CCD “optical” PHOTOMETRY

Photometric Techniques I:
Observations, preliminary reductions and calibrations

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REFERENCES

CCD photometric properties

- **MACKAY, ARAA, 24, 259, 1986**
- **LEACH et al., PASP, 92, 233, 1980**
- **GUDEHUS et al., AJ, 90, 130, 1985**
- **MELLIER et al., AA, 157, 96, 1986**
- **AMELIO, Scientific American, 1974**

Data calibration

BESSELL, PASP, 89, 591,1979
COUSINS, MNASSA, 39, 93, 1980
BECKERT et al., PASP, 101, 849, 1989
ORTOLANI, CCD ESO Manual:calibration, 1992

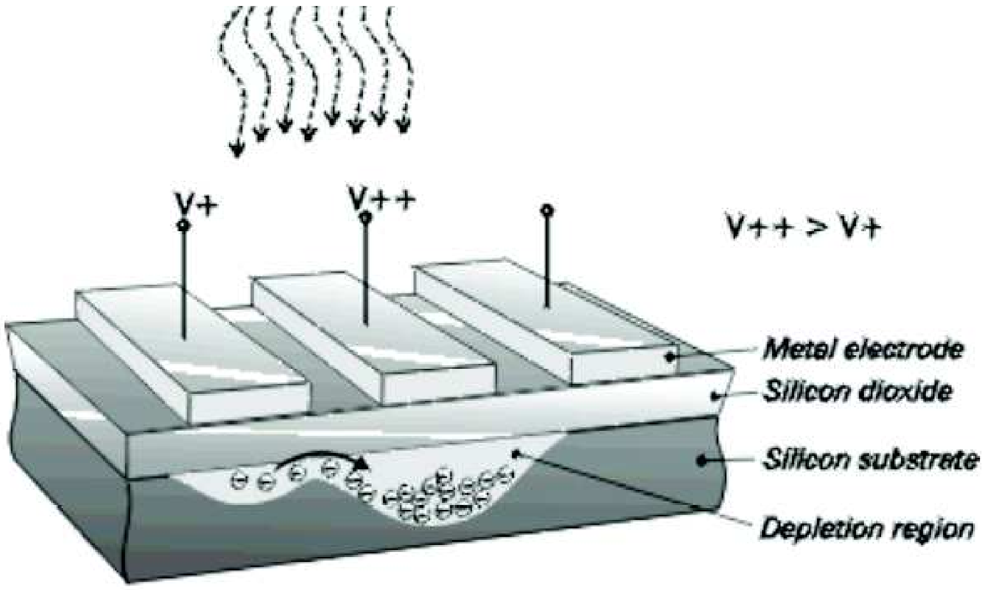
Reduction problems, errors observing techniques, sampling

- PEDERSEN, ESO Danish Tel. Manual, 1984 (obs. techn.)

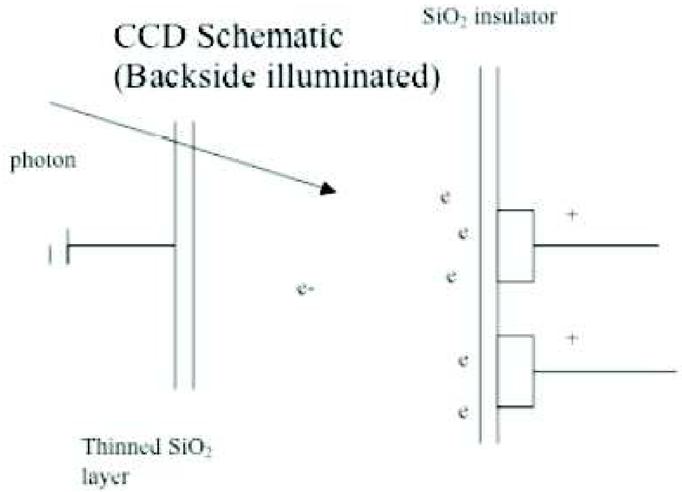
STETSON papers, for example:

- STETSON, Dom. Astr. Obs. Prepr., 1988 (flats, accuracy)
- STETSON, PASP, 117, 563, 2005 (cal. accuracy)

- ORTOLANI, “The optimization of the use... ESO/OHP workshop, 1986, p. 183 (reductions, general)
- KING, PASP, 95, 163, 1983 (sampling, star size)
- BUONANNO et al., PASP, 101, 294, 1989 (sampling)
- DIEGO, PASP, 97, 1209, 1985 (star shapes and size)
- MATEO, PHD thesis (completeness corrections !)



A CCD picture element



Q(λ) for different CCDs: frontside and backside CCDs

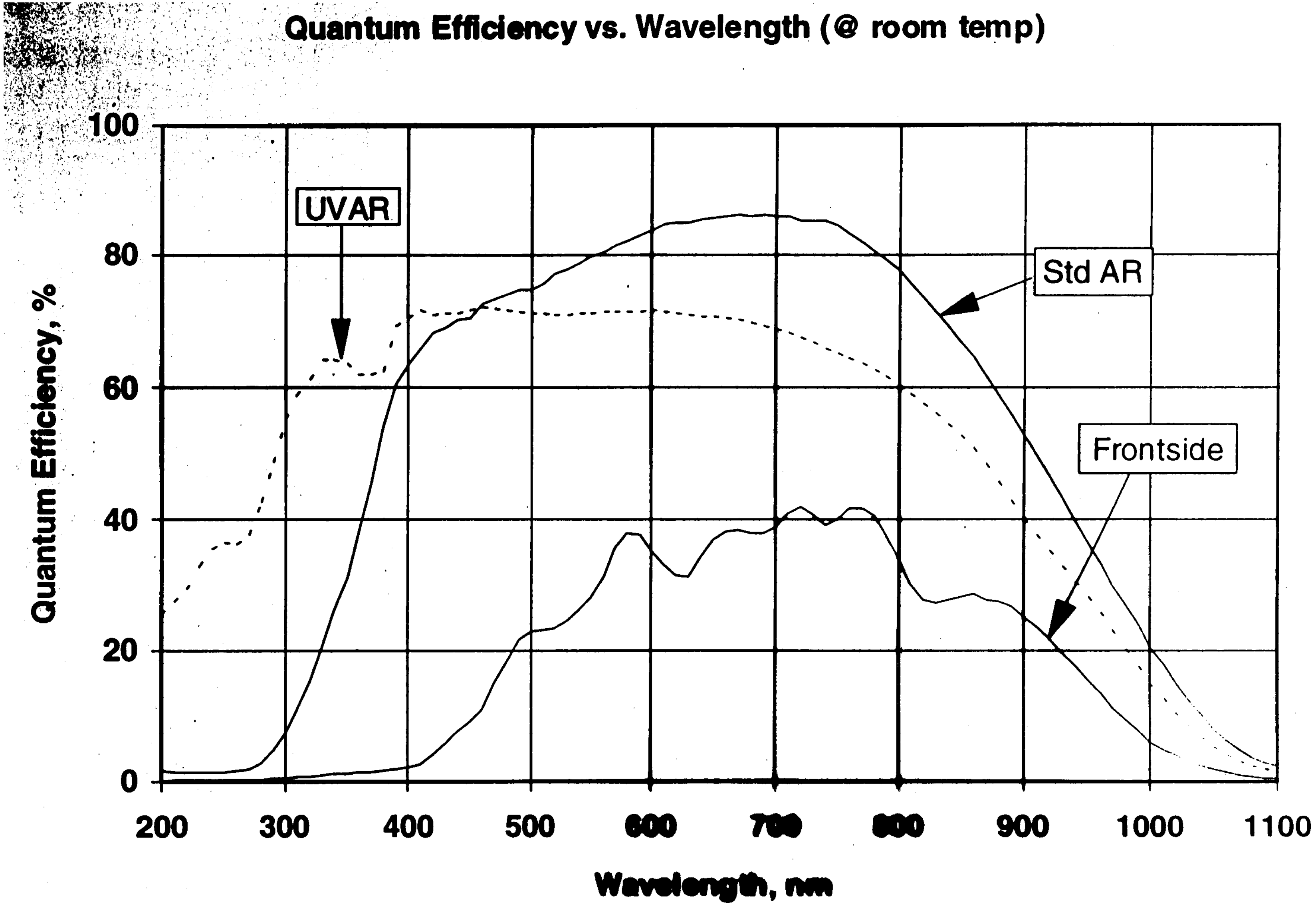


FIGURE 7 *Typical QE curves*

Some preliminary conclusions…

- **In the CCDs there are not pixel gaps.**
- **Charges can spill and the psf can change with the wavelength.**
- **The gain is very stable and not much dependent on the temperature.**
- **The wide band passband systems can change from different CCDs if the same filters are used.**

Two major steps: observing and reductions

Observing: (1) calculation of the S/N,

(2) observational strategies

Reductions: (1) preliminary reductions (bias, ff…)

(2) absolute calibration

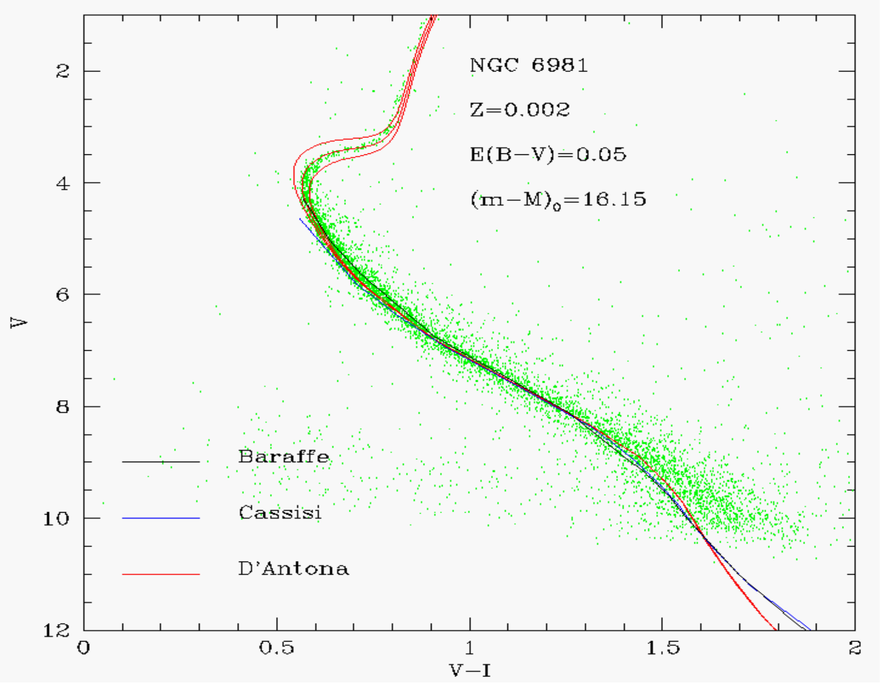
(3) photometry of the single stars

The goal

Why do we need accurate stellar photometry (1-5%) ?

Example: old star clusters, K giants

ΔV 0.1 mag. at TO~Δage 1.5 Gyr
ΔE(B-V)=0.03 ~ ΔV 0.1 mag.



