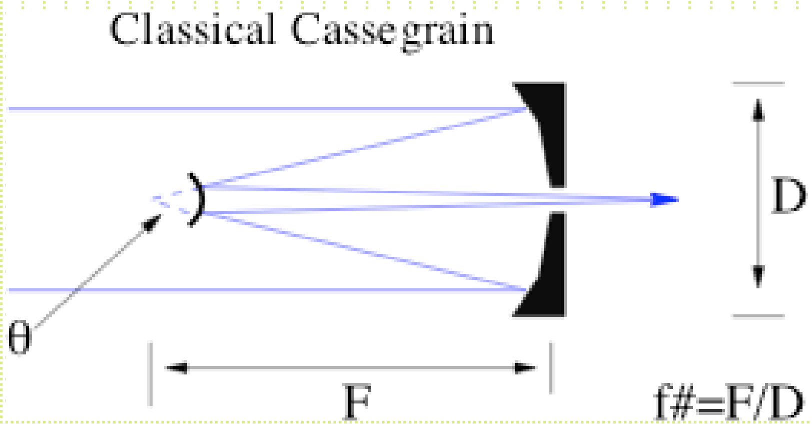
Imaging Cameras

- Imagers can be put at almost any focus, but most commonly they are put at prime focus or at cassegrain.



- The scale of a focus is given by

  S=206265/(D x f#) (arcsec/mm)

Examples:

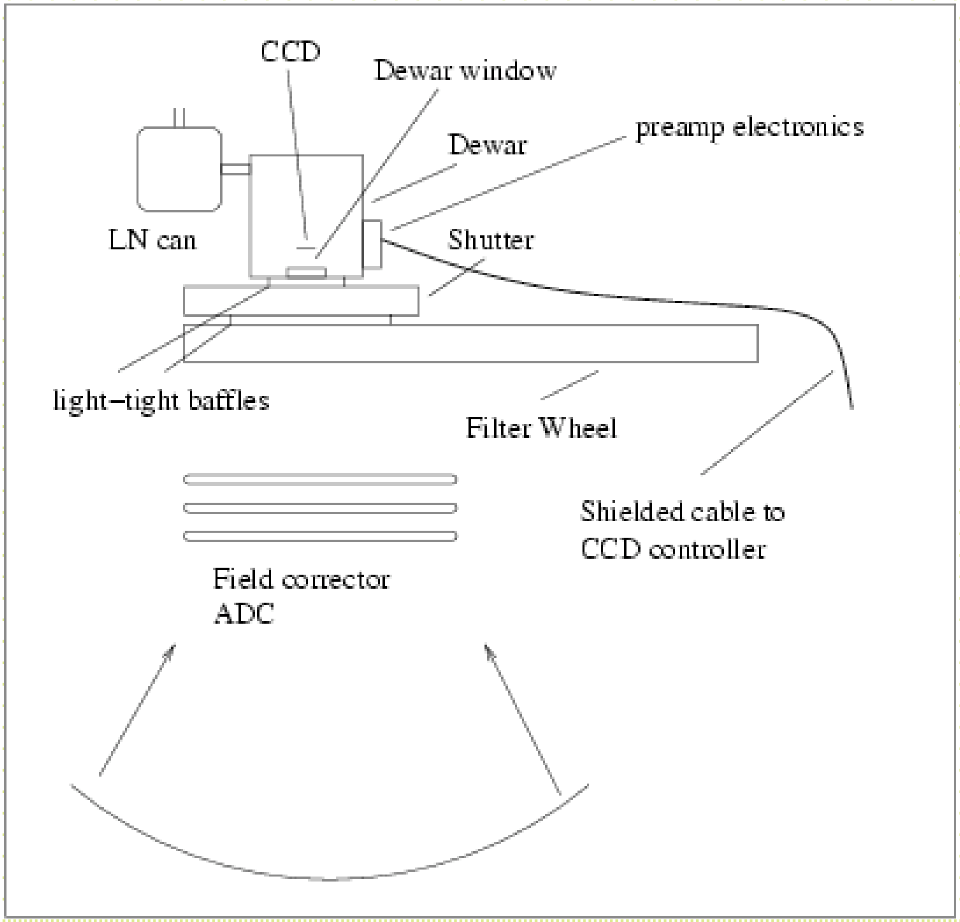
1. 3m @f/5 (prime) 13.8 arcsec/mm (0.33"/24μpixel)
2. 1m @f/3 (prime) 68.7 arcsec/mm (1.56"/24μpixel)
3. 1m @f/17 (cass) 12.1 arcsec/mm (0.29"/24μpixel)
4. 10m @f/1.5 (prime) 11.5 arcsec/mm (0.27"/24μpixel)
5. 10m @f/15 (cass) 1.15 arcsec/mm (0.03"/24μpixel)

- Classical cassegrain (parabolic primary + convex hyperbolic in front of prime focus) has significant coma.

$$C = \frac{3\theta}{16f^2} \quad \text{for 3m prime focus, } 1'' @ 2.2'$$

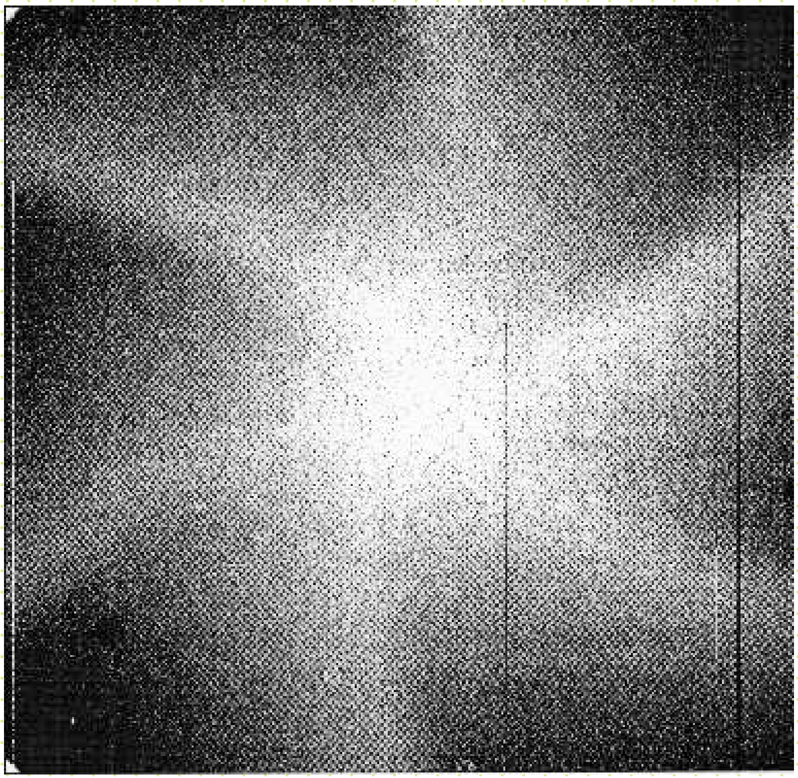
- For a classical cassegrain focus or prime focus with a parabolic primary you need a corrector.
- The Richey-Chretien design has a hyperbolic primary and secondary designed to balance out coma and astigmatism in the focal plane.

