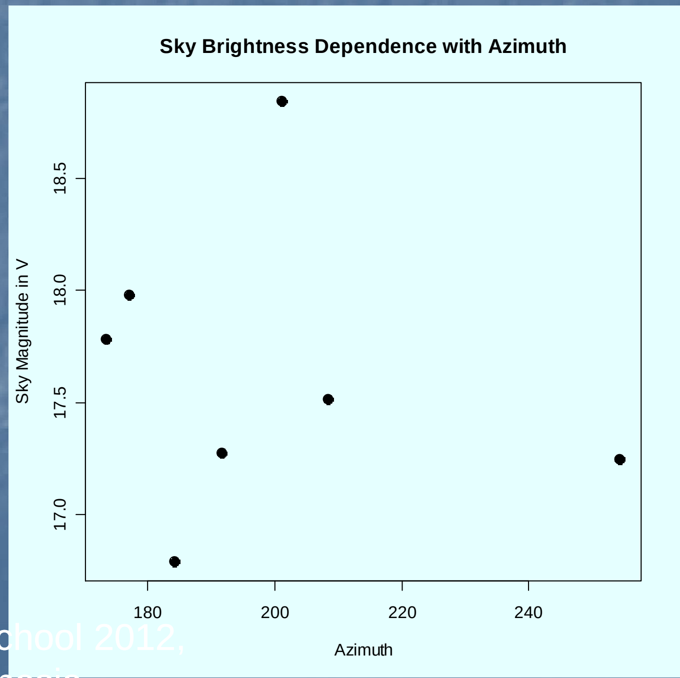




The sky brightness

- Expressed in magnitude/[“]^2
- Determined photometrically (absolute technique)
- Aperture photometry at sky
- Guideline: Dawson (1984) or International Dark sky Association





The heart of physical modelling of astronomical instrument : *The Signal-to-noise ratio* (Gray 1992, Honeycutt 1993, Wagner 1992)

$q(\lambda)$: Spectral response

N_s,N_b : Rate of arrival of object and sky photons, respectively

t : integration time

η: - uncertainty in the sky determination

- Number of pixels are contained within the numerical diaphragm (object & sky)

R: *read-out noise* (rms)

$$\left(\frac{S}{N}\right) = \frac{qN_S t}{\sqrt{qN_S t + \eta(qN_b t + R^2)}}$$

$$\eta = n_{pix}(1 + \frac{n_{pix}}{n_b})$$

$$N_S = \frac{\pi}{4} D^2 \varepsilon_m \Delta\lambda_m \kappa_m 10^{-0.4(m_* + k_\lambda F(z))}$$

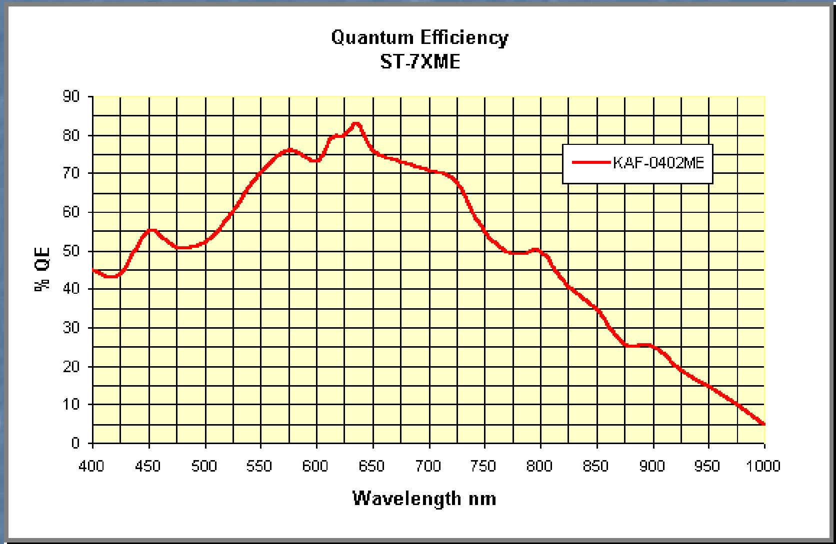
$$N_b = \frac{\pi}{4} D^2 \varepsilon_m \Delta\lambda_m \kappa_m \frac{\pi}{4} d^2 10^{-0.4 m_{sky}}$$

$$\frac{hc}{\lambda} = 3.6 \times 10^{-12} \text{ erg } (\lambda = 5500 \text{ A})$$

$$\log f_\lambda = -0.4V - 8.43 \text{ (Allen, 1973) for } V = 0.0$$

Parameters

Of Detector



	q	R	d[“]	n_{pix}	n_{bg}
PMT	0.15	0	9-20	1	1
CCD	0.75	5-15	3	30	200

Parameters of analyzer

- $\Delta\lambda_m$:
  - Broad-band photometry : 890-1000 Å
  - Intermediate-band photometry: 100 Å
  - Narrow-band photometry: 10 Å
  - Spectroscopy : $\approx \lambda/R$, R=resolution

ε_m?