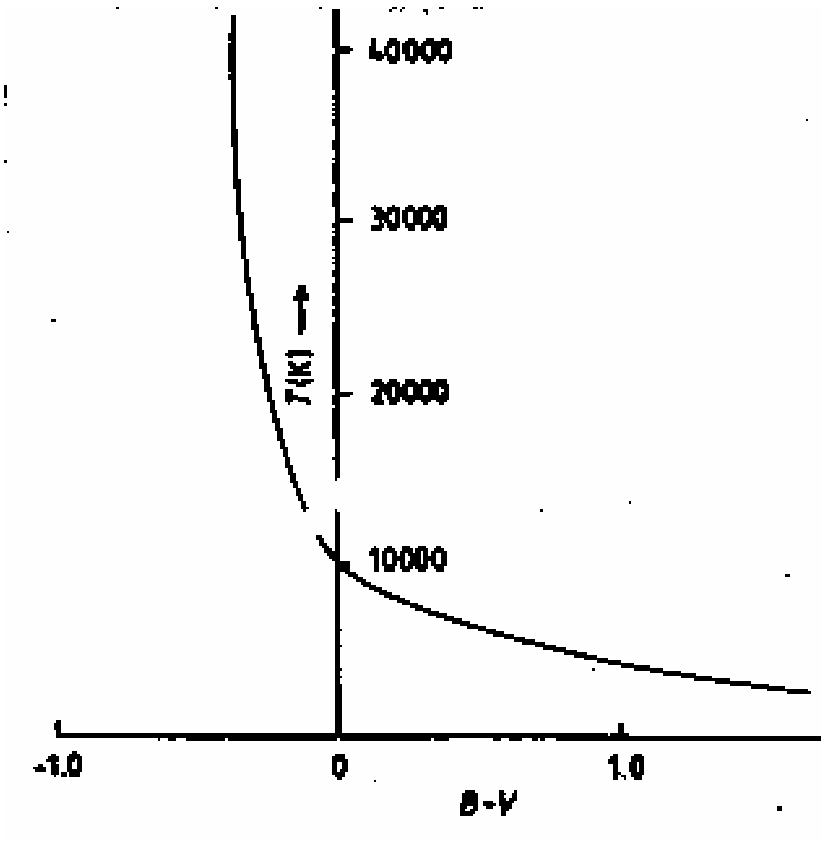
Temperature/color index relation

Main sequence stars:

$B-V = -0.865 + 8540T^{-1}$

$T = 8540[(B-V)+0.865)$ ^{o}K

$\Delta B-V=0.01 \xrightarrow{} \Delta T=35$ ^{o}K



The effect on metallicities is:

$\Delta(B-V)=0.03$ $\sim\Delta T=100K$ ➡

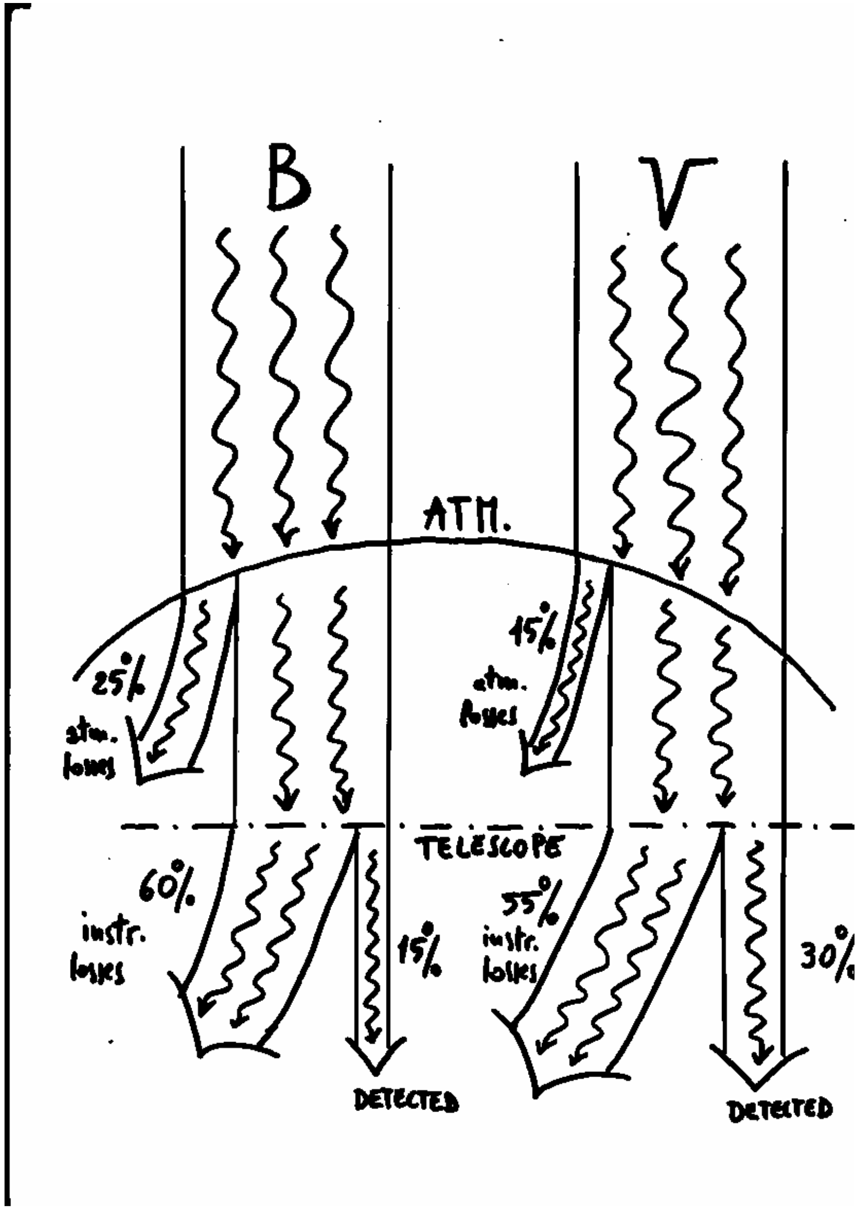
$\Delta[Fe/H]\sim0.07$, $\Delta[Ca/Fe]\sim0.1$! (K stars)

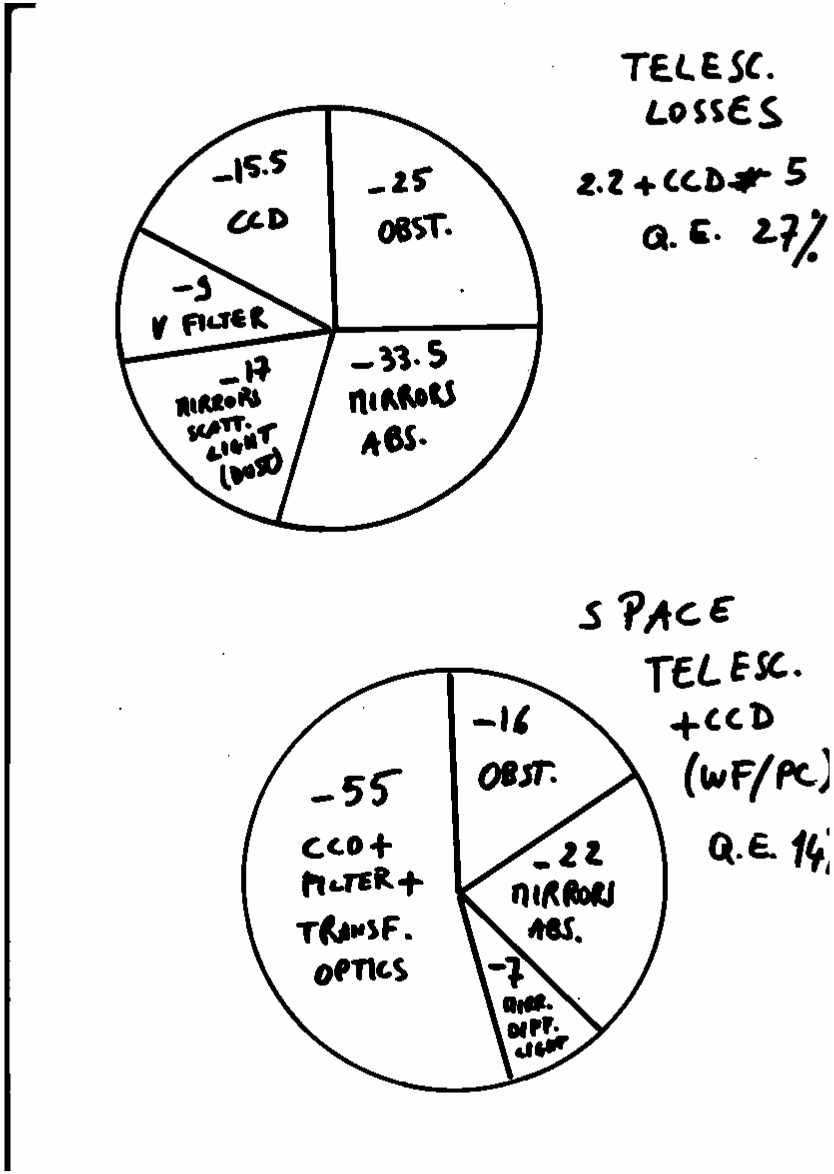
Good absolute calibration required !