Direct Camera design/considerations



Shutters

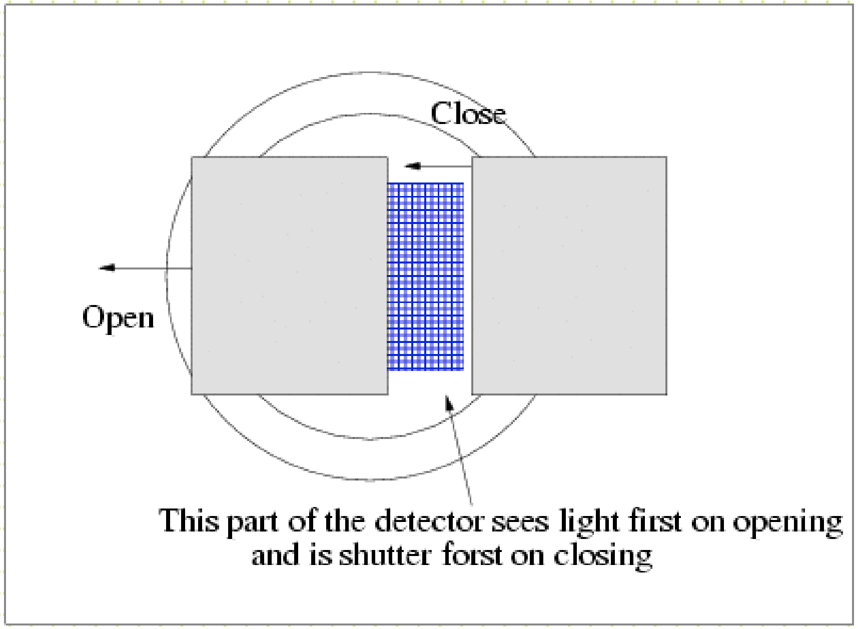
- The standard for many years has been multi-leaf iris shutters. As detectors got bigger and bigger, the finite opening time and non-uniform illumination pattern started to cause problems.
- 2k x 2k 24μ CCD is 2.8 inches along a diagonal.
- Typical iris shutter - 50 milliseconds to open. Center of a 1s exposure is exposed 10% longer than the corners.



Shutter vignetting pattern produced by dividing a 1 second exposure by a 30 second exposure.

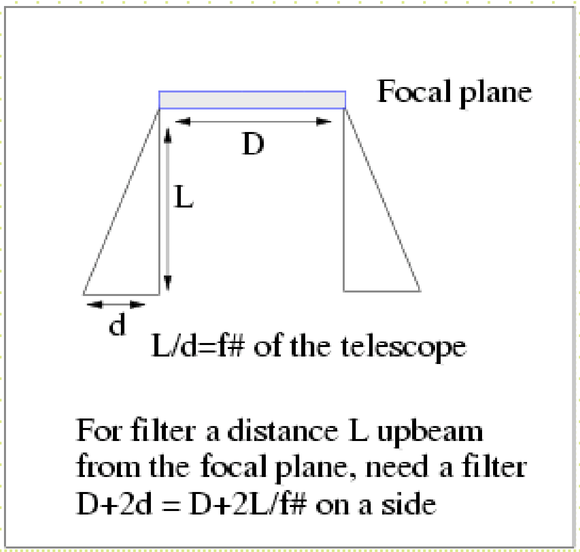
Double-slide system

- The solution for mosaic imagers and large-format CCD has been to go to a 35mm camera style double-slide system.



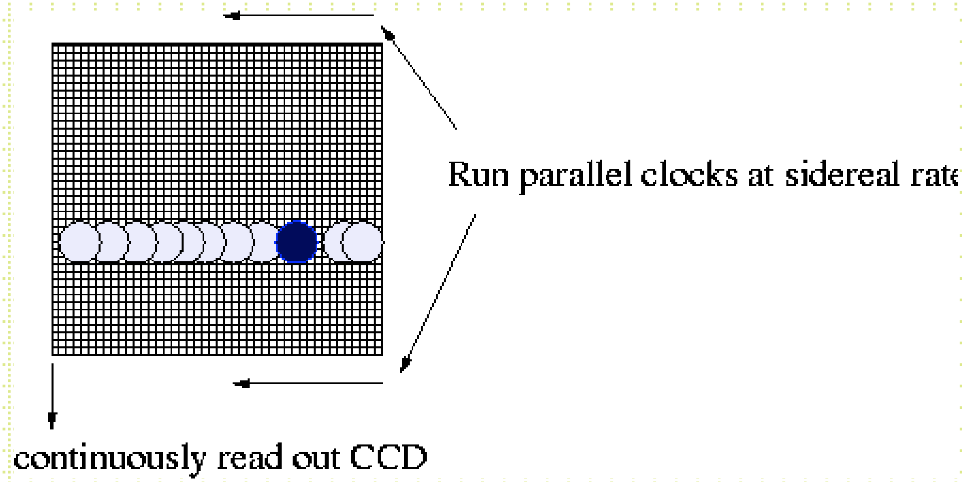
Filter Wheel

- Where do you put the filter? There is a trade off between filter size and how well focussed dust and filter imperfections are.



Drift Scanning

- An interesting option for imaging is to park the telescope (or drive it at a non-sidereal rate) and let the sky drift by.
- Clock out the CCD at the rate the sky goes by and the accumulating charge ``follows'' the star image along the CCD.