- Keeping in mind:
  - Transmissivity of a (new) lens : ~85%
  - Reflectivity of a (new) mirror : ~97%
- The case of imaging/photometry:

$$\varepsilon_m = \varepsilon_{\text{telescope}} \varepsilon_{\text{diaphragm}} \varepsilon_{\text{filter/AO/polarizer}}$$

- The case of spectroscopy:

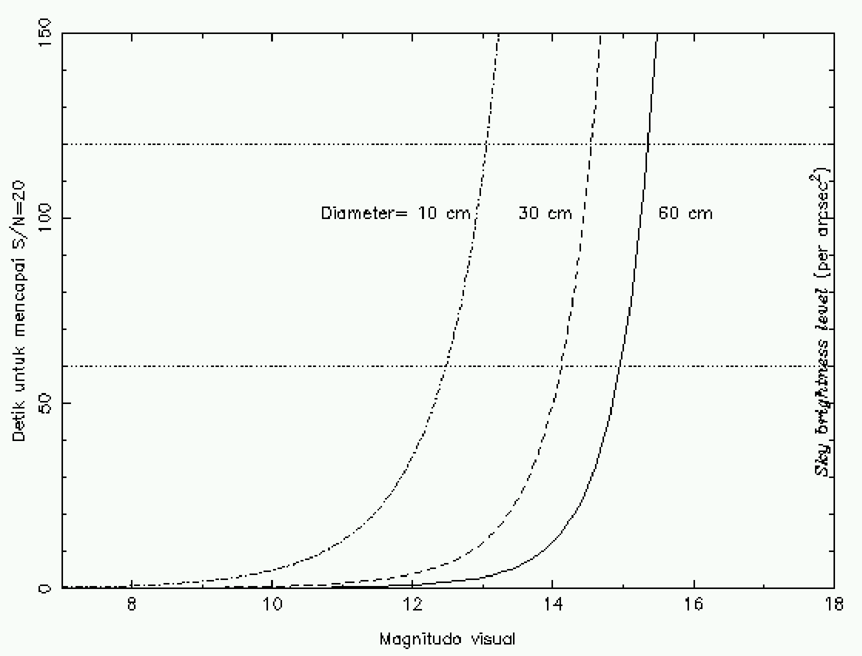
$$\varepsilon_m = \varepsilon_{\text{telescope}} \varepsilon_{\text{slit}} \varepsilon_{\text{collimator}} \varepsilon_{\text{grating}} \varepsilon_{\text{camera}}$$

Detective Quantum Efficiency

$$DQE = \frac{\left(\frac{S}{N}\right)_{out}^2}{\left(\frac{S}{N}\right)_{in}^2}$$

$$\left(\frac{S}{N}\right)_{in}^2 = qN_S t$$

A measure of to what extend our instrument behave ideally.

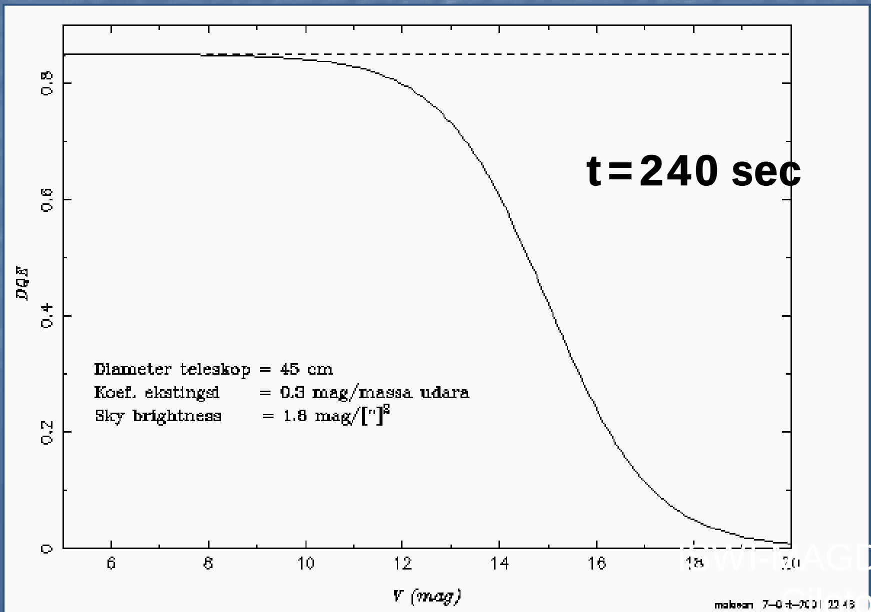


Instrumental limiting magnitude:

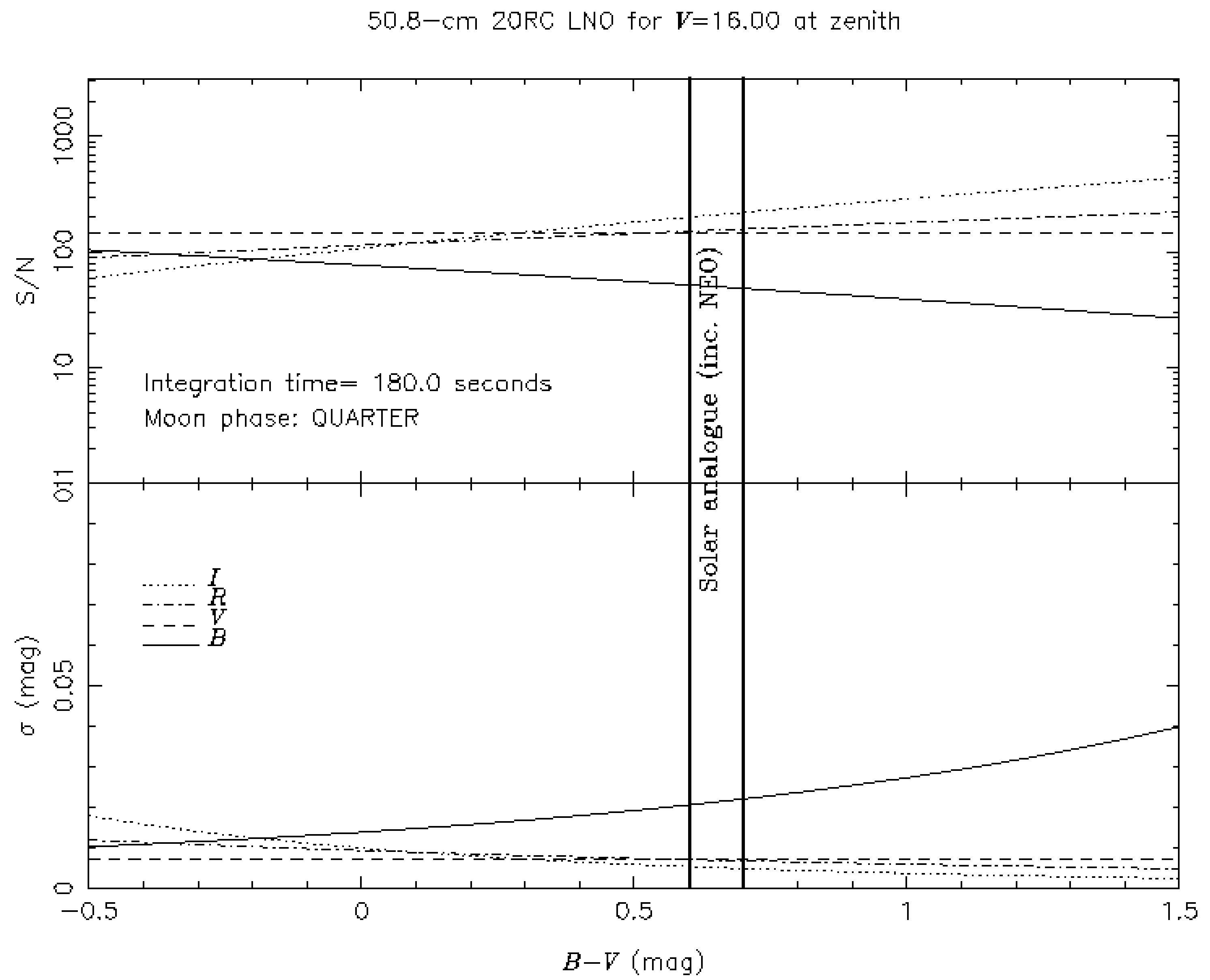
S/N=20 : Detectable

S/N>50 : measurable

S/N>100 : accurately measurable

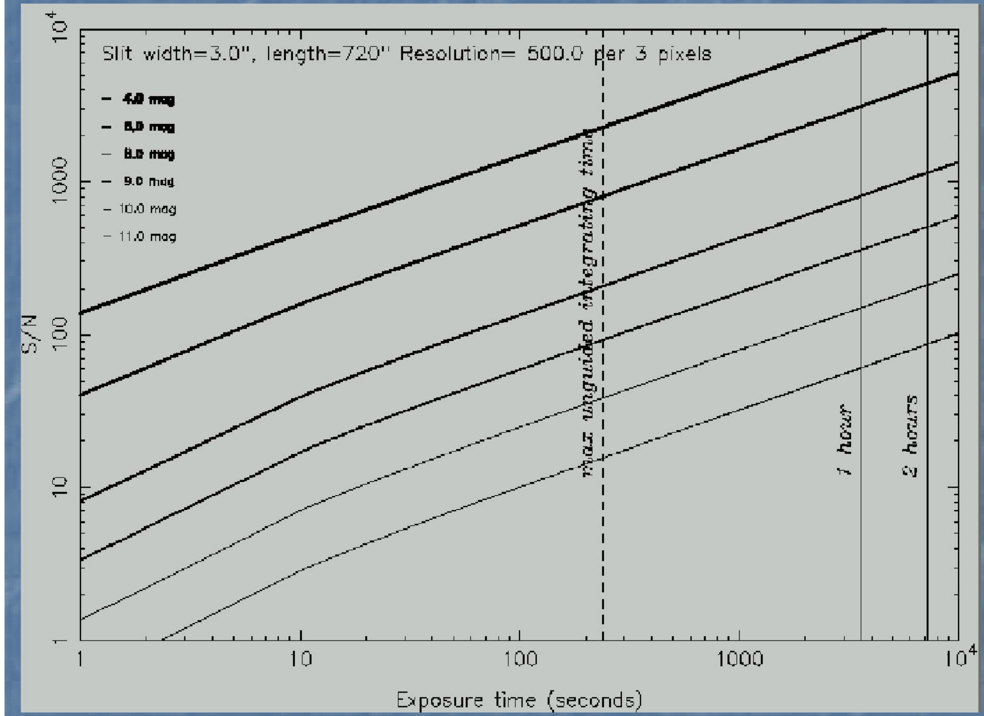


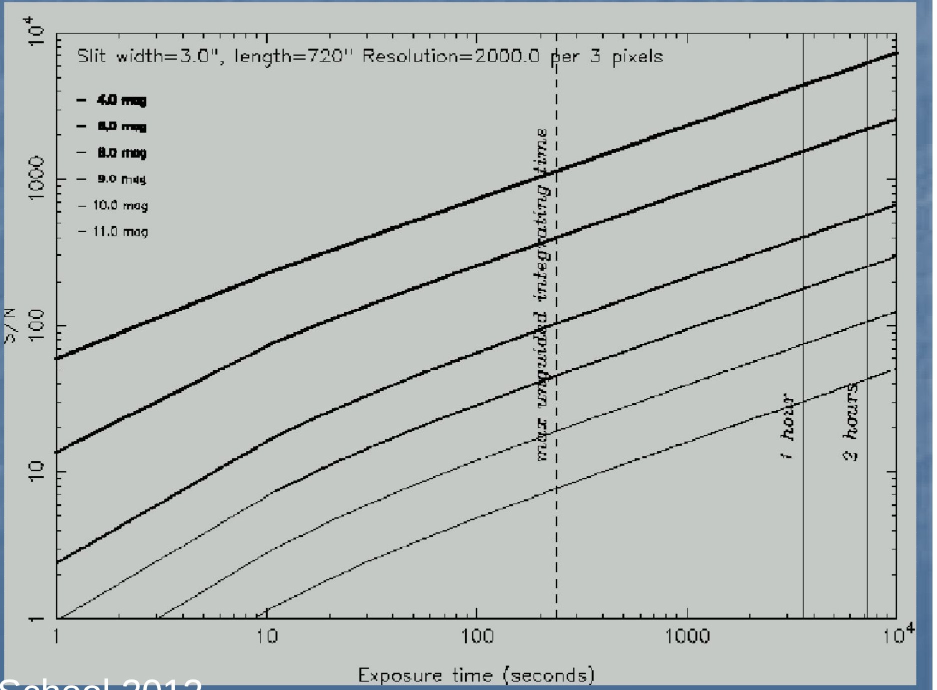
THE CASE OF IMAGING AND PHOTOMETRY



50.8−cm 20RC LNO for V=16.00 at zenith
S/N
1000
100
10
1
Integration time= 180.0 seconds
Moon phase: QUARTER
Solar analogue (inc. NEO)
I
R
V
B
σ (mag)
0.05
0
−0.5
0
0.5
1
1.5
B−V (mag)

THE CASE OF SPECTROSCOPY





Why can astronomers obtain good results with (modest) telescope ?

- We can "buy" no instrument suitable for our specifications, because the instrument cannot be built without any purposes.
- If you would make a project on the research, it is the first request for instrumentation in the world.

Develop and build our instrument by yourself !!
No instrument, no new science !

Every team which discovered historical results produced the instrument optimized for their research purposes by themselves. This is the natural and basic process for scientific research.

ANSWER