The choice of the telescope/CCD

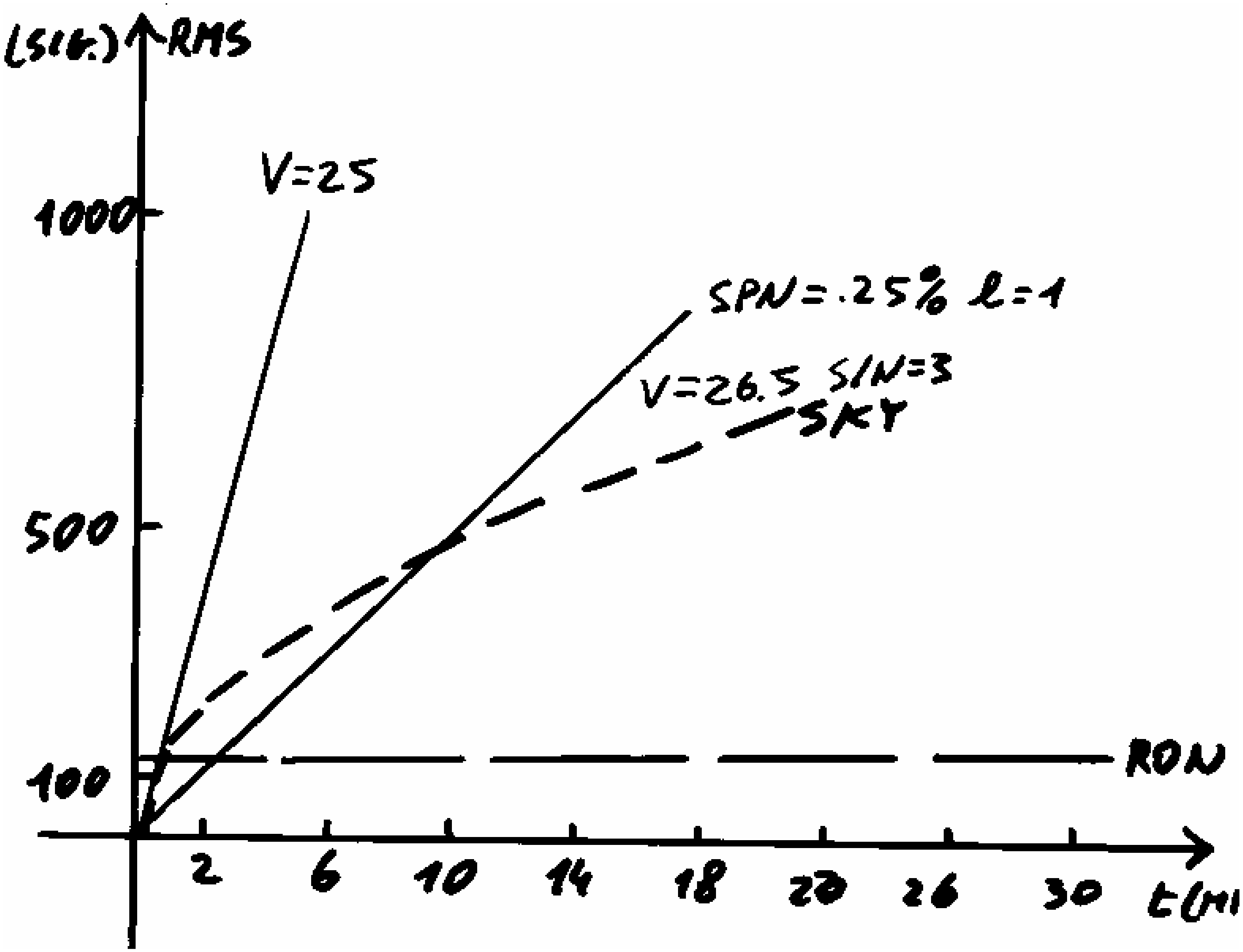
- Check the exposure time needed for the S/N
- A big telescope doesn’t mean more accurate photometry (avoid very short exposures !)
- Choose the optimal CCD camera for the specific bands: a larger telescope doesn’t compensate a non-optimized CCD
- Remember that most of the photons in BVRI are lost in the telescope/instrumentation (not in the atmosphere)

Most of the photons are lost in the detection system (telescope+instrument)





EXAMPLE OF NOISE SOURCES AND SIGNAL AS A FUNCTION OF THE EXPOSURE TIME



SIGNAL TO NOISE RATIO
LIMITING MAGNITUDE WITH CCDs

$S/N = \frac{s \times t}{N}$ AT LIMIT $S/N < {10 \atop 3}$

$$N^2 = \sigma^2_{SHOT} + \sigma^2_{R.O.N.} + \sigma^2_{SPN} + \sigma^2_{DARK+COSMICS} + \sigma^2_{SKY}$$

$$N = \sqrt{s \times t + RON^2 \times A_{ST.} + SKY \times t \times A_{ST.} + (F \times SKY \times t)^2 + DARK \times t \times A_{ST}}$$

WITH: $A_{ST.} = FWHM^2 \times \pi$ (KING, PASP, 95, 163)

$s_{V=0} = R^2_{TEL.} \times \pi \times$ [redacted] $10^6 \times Q.E._{TOT.}$ (fot/sec.)

$F^2 = F_1^2 \times A_{ST} + F_2^2 \times A_{ST}/4 + F_3^2 \times A_{ST}/9 \ldots$

$F_1, F_2, F_3 \ldots$: SPATIAL NOISE COEFF. AT $\ell = 1, 2, \ldots$

$$m_{lim} = -2.5 \, LOG \left(\frac{(S/N) \times N}{s_{m=0} \times t} \right)$$

WITH $N \propto \sqrt{A_{t.}}, t, \sqrt{t}, \sqrt{Q.E.}$
$s \propto Q.E., A_{tel}$, mag. zero point

$\rightarrow m_{lim} \propto \sqrt{A_{TEL}}, \sqrt{t}, \sqrt{Q.E.}$ IF SKY IS NOT VERY HIGH

SUGGESTIONS FOR A SUCCESSFUL OBSERVING RUN

- **Use nomograms for the object sequences**
- **Plan tests for error sources (shutter timing, linearity deviations, sky variability, vignetting, sky concentration…).**

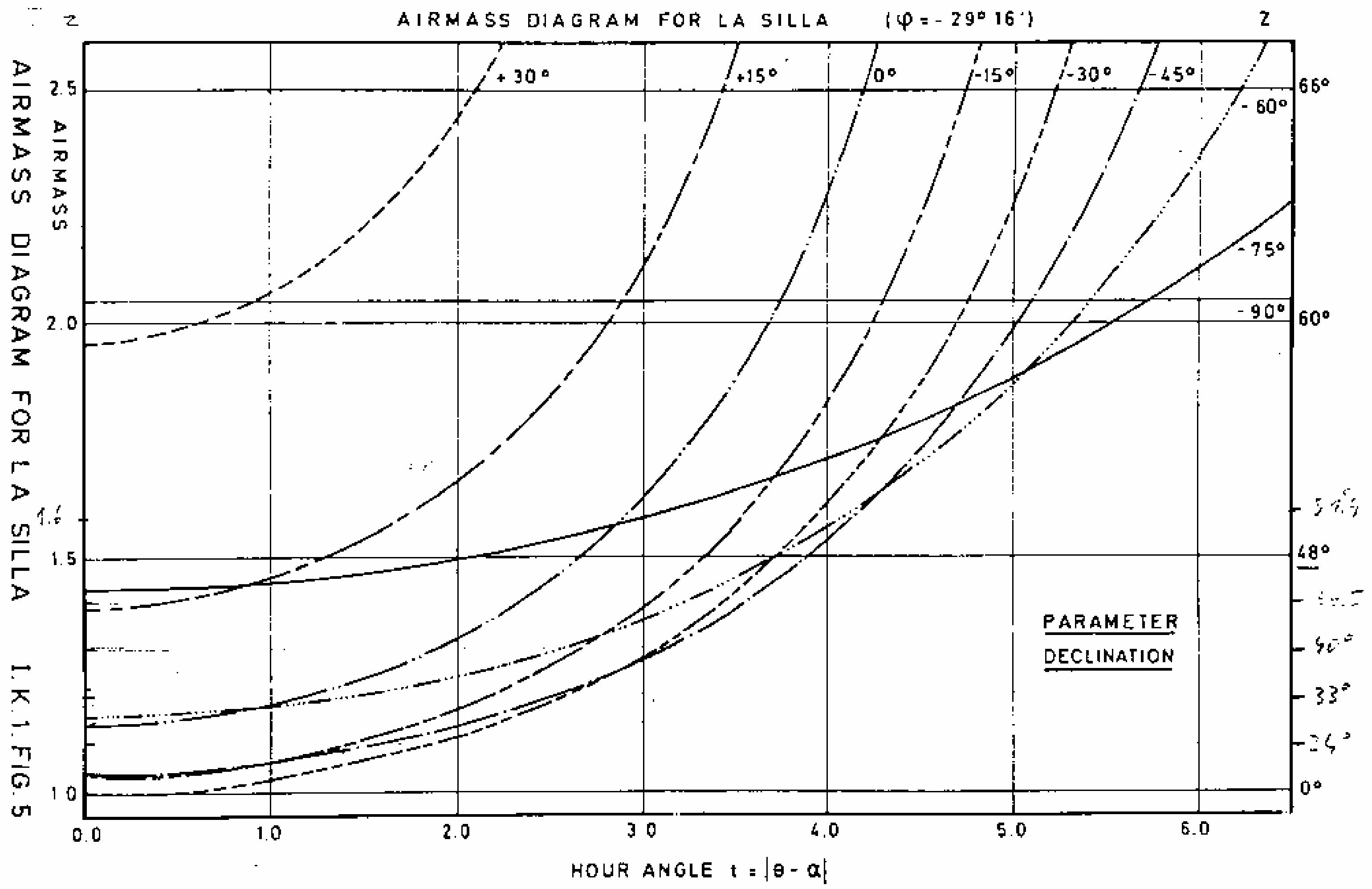
AT THE TELESCOPE…:

- **Measure at least a couple of standard stars on line**
- **Check the flat fields at the telescope**
- **Take notes, and make a report of any peculiarity (even if you trust your memory…)**

- **Repeated observations are fundamental**

LA SILLA NOMOGRAM

senh = senδsenϕ + cosδcosϕsenH



AIRMASS DIAGRAM FOR LA SILLA I.K.1.FIG.5

A TYPICAL OBSERVING SEQUENCE

- Preliminary operations (focus, pointing…);
- Standard stars
- Target(s)
- Standard stars at half of the night
- Target(s)
- Standard stars at the end of the night
- Sky flat fields

At the beginning. The standard sequence

- At the sunset: (1) take sky flats (if not already in the library), (2) check active optics and focus.
- Take a sequence of standard stars (at least one standard field, if possible two): observe the standards in all the required filters (minimum through two filters). Exposure time longer than the minimum calculated for the shutter accuracy.
- Repeat it. Take another one 5-10 time longer and repeat it. Shift and repeat the whole sequence.
- Observe with two exp times in all the filters.
- Repeat with the first filter (check atm stability).

OBSERVATIONS OF THE TARGETS

- The targets (as well as the standard fields) should be located within about +/-2 hours from the meridian. Avoid near the zenit with altazimut telescopes.
- Observe with a short exposure time to be sure to avoid saturation (typically 10s – 1 min.).
- Proceed with a long exposure, or multiple exp.
- Repeat with another filter.
- Focus (seeing) and saturation should be checked.
- Another standard sequence may be required.

FOR A HIGHER PHOTOMETRIC ACCURACY

- Multiple exposures in the same frame.
- Put the objects in the same position of the standard stars , on the CCD.
- Defocus (for bright, isolated objects only). Millimagnitudes can be reached only from defocused images (see also Corot, Kepler…)
- Faint objects are sensitive to the flat field correction: multiple shifted observations, drift scanning technique.

“Standard” preliminary reductions of CCD images:

corr. ima. = [(raw-bias)-(dark-bias)]/flat

flat field = (sky flat – bias)/ave. value

High and low frquency flat fields may be required from the sky (low fr.) and from the dome (high fr.)

Assumptions: the detector is linear, the bias is constant and the gain does’t depend on the signal...

QUESTION:

Flat field subtraction or division ?

In the infrared (JHK) the sky must be subtracted before ! Why ? Non linearity effects.

Don’t degrade the S/N of your original images !

Be careful with the divisions between images

An accurate preliminary reduction is a complex operations. In order to avoid degradation of the S/N the noise propagation for each mathematical operation should be evaluated. For example, if a and b are statistically independent quantities:

if: $c = a/b$ then $\sigma_c^2 = \sigma_a^2/b^2 + a^2/b^4 \sigma_b^2$

In many cases the bias and dark can be replaced by a fixed value.

The first operation: BIAS subtraction

1) from overscan columns (problems with charge transfer);

2) from very short dark exposures (it can be higher, because of CCD “heating” ?);

3) from signal vs. noise diagrams (from flat field couples).