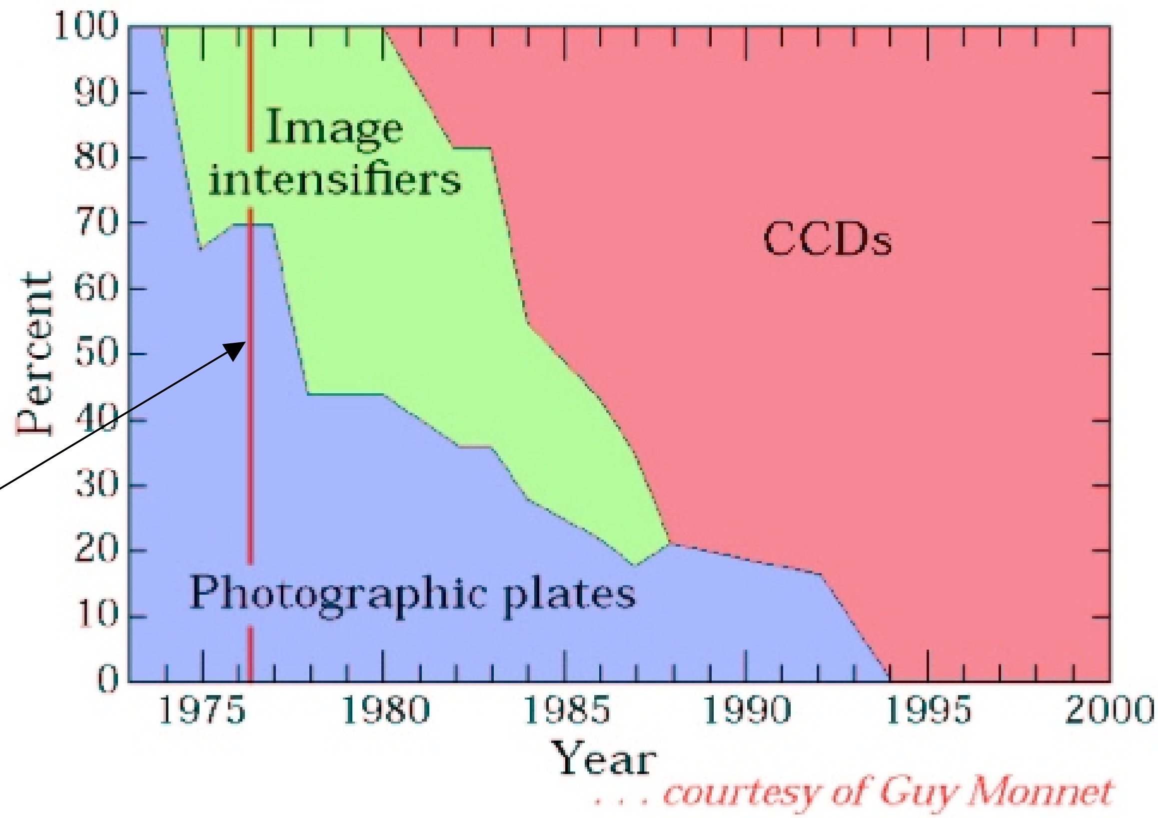
Drift Scanning

- End up with a long strip image of the sky with a \`height' = the CCD width and a length set by how long you let the drift run (or by how big your disk storage is).
- The sky goes by at 15 arcseconds/second at the celestial equator and faster than this by a factor of $1/\cos(\delta)$ as you move to the poles.
- So, at the equator, PFCam, with 2048 x 0.3" pixels you get an integration time per object of about 40 seconds.

Drift Scanning

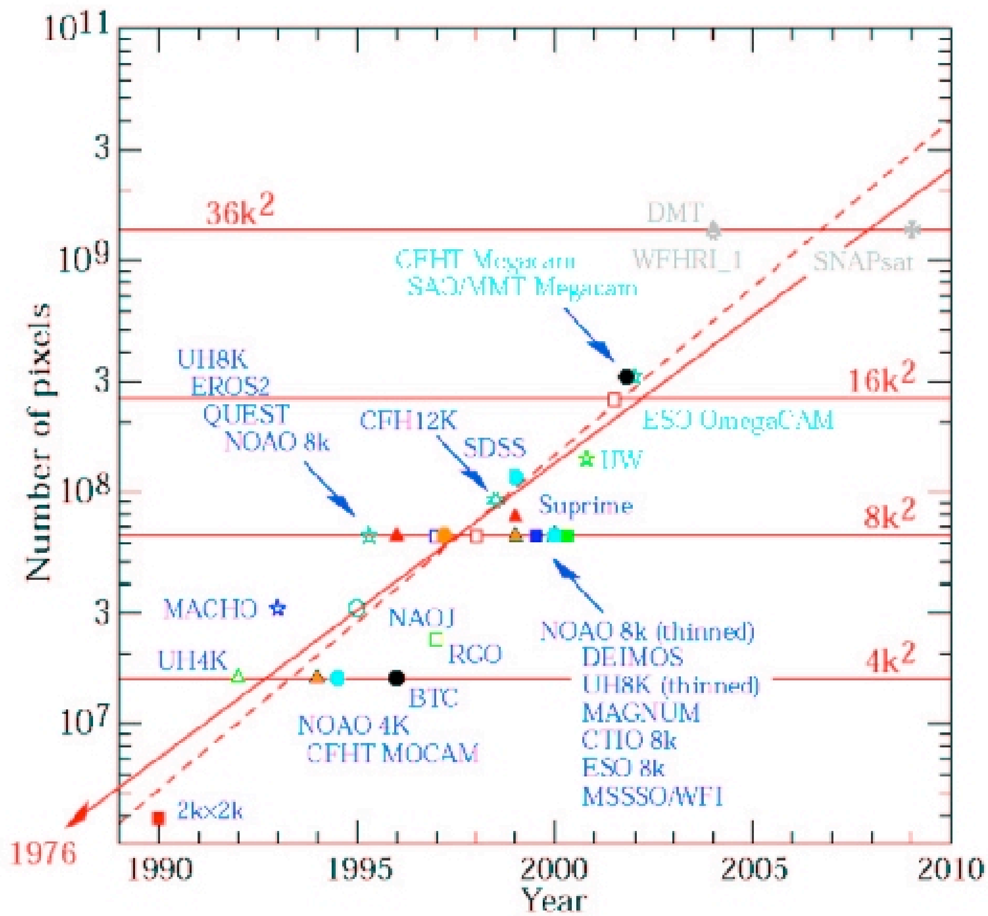
- What is the point?
  - Superb flat-fielding (measure objects on many pixels and average out QE variations)
  - Very efficient (don’t have CCD readout, telescope setting)
- Problem:
  - Only at the equator do objects move in straight lines, as you move toward the poles, the motion of stars is in an arc centered on the poles.
- Sloan digital survey is a good example
- Zaritsky Great Circle Camera is another

Detectors (ESO transition to CCDs)



First astronomical CCD, JPL 400x400

Pixels/Camera

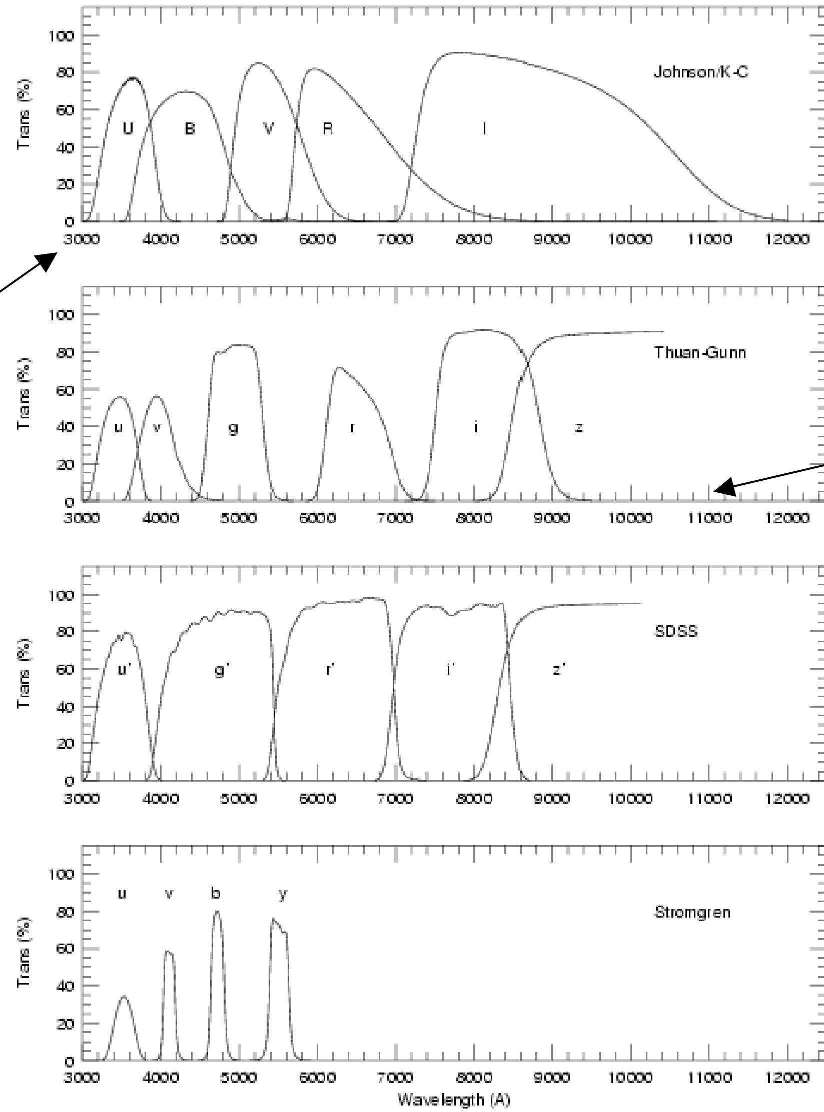


Direct Imaging

- Filter systems
  - Photometry
    - Point sources
      - Aperture
      - PSF fitting
    - Extended sources (surface photometry)
    - Star-galaxy separation