CHECK BIAS AT THE TELESCOPE

Errors in the bias level may affect the photometric accuracy with low sky.

FLAT FIELDS

1) from dome exposures
2) from twilight sky
3) from internal lamps

Problems with: REFLECTED LIGHT (sky concentration), light distribution (dome flats), colors (lamps), signal to noise ratio (sky flats).

Errors up to 10%.

Combined flat field corrections sometimes needed

Check the noise of the corrected images

Check the accuracy with distributed standard stars

Avoid very high signals and very short exposures.

Effect of the flat field corrections on the noise of a image.

The noise decreases with the scale length because of the bigger sampling.

From Leach et al. 1980.

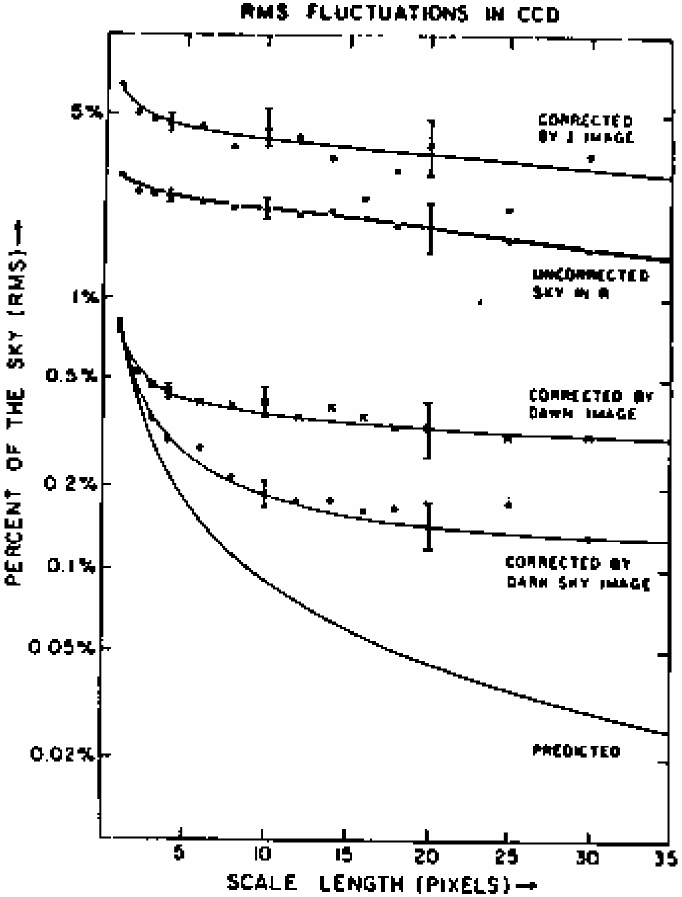


FIG. 6—The rms variation between the means of groups of pixels as a function of the scale length for four images of the night sky. The top plot is for image (d) of Table I, running through image (g) at the bottom. The plots exhibit a progression of increasingly accurate flat-field correction, with the best results obtained when sky was used to correct sky and the worst results occurring when a flat-field of the wrong color was used. The predicted line assumes that counting and readout noise are the only contributors to the nonuniformities, and varies as the inverse of the scale length.

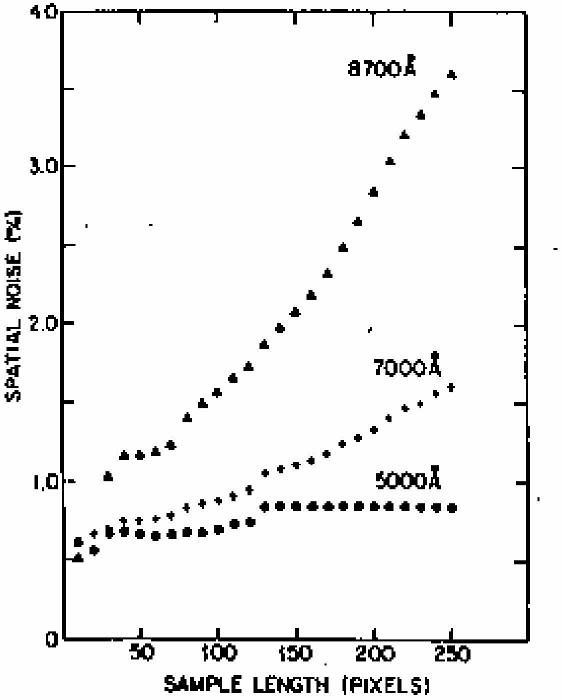


FIG. 11. CCD spatial noise as a function of wavelength and sample size.

SKY CONCENTRATION: an increasing problem...

"Calibrating and understanding HST and ESO instruments" in April 1995 and published in the proceedings edited by P. Benvenuti and printed by ESO. The paper is by M.I.Andersen, L. Freyhammer, and J. Storm and can be found on page 87 in the proceedings.

Web address:

http://www.ls.eso.org/lasilla/Telescopes/2p2T.old.obsolete/D1p5M/RepsFinal/Final/gain_calibration.ps

Andersen et al., 1995

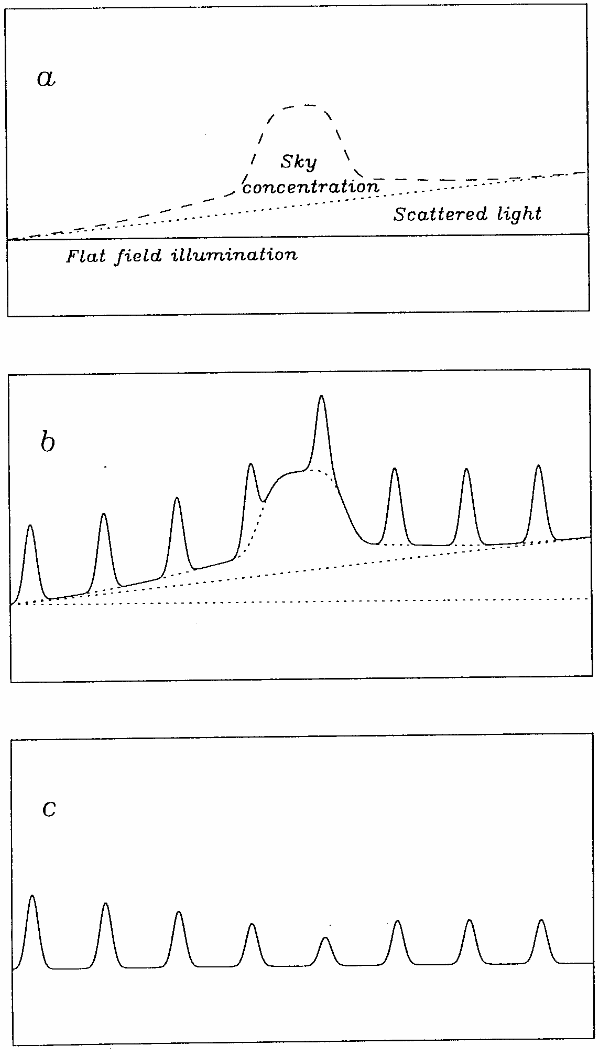
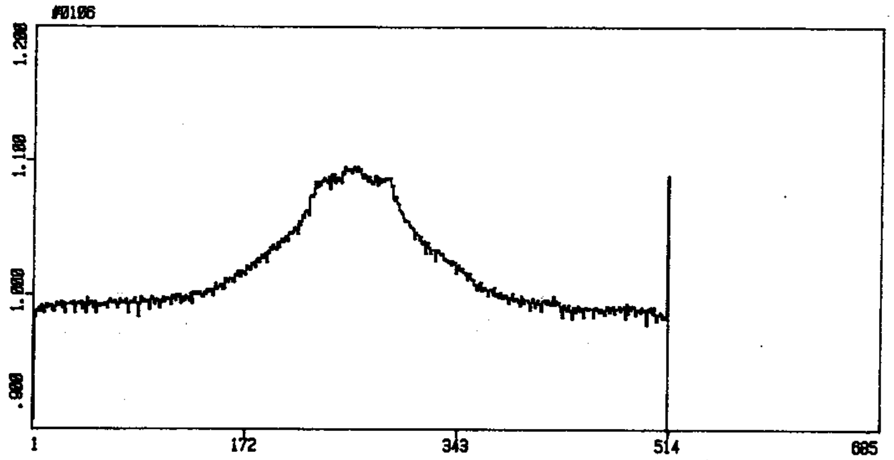


Figure 1: *a)* An example of a flatfield exposure from a focal reducer type instrument with the various error contributions shown as dashed and dotted lines.

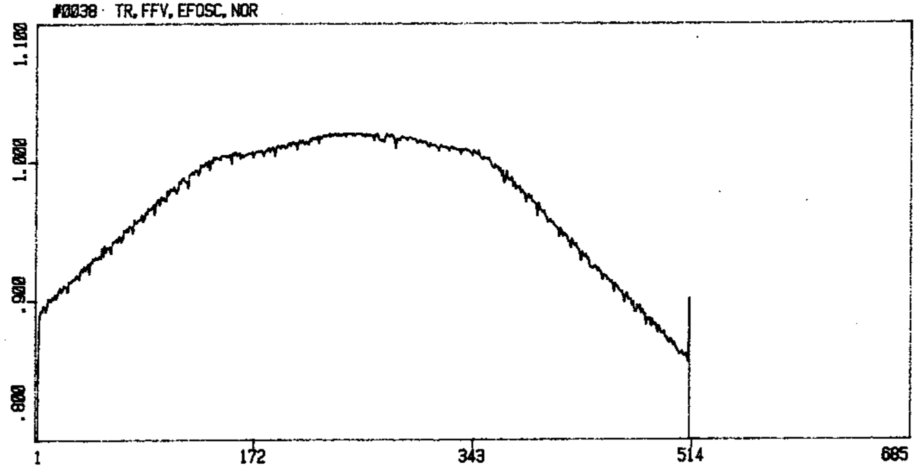
b) An example of a science exposure with eight equal brightness stars superimposed on a flat sky background. The scattered light and sky concentration is assumed to originate preferentially from the sky light and thus to be identical to the distribution in the flat field in panel a.

c) The resulting science frame after flatfielding with the uncorrected flatfield from panel a. Note that the background appear perfectly flat but the stars no longer have equal brightness. These intensity errors are the ones we try to determine and correct for.