Filter Systems

- There are a bunch of filter systems
  - Broad-band (~1000Å wide)
  - Narrow-band (~10Å wide)
  - Some were developed to address particular astrophysical problems, some are less sensible.



3100Å is the UV atmospheric cutoff

1.1μ silicon bandgap

Filter Choice: Example

- Suppose you want to measure the effective temperature of the main-sequence turnoff in a globular cluster.

color	relative time to reach δT_{eff}=100
B-V	4.2
V-R	11.5
B-I	1.0
B-R	1,7

Narrow-band Filters

- Almost always interference filters and the bandpass is affected by temperature and beam speed:

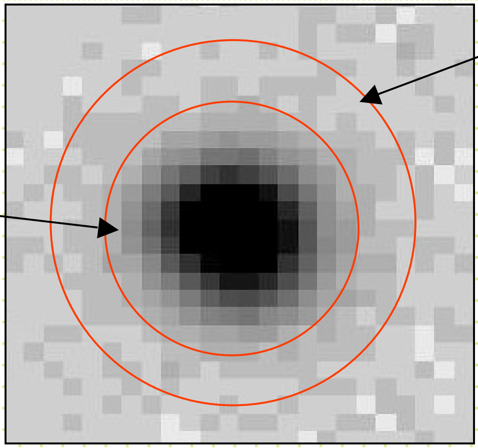
$$\Delta CWL = 1\text{Å}/5^\circ C$$

$$\Delta CWL = 17\text{Å};\ f/13 \Rightarrow f/2.8$$

Photometry

- Aperture Photometry
  - DaCosta, 1992, ASP Conf Ser 23
  - Stetson, 1987, PASP, 99, 191
  - Stetson, 1990, PASP, 102, 932

Sum counts in all pixels in aperture



Determine sky in annulus, subtract off sky/pixel in central aperture

Aperture Photometry

$$I = \sum_{ij} I_{ij} - n_{pix} \times \text{sky/pixel}$$

Total counts in aperture from source

Number of pixels in aperture

Counts in each pixel in aperture

$$m = c_0 - 2.5\log(I)$$

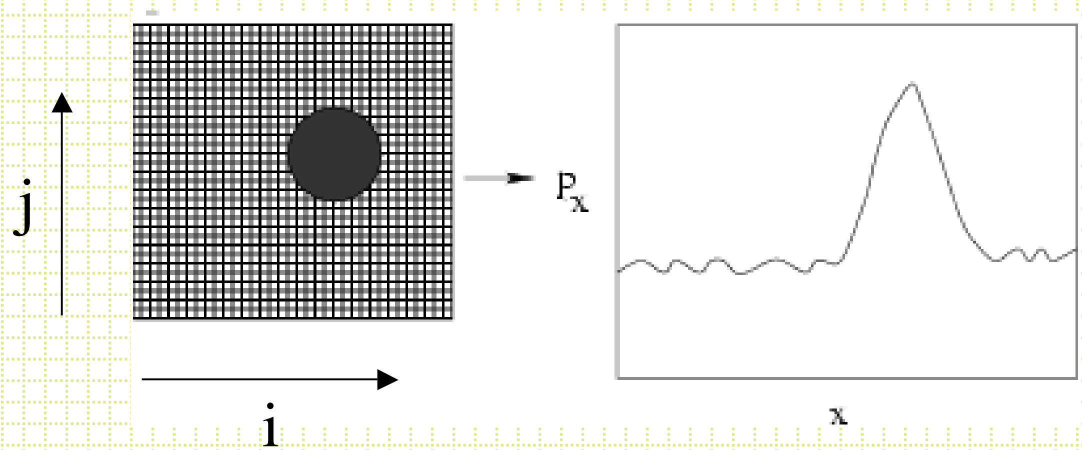
Aperture Photometry

- What do you need?
  - Source center
  - Sky value
  - Aperture radius

Centers

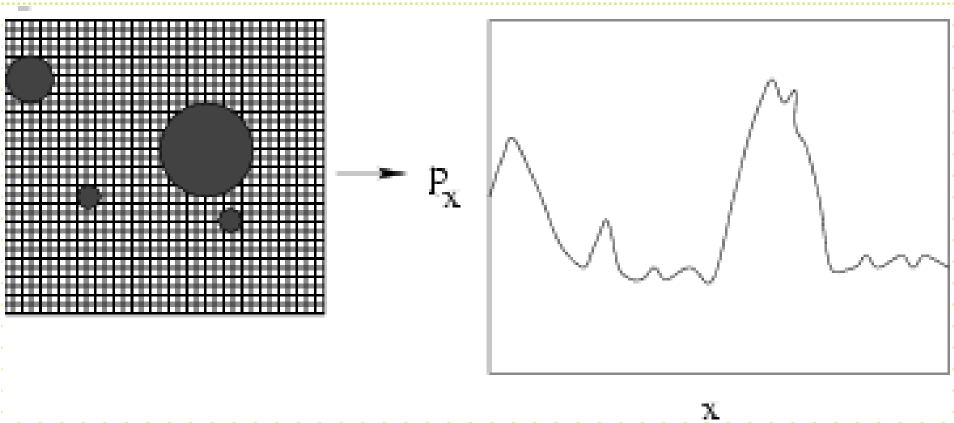
- The usual approach is to use ``marginal sums''.

$$\rho_{x_i} = \sum_j \mathrm{I}_{ij} \qquad \text{: Sum along columns}$$



Marginal Sums

- With noise and multiple sources you have to decide what is a source and to isolate sources.



- Find peaks: use $\partial\rho_x/\partial x$ zeros
- Isolate peaks: use ``symmetry cleaning''
  1. Find peak
  2. compare pairs of points equidistant from center
  3. if $I_{left} >> I_{right}$, set $I_{left} = I_{right}$
- Finding centers: Intensity-weighted centroid

$$x_{center} = \frac{\sum_i \rho_{x_i} x_i}{\sum_i \rho_{x_i}}; \quad \sigma^2 = \frac{\sum_i \rho_i x_i^2}{\sum_i \rho_i} - x_i^2$$

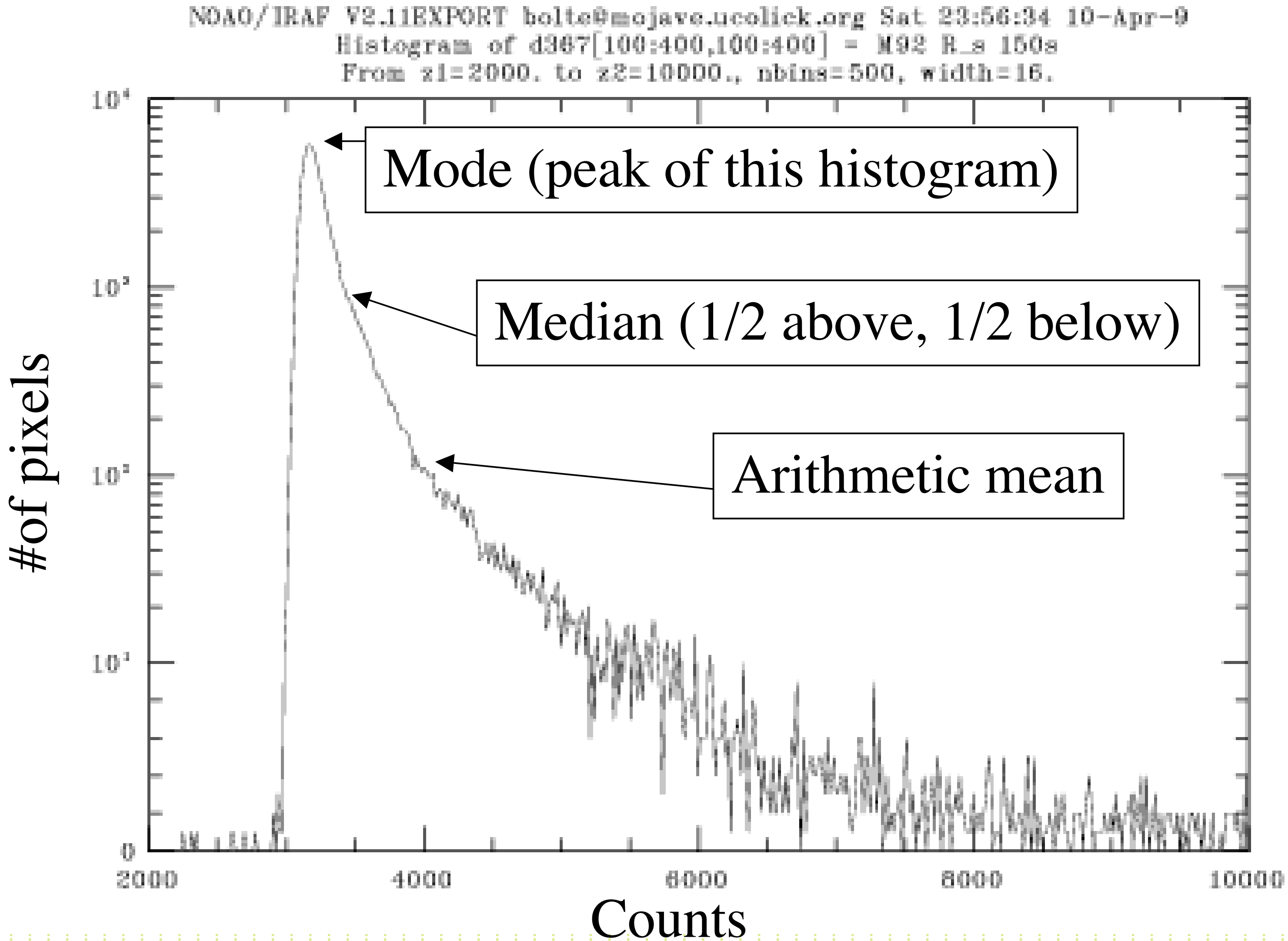
- Alternative for centers: Gaussian fit to ρ:

$$\rho_i = \text{background} + \underbrace{h}_{\text{Height of peak}} \bullet e^{\left[-\left((x_i - \underbrace{x_c}_{\text{Solving for center}})/\sigma\right)^2/2\right]}$$

- DAOPHOT FIND algorithm uses marginal sums in subrasters, symmetry cleaning, reraster and Gaussian fit.

Sky

- To determine the sky, typically use a local annulus, evaluate the distribution of counts in pixels in a way to reject the bias toward higher-than-background values.
- Remember the 3 Ms.



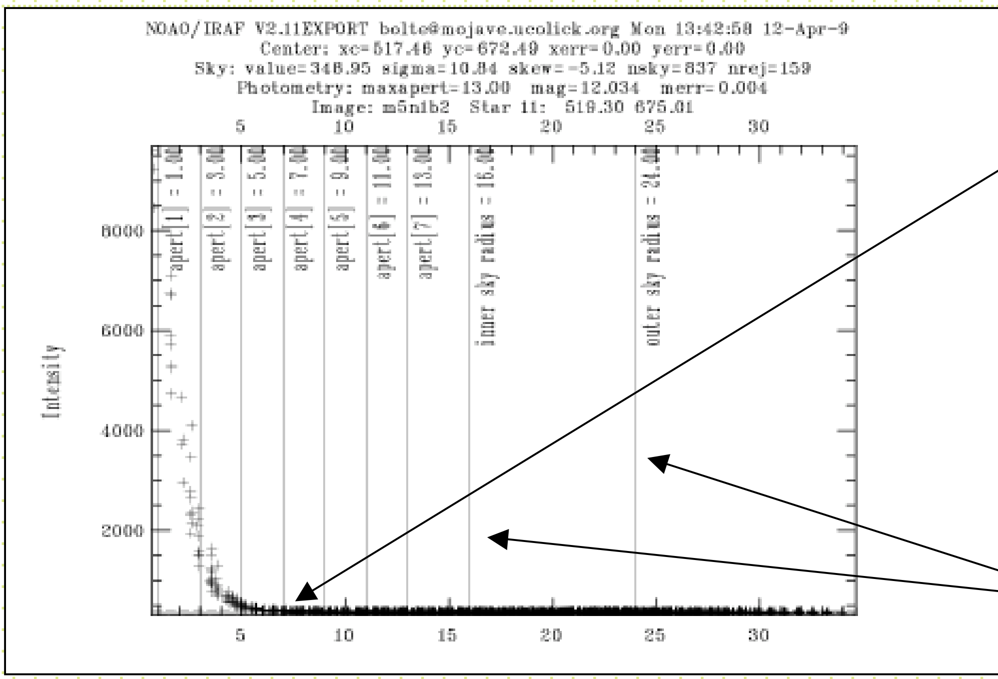
Because essentially all deviations from the sky are positive counts (stars and galaxies), the mode is the best approximation to the sky.

Some Small Details

- Pixels are square. What about the partial pixels at a given radius? Usual approach is to assume uniform brightness throughout pixel and calcualte fraction within *r* of the aperture center.
- What about aperture size?

Aperture size and growth curves

- First, it is VERY hard to measure the *total* light as some light is scattered to very large radius.



Radius from center in pixels

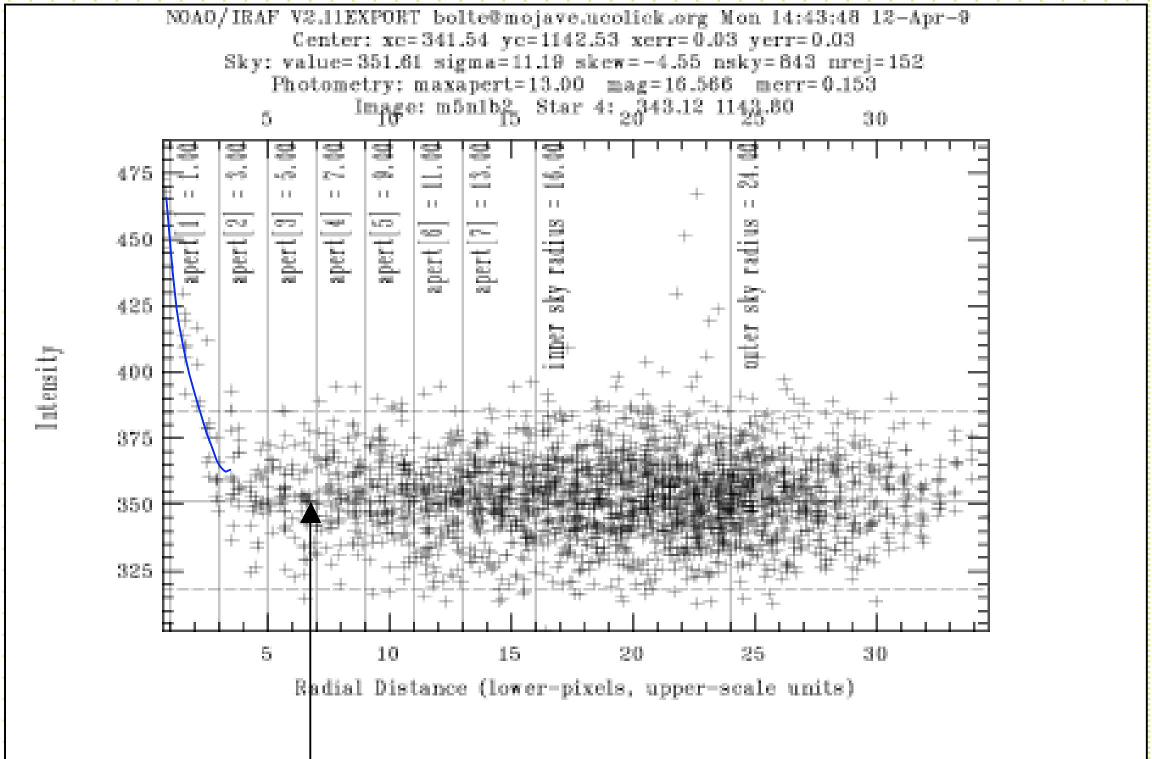
Perhaps you have most of the light within this radius

Radial intensity distribution for a bright, isolated star.

Inner/outer sky radii

- Radial intensity distribution for a faint star:

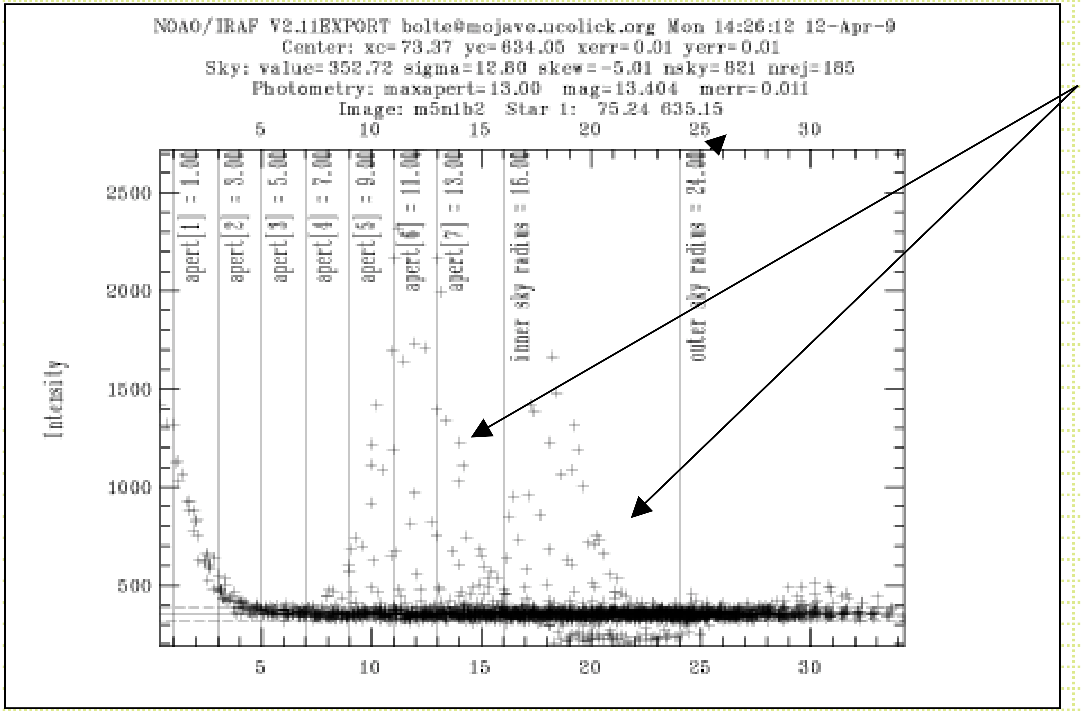
Same frames as previous example



Bright star aperture

The wings of a faint star are lost to sky noise at a different radius than the wings of a bright star.

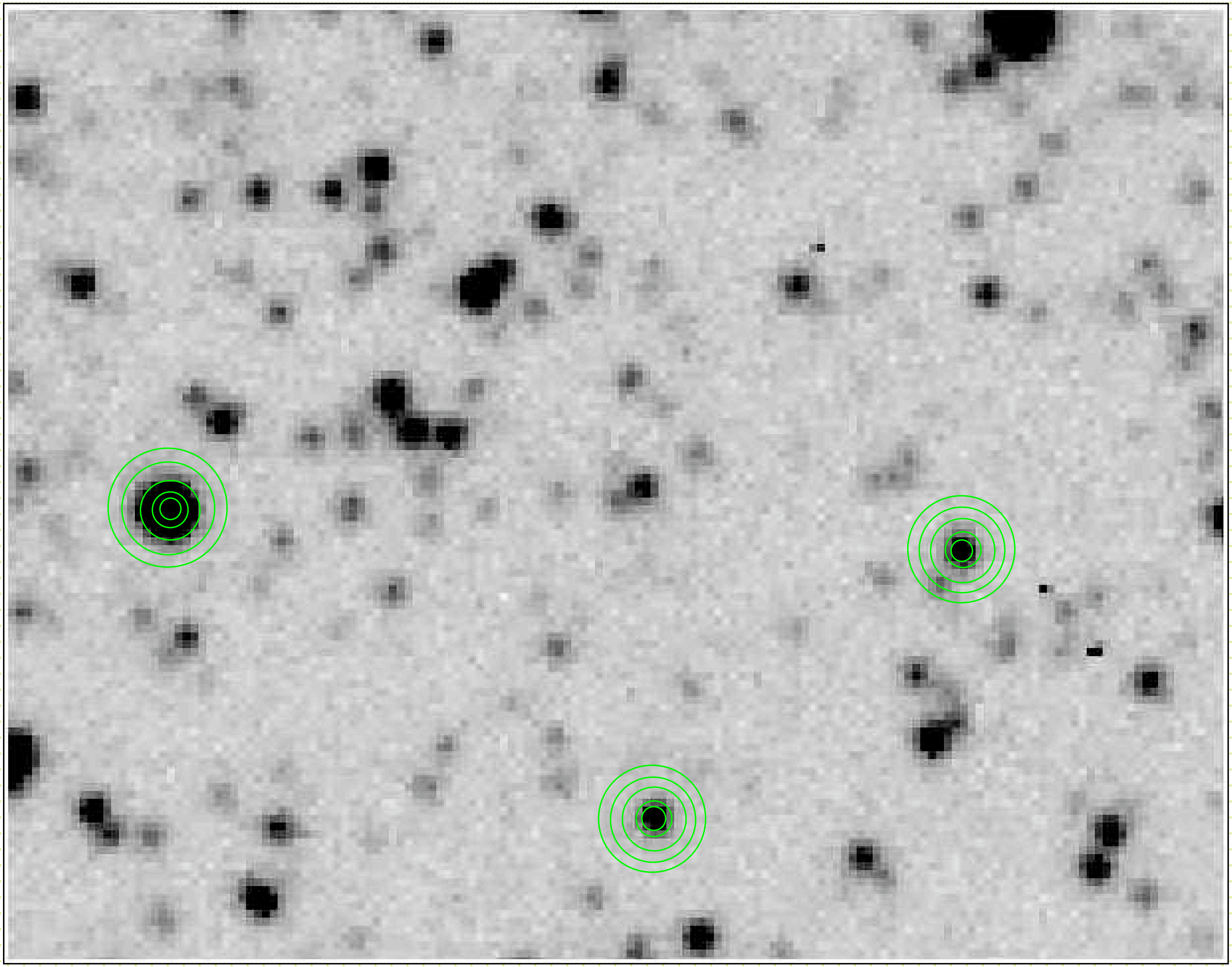
Radial profile with neighbors



Neighbors OK in sky annulus (mode), trouble in star apertures

One approach is to use `growth curves'

- Idea is to use a small aperture (highest S against background and smaller chance of contamination) for everything and determine a correction to larger radii based on several relatively isolates, relatively bright stars in a frame.
- Note! This assumes a linear response so that all point sources have the same fraction of light within a given radius.
- Howell, 1989, PASP, 101, 616

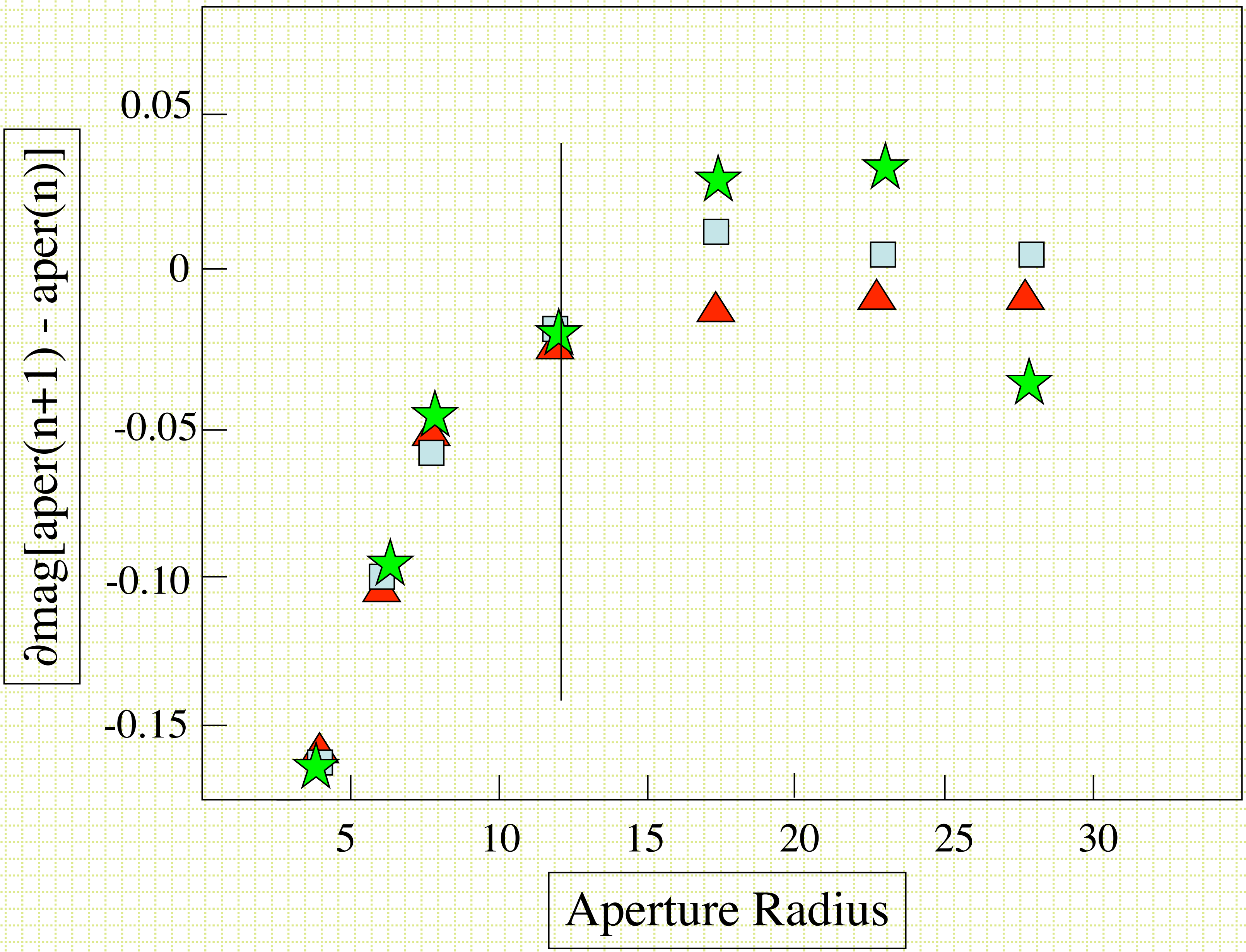


Growth Curves

∂mag for
apertures n-1, n

Aperture	2	3	4	5	6	7	8
Star#1	0.43	0.31	0.17	0.09	0.05	0.02	0.00
Star#2	0.42	0.33	0.19	0.08	0.21	0.11	0.04
Star#3	0.43	0.32	0.18	0.10	0.06	0.02	-0.01
Star#4	0.44	0.33	0.18	0.22	0.14	0.12	0.14
Star#5	0.42	0.32	0.18	0.09	0.19	0.21	0.19
Star#6	0.41	0.33	0.19	0.10	0.05	0.30	0.12
cMean	0.430	0.324	0.184	0.094	0.057	0.02	0.00

Sum of these is the total aperture correction to be added to magnitude measured in aperture 1


0.05
0
-0.05
-0.10
-0.15
∂mag[aper(n+1) - aper(n)]
5
10
15
20
25
30
Aperture Radius

DAOGROW

- Stetson, 1990, PASP, 102, 932 presented a fitting function for growth curves.
- Gaussian core + exponential + inverse power law for large radius

Aperture Photometry Summary

1. Identify brightness peaks

2. $\sum_{xy} I_{xy} - (\text{sky} \bullet \text{aperture area})$

Use small aperture

3. Add in ``aperture correction'' determined from bright, isolated stars

Easy, fast, works well except for the case of overlapping images

Crowded-field Photometry

- As was assumed for aperture corrections, all point sources have the same PSF (linear detector).
- Various codes have been written that:
  1. Automatic star finding
  2. Construction of PSF
  3. Fitting of PSF to (multiple) stars
- DAOPHOT, ROMAPHOT, DOPHOT, STARMAN
- Will spend some time on the use of DAOPHOT

DAOPHOT

- Stetson, 1987, PASP, 99, 191
- Stetson, DAOPHOT Users' Manual
- Main subroutines:
  - FIND
  - PHOT
  - PSF
  - ALLSTAR (DAOPHOT II)
- Couple of parameter files:
  - daophot.opt
  - photo.opt

- daophot.opt

HI=65635 (in counts)
LO=5 (in standard deviations: sky-5σ)
GA=3.9 (gain in e-/dn)
RE=2.05 (readout noise in units of DN)
FI=3 (PSF fitting radius)
PS=12 (PSF radius)
TH=3.5 (threshold in units of sky standard deviations)
AN=-6 (analytical form of PSF)
WA=-2 (`watch' - level of verbosity for feedback)
VA=2 (spatial variability of PSF)

- photo.opt

A1=3 (1st aperture radius=3 pixels)
A2=0 (if a zero is encountered, DAOPHOT ignores the rest of the apertures)
Etc
A9=19
AA=22
AB=25
AC=29
IS=35 (inner sky radius)
OS=45 (outer sky radius)

DAOPHOT FIND

- Needs gain, RN, HIBAD, LOBAD, FWHM
- Find convolves the frame with a gaussian with σ = FWHM/2.35. This improves the S/N for objects with a point-source PSF.
- For subrasters, constructs marginal sums and uses derivative zeros to isolate objects
- Fits two 1-D gaussian in x and y
- Calculates ``sharpness'' and ``roundness''
- Writes a .coo file with: n,x,y,mag,sharp,round

- Determine the right threshold with a couple easy tests:
  1. Plot #stars found vs threshold level
  2. Use IRAF *fields* and *tvmark* to put dots at the x,y positions in the .coo file
- Output file default name is framename.coo
- First time through a frame, the strong blends will not be properly parsed into individual centroids.

PHOT

- Requires photo.opt file in directory to define apertures and sky annulus
- Requires input .coo file
- Calculates sky-subtracted magnitude for each aperture (usually only one)
- Determines the sky value for each object
- Output: framename.ap

PSF

- PSF uses stars on the frame to create a PSF. DAOPHOT uses an analytical core plus a 2-D lookup table.
  - For any star: $m=c_0-2.5\log(\text{psf scaling factor})$
- DAOPHOT options are variants on bivariate:

$$I(r) \propto e^{-r^2/2\alpha^2} \qquad \text{Gaussian}$$

$$\propto \frac{1}{1+\left(r^2/\alpha^2\right)^{\beta}} \qquad \text{Moffet}$$

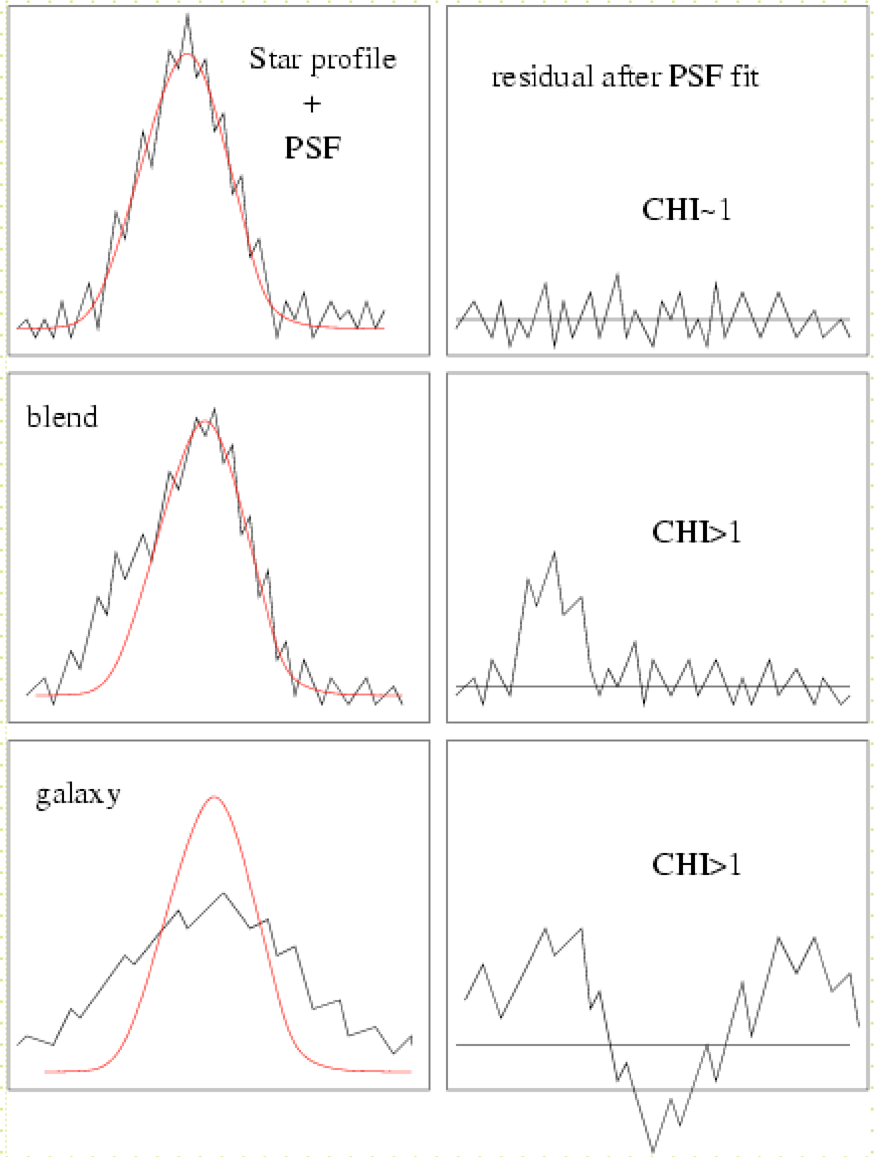
Fitting radius: ~FWHM; PSF radius: ~ 4 x FWHM

- To construct a PSF
  1. Choose unsaturated, relatively isolated stars
  2. If PSF varies over the frame, sample the full field
  3. Make 1st iteration of the PSF
  4. Subtract psf-star neighbors
  5. Make another PSF
- Output of PSF routine is a framename.psf which has a header containing the parameters defining the analytical function and an encoded look up table of residuals.

Allstar (DAOPHOT II)

- Use the .ap file and .psf as input (x,y,sky for every object)
- Based on PSF radius, group objects into sets that need to be simultaneously fitted with PSFs
- Fit PSFs to groups
- Return: framename.als
  - x, y, mag, ∂mag, chi

Scaling factor   ratio of actual psf fit to how well it should have fit