FF V AVS 8180 EFOSC + CCD#11
XADD 160,165
SCAN Y



sky concentration
CCD #11 at EFOSC

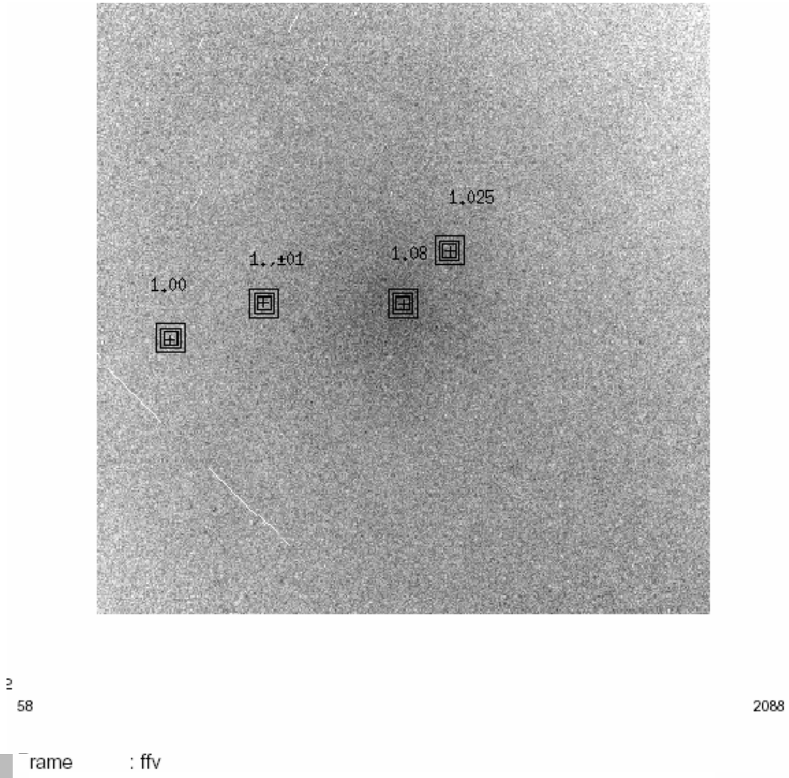


Vignetted flat field

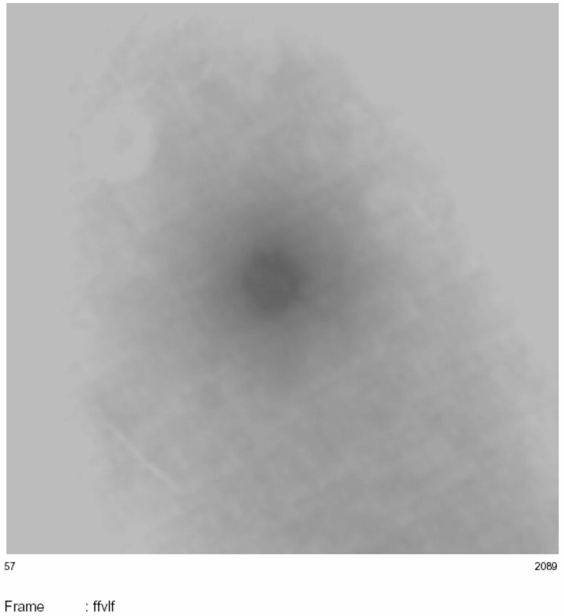
CCD #3 at EFOSC1

TNG + OIG, 2008

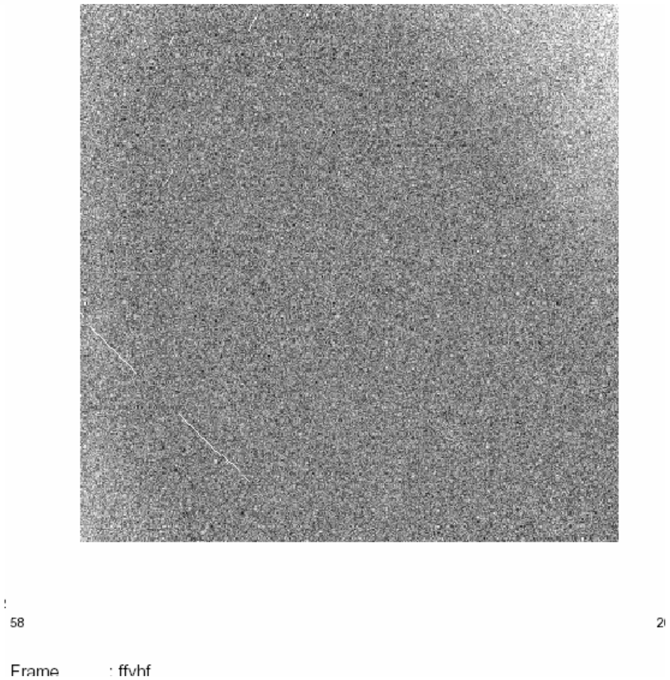
Sky flat, V



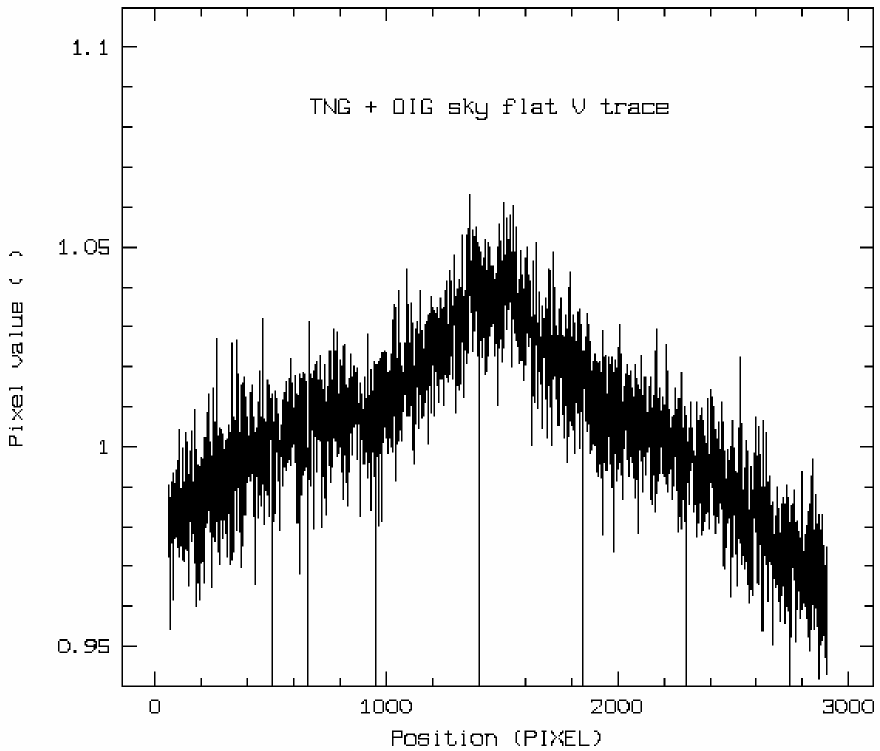
Light concentration

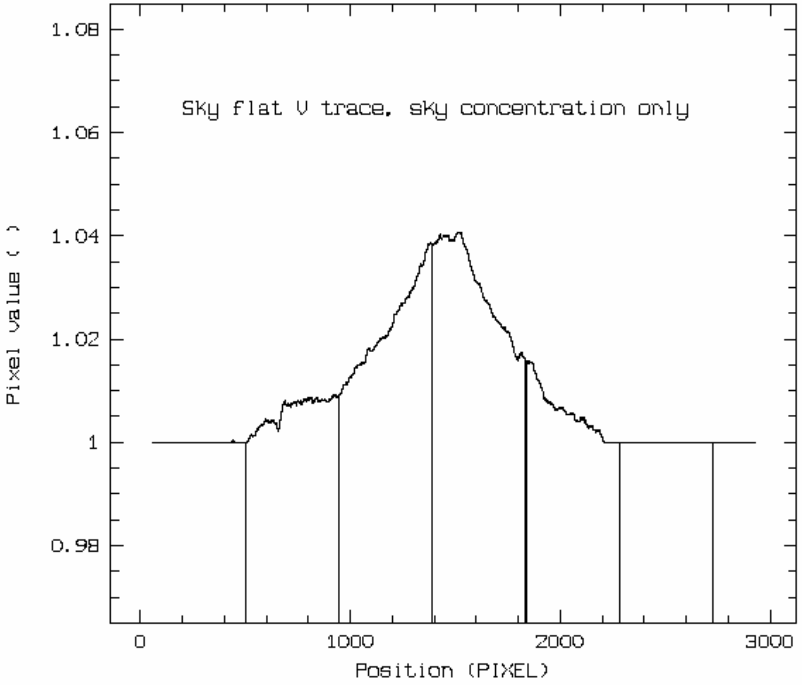


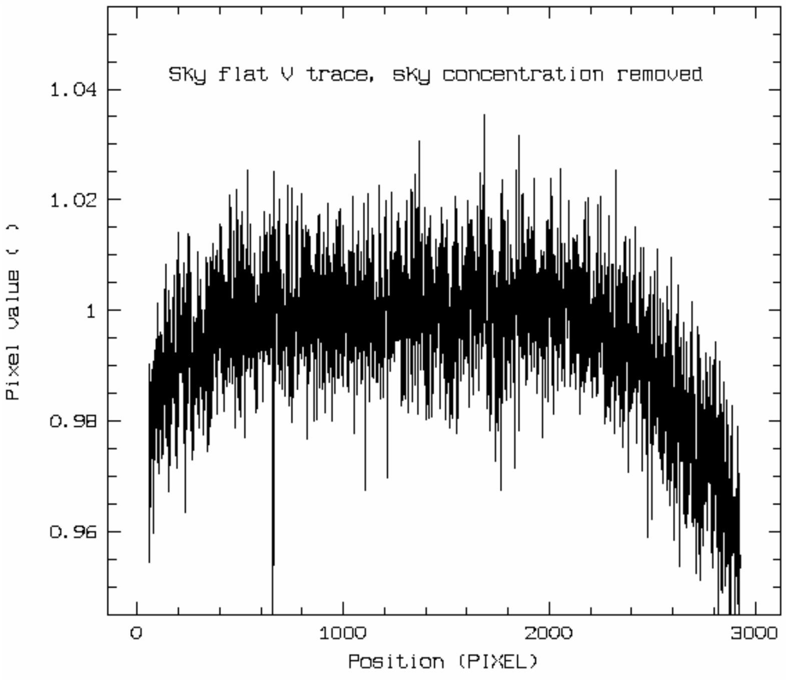
High frequency



Corner to corner scans







Photometric calibration

- Standard stars out of the field

-The calibration equations: reduction to the standard system and determination of the zero points (calibration parameters)

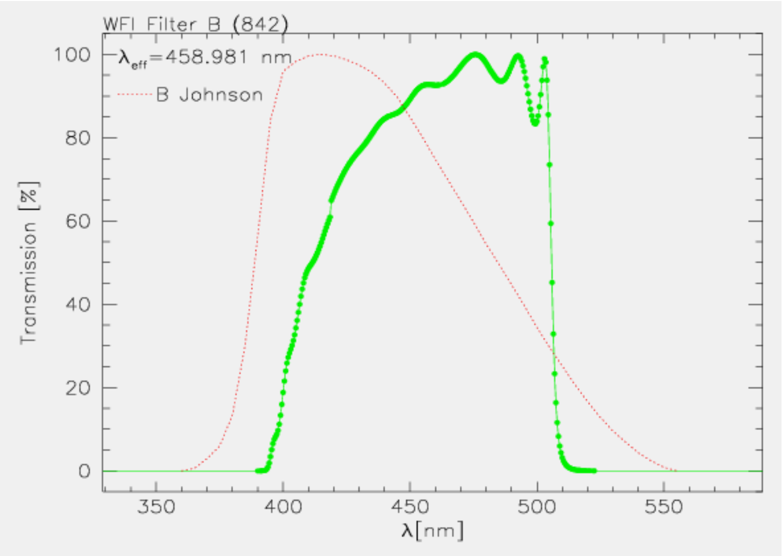
Problems: seeing variations, aperture corrections, air mass corrections, sky transmission variations, shutter time delay corrections, and red leaks …

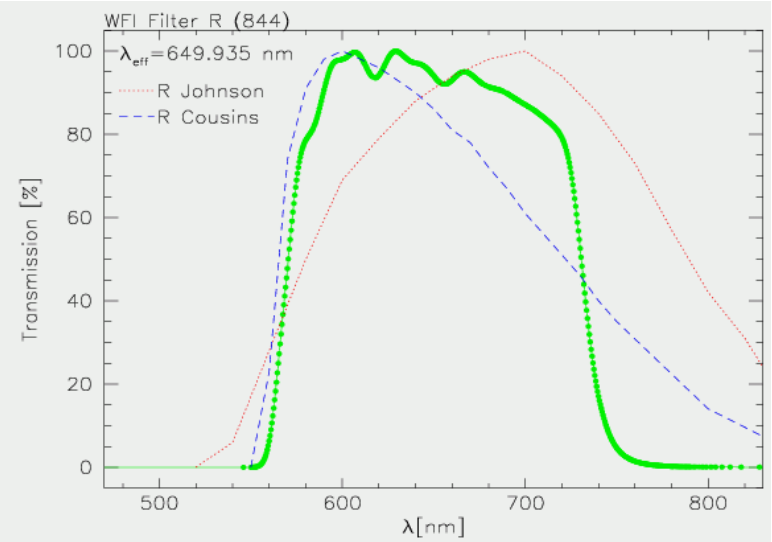
Calibration errors +/-0.01 - 0.02 mag.

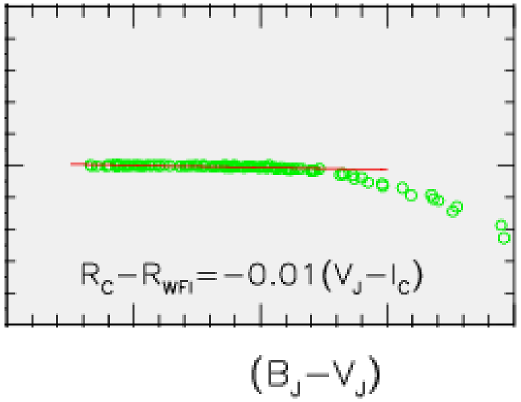
It is important to realize that, even if the filters are properly selected any observational system is always different from the standard one.

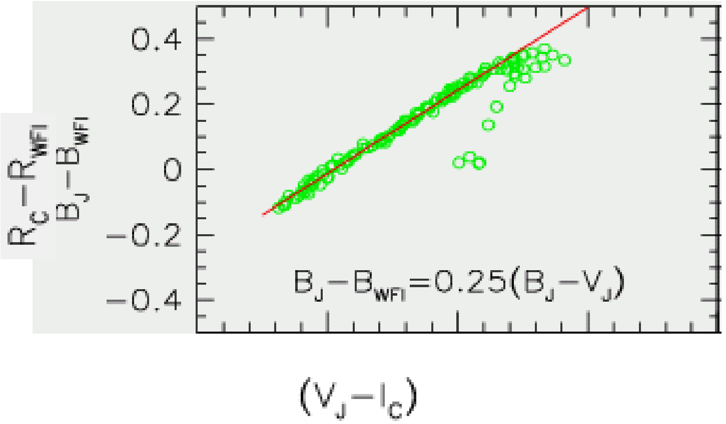
The Asiago Data Base on Photometric Systems lists 218 systems (see http://ulisse.pd.astro.it/ADPS/enter2.html)!!!

But, even when you have chosen your photometric system, you might still be in trouble! See, for example, WFI at the ESO 2.2m:









CHECKING THE REAL EXPOSURE TIME

Shutter timing delays may occur. Safe exposure times are typically between 10 to 30 s. The delay usually extends the real exposure time. Furthermore the exposure time can be variable across the field.

Check with different exposure times.

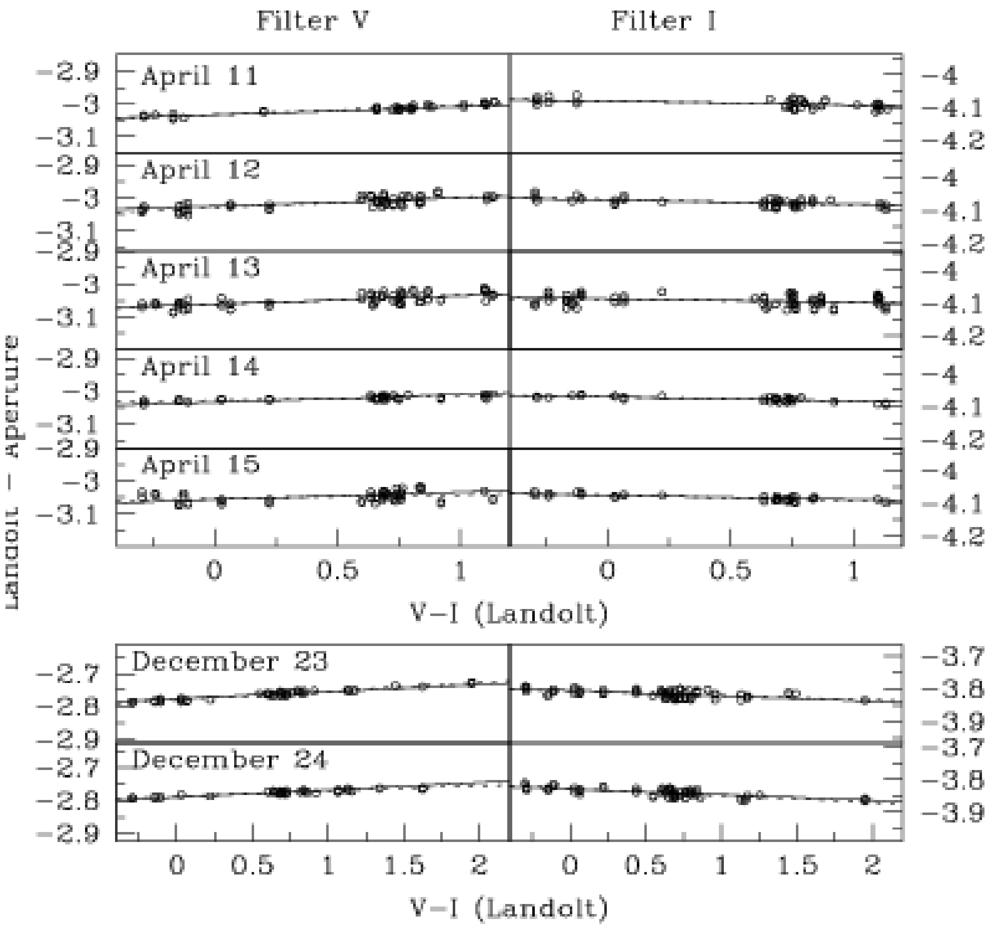
ABSOLUTE photometric calibration

Let’s suppose that we have collected a set of images of our program objects through a set of filters properly designed to reproduce a **“standard” photometric system** for which **a large set of standard stars**, covering a large color interval, are available in the literature (for example Landolt, AJ 104, 340, 1992 for UBVRI).

The standard stars define our photometric system.

In order to calibrate the magnitudes and colors of our program objects, we need to observe the standard star fields, at different times during the night, making sure that the observed standards cover a sufficently large color interval at least as the targets interval.

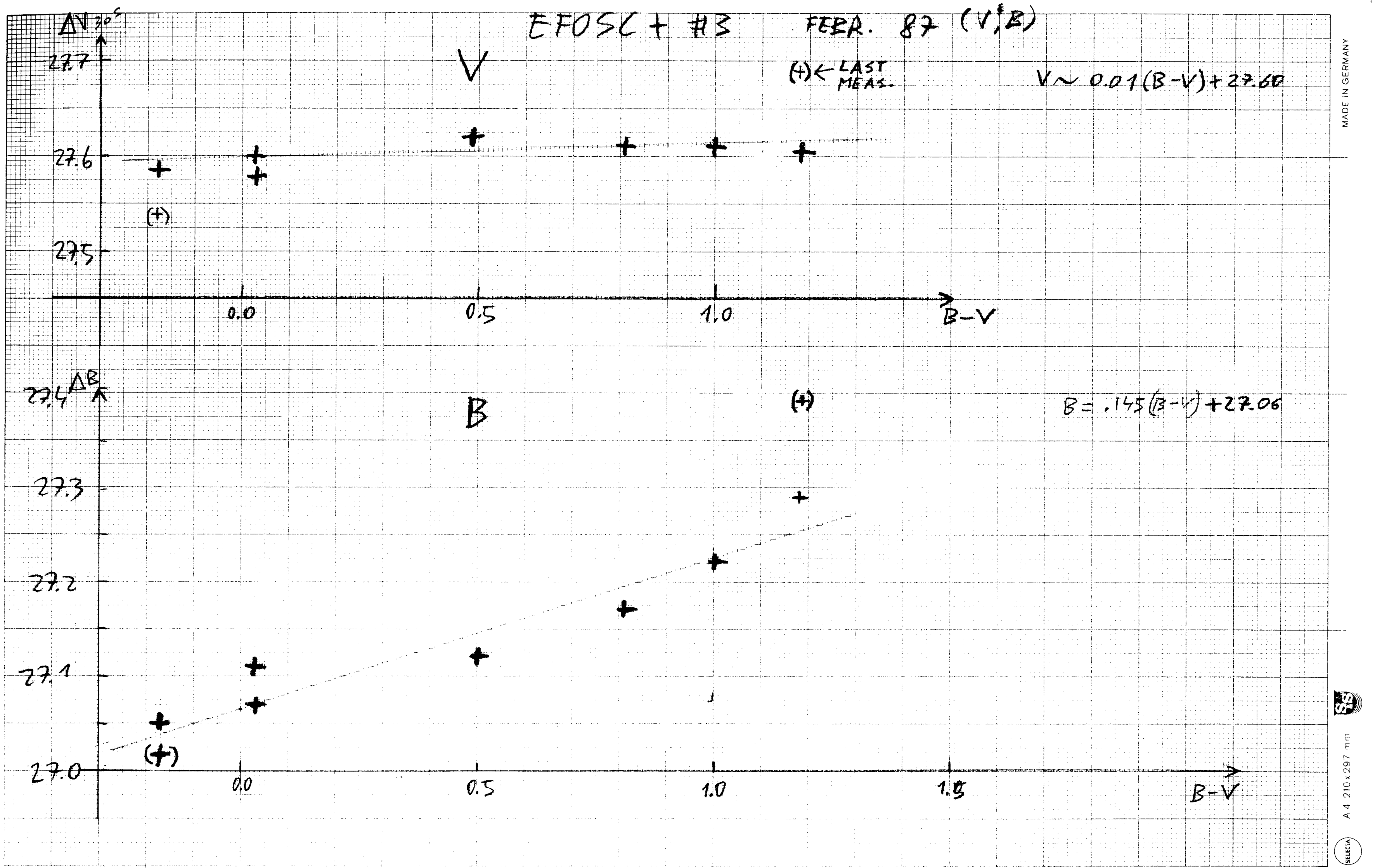
A diagram with the color index vs. the difference between the instrumental magnitudes (m=-2.5logI) and the standard ones (from the catalogues) will be produced. The linear interpolation to the data will give the slope and the zero point of the calibration equation. The zero point corresponds to the counts (or instrumental magnitude) from a m=0 star.



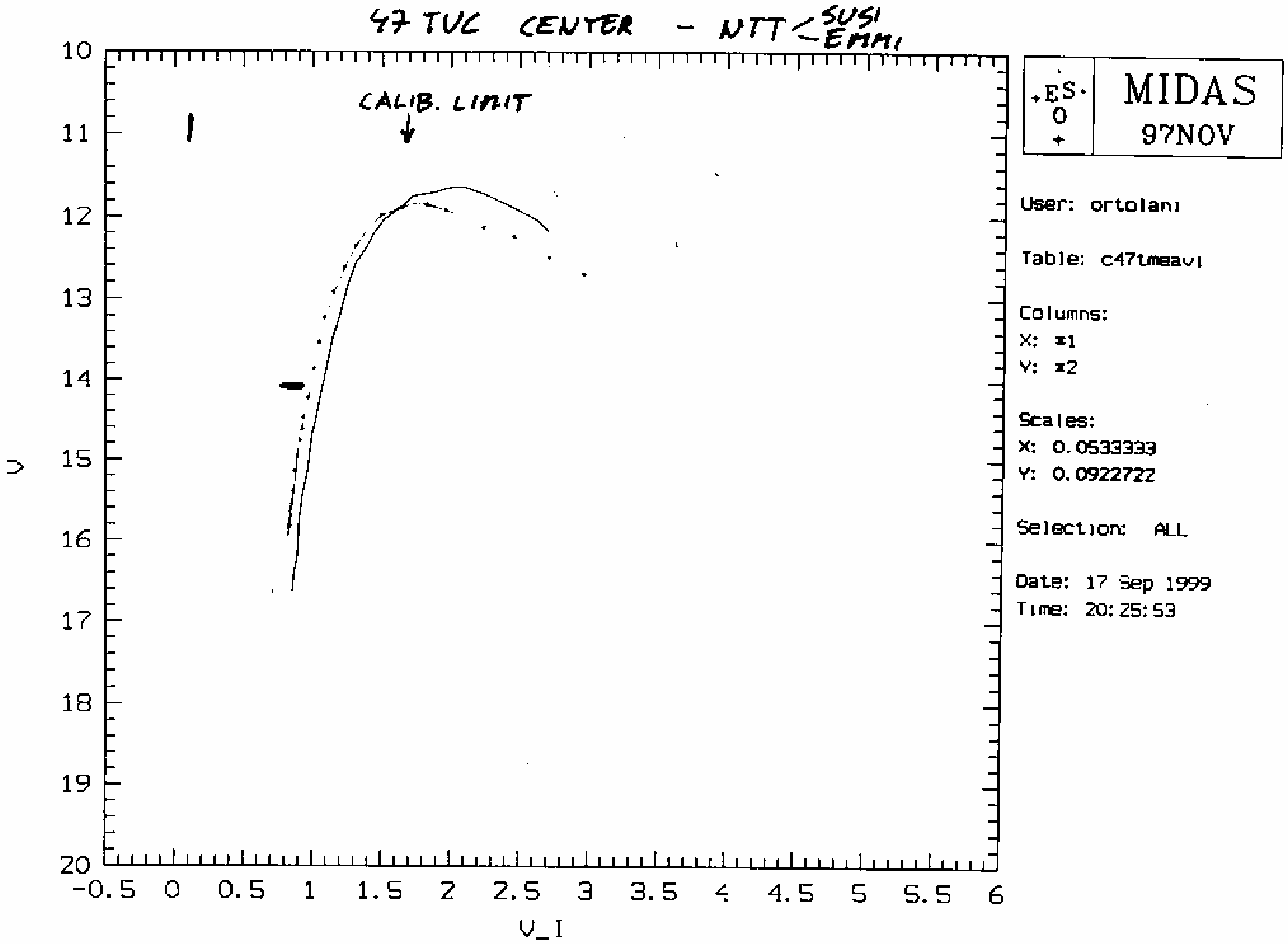
For well designed observing systems, and for not too extreme colors, a linear fit may be enough.

Example of calibration eq.s to the Johnson-Cousins standard system for rhe ESO-Dutch telescope (from Rosenberg et al. 2000). Notice the concentration of data around V-I = 0.7. The slope depends mainly on the extreme blue and red standards.

The slope is constant, the zero point changes from night to night.
The B and the U coefficients are higher than V and I



Extrapolations from the calibration equations are not recommended, example:



User: ortolani

Table: c47tmeavi

Columns:
X: #1
Y: #2

Scales:
X: 0.0533333
Y: 0.0922722

Selection: ALL

Date: 17 Sep 1999
Time: 20:25:53

RED LEAKS

Red leaks in the photometric systems in theory can be detected cheking the flat fields or the distribution of standard stars measurements. In fact they must be checked in laboratory.

A RECIPY

Simple quantitative considerations show that the red leaks for 1 % absolute photometry should be reduced down to 10^{-5} in the U band 10^{-4} in the B and 10^{-3} in the V, assuming that it is dominating at 0.9 μ in a 0.1 μ wide band (Ortolani, ESO La Silla technical note, 1985).

General remarks

From the previous examples we have learned a few important things:

1. Observations must be calibrated into a standard system.
2. We need to use as much as possible a starting “standard” photometric system, but the reddening law and the models can be different.
3. If your photometric bandpasses are far from any existing photometric system, you have to calibrate your system starting, for example, from A0 stars (good luck!);

THE ZERO POINT OF THE CALIBRATION

The next step is to calculate the aperture correction, i.e. the zero point difference between the (fitting) instrumental magnitudes of the program stars, and the aperture photometry used to obtain the calibration coefficents of the standard stars.

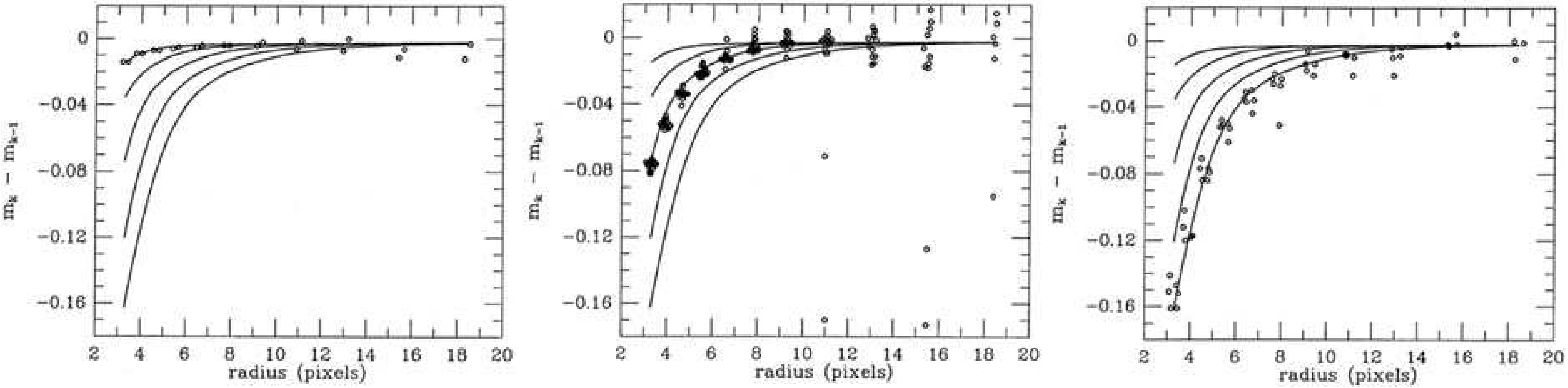
THE APERTURE CORRECTION

OR

HOW MUCH LIGHT OF THE STANDARD vs. OUR STARS IS INCLUDED IN THE MEASUREMENTS ?

It could be a large correction and a delicate step if:

- **The standard stars have been defocused or the seeing is very different among different frames;**
- **Very difficult in very crowded fields**
- **In general you should create empirical GROWTH CURVES…**



Examples of **growth curves** for different seeing conditions, from the same observing run.

In crowded fields the growth curves could be noisy due to blends.

In order to improve the correction, one can fit to the aperture photometry differences a model, or use diagnostic diagrams.

A very useful reference: sinthetic growth curves from lorentzian model profiles (Diego, PASP, 1985)

A practical, useful result:

the aperture correction, when the FWHM is equal to the aperture radius, is around 0.3 magnitudes.

1214 F. DIEGO

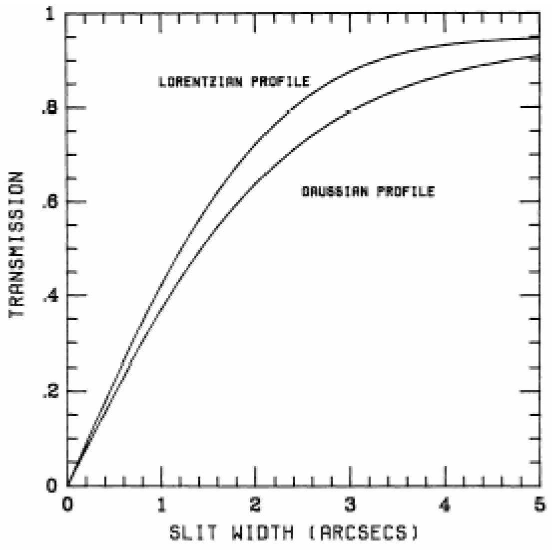


FIG. 5–Transmission of a long slit for a FWHM seeing of 2.0 arc secs, for Gaussian and Lorentzian point-spread functions.

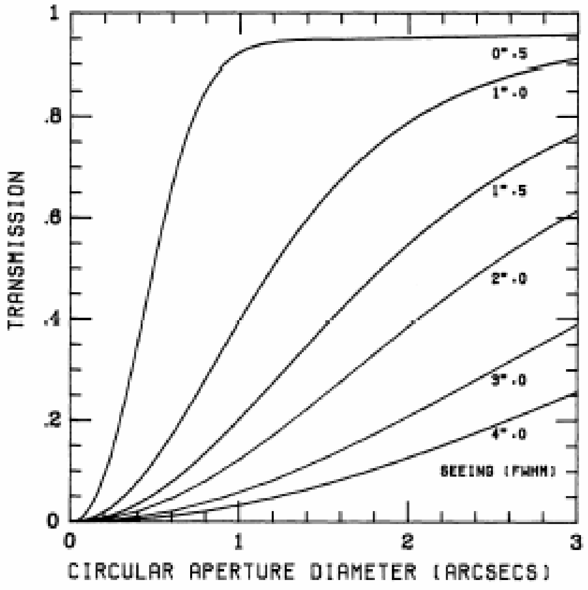


FIG. 6–Small circular aperture transmission as a function of seeing FWHM (in arc secs).

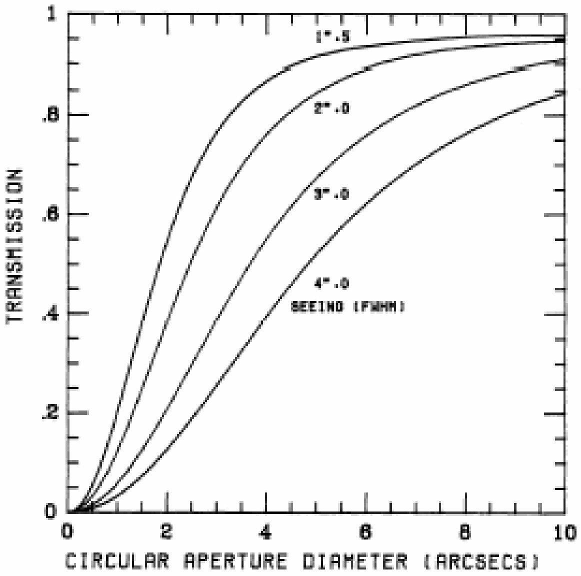
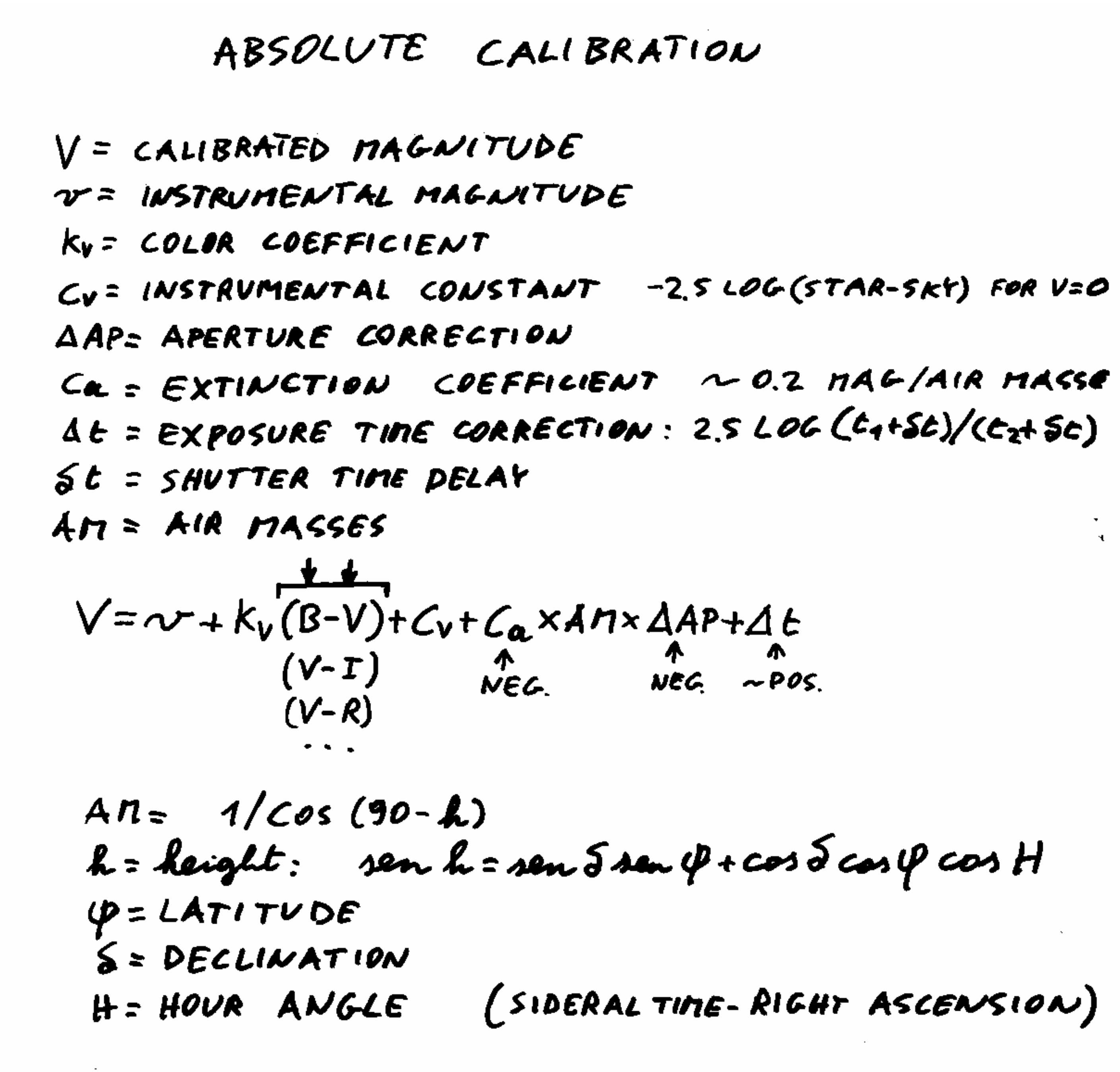


FIG. 7–Large circular aperture transmission as a function of seeing FWHM (in arc secs).

Once the calibration coefficents have been obtained, the aperture corrections, atmospheric extinctions and time differences have been calculated, the corresponding calibration equations can be applied to the instrumental magnitudes of the program stars, to transform them into calibrated magnitudes.



ABSOLUTE CALIBRATION

V = CALIBRATED MAGNITUDE

v = INSTRUMENTAL MAGNITUDE

k_V = COLOR COEFFICIENT

C_V = INSTRUMENTAL CONSTANT −2.5 LOG(STAR−SKY) FOR $V=0$

ΔAP = APERTURE CORRECTION

C_a = EXTINCTION COEFFICIENT ~ 0.2 MAG/AIR MASSE

Δt = EXPOSURE TIME CORRECTION: $2.5 \text{ LOG } (t_1+\delta t)/(t_2+\delta t)$

δt = SHUTTER TIME DELAY

AM = AIR MASSES

$$V = v + k_V \overbrace{\underset{\substack{(V-I)\\ (V-R)\\ \cdots}}{(\overset{\downarrow}{B}-\overset{\downarrow}{V})}} + C_V + \underset{\substack{\uparrow\\ \text{NEG.}}}{C_a} \times AM \times \underset{\substack{\uparrow\\ \text{NEG.}}}{\Delta AP} + \underset{\substack{\uparrow\\ \sim\text{POS.}}}{\Delta t}$$

$AM = 1/\cos(90-h)$

h = height: $\text{sen } h = \text{sen } \delta \text{ sen } \varphi + \cos\delta \cos\varphi \cos H$

φ = LATITUDE

δ = DECLINATION

H = HOUR ANGLE (SIDERAL TIME − RIGHT ASCENSION)

BUT, it is not enough: the calibrated index is unknown...

(2) THE FULL CALIBRATION SYSTEM: TWO EQUATIONS ARE NEEDED

CALIBRATION EQUATIONS

FROM STAND.
$$\begin{cases} B = b + K_B(B-V) + C_B + \dots \text{(ATM. EXT.)} \\ V = v + K_V(B-V) + C_V + \dots \text{(ATM. EXT.)} \end{cases}$$

WITH B, V MAGNITUDES IN THE STANDARD SYSTEM

b, v INSTRUMENTAL MAGNITUDES

K_V, K_B, C_V, C_B CONSTANTS

$$\rightarrow B-V = b - v + (B-V)(K_B - K_V) + C_B - C_V$$

$$B-V = (b-v)\frac{1}{1+K_V-K_B} + (C_B - C_V)\frac{1}{1+K_V-K_B}$$

WHERE $\frac{1}{1+K_V-K_B} \gtrsim 1$

CONCLUSIONS

An important conclusion is that we always need to observe our objects in two bands. From a physical point of view this means that we need a parameter in order to define the shape of the spectrum. Then the corrections corresponding to their spectra will be applied in order to transform their “instrumental magnitude system” into the system defined by the standard stars.

Objects observed in a single band cannot be calibrated if their spectral type is not known. Possible errors are of the order of magnitude of the slope of the calibration line.

HOWEVER:

1) **peculiar spectra objects cannot be properly calibrated (for example multiple black body spectra, late type stars with peculiar metallicities…);**

2) **Very red or very blue stars are very difficult to calibrate because there are very few good standard stars with colors below B-V=0.4 or above 1.2. Stars outside this interval are often variables (red stars are long period variables, blue stars are often pulsating stars within the instability strip). The reddening should be also considered because it changes the shape of the spectra. Deviations from the linear interpolation are expected.**

Recent tests indicate errors up to 0.3 magnitudes in the V-I color from the WFI at 2.2 …

SUGGESTIONS FOR AN ACCURATE CALIBRATION

- CAREFULLY CHECK THE FLAT FIELDS, COMPARE SKY AND DOME FLATS
- CHECK THE SHUTTER TIMING MEASURING IN REAL TIME THE STANDARD STARS. DELAYS UP TO 0.5 s SHOULD BE EXPECTED ! THIS IS A REAL PROBLEM FOR BRIGHT STARS.
- BE CAREFUL TO HAVE THE PEAK OF THE STANDARD STARS AT LEAST 10% BELOW THE SATURATION LIMIT (50% RECOMMENDED). DEFOCUSED IMAGES GIVE MUCH MORE ACCURATE MEASUREMENTS (BUT…)
- REPEAT THE OBSERVATIONS OF THE STANDARDS, POSSIBLY INCLUDING DIFFERENT EXPOSURE TIMES AND CHANGING THEIR POSITIONS ON THE CCD, AND MEASURE THE INSTURMENTAL MAGNITUDE IN REAL TIME.

Calibration errors

There are several sources of calibrations errors

- Photometric errors of the standard stars, including variability;
- Linearity deviations;
- Reddened standard stars;
- Residuals from flat fields
- Shutter timing delay or patterns;
- Non linear color equations
- Sky transmission fluctuations
- WRONG APERTURE CORRECTIONS IN CROWDED FIELDS

Following Stetson (2005) the shutter timing can be the major source of errors even at modern telescopes. SUGGESTIONS: multiple observations of standard stars with different exposure times!

Remember that the mechanical shutters degrades with time

The photometry: Stellar Photometry Packages

RICHFILD	Tody	1981	KPNO	
INVENTORY	West, Kruszewsky	1981	Irish Astr. J. 15, 25 (MIDAS man.)	
ROMAFOT	Buonanno et al.	1983	A&A, 126, 278	
DAOPHOT	Stetson	1987	PASP, 99, 191	DAOPHOT
ALLSTAR	Stetson	1994	PASP, 106, 250	
ALLFRAME	Stetson	1994	PASP, 106, 250	
DoPHOT	Schechter,Mateo Shara	1993	PASP 105, 1342	
ePSF	Anderson, King	2000	PASP, 112, 1360	

Plus a number of less used or generic photometry softwares (Wolf, Lund Starman, SEXTRACTOR, etc.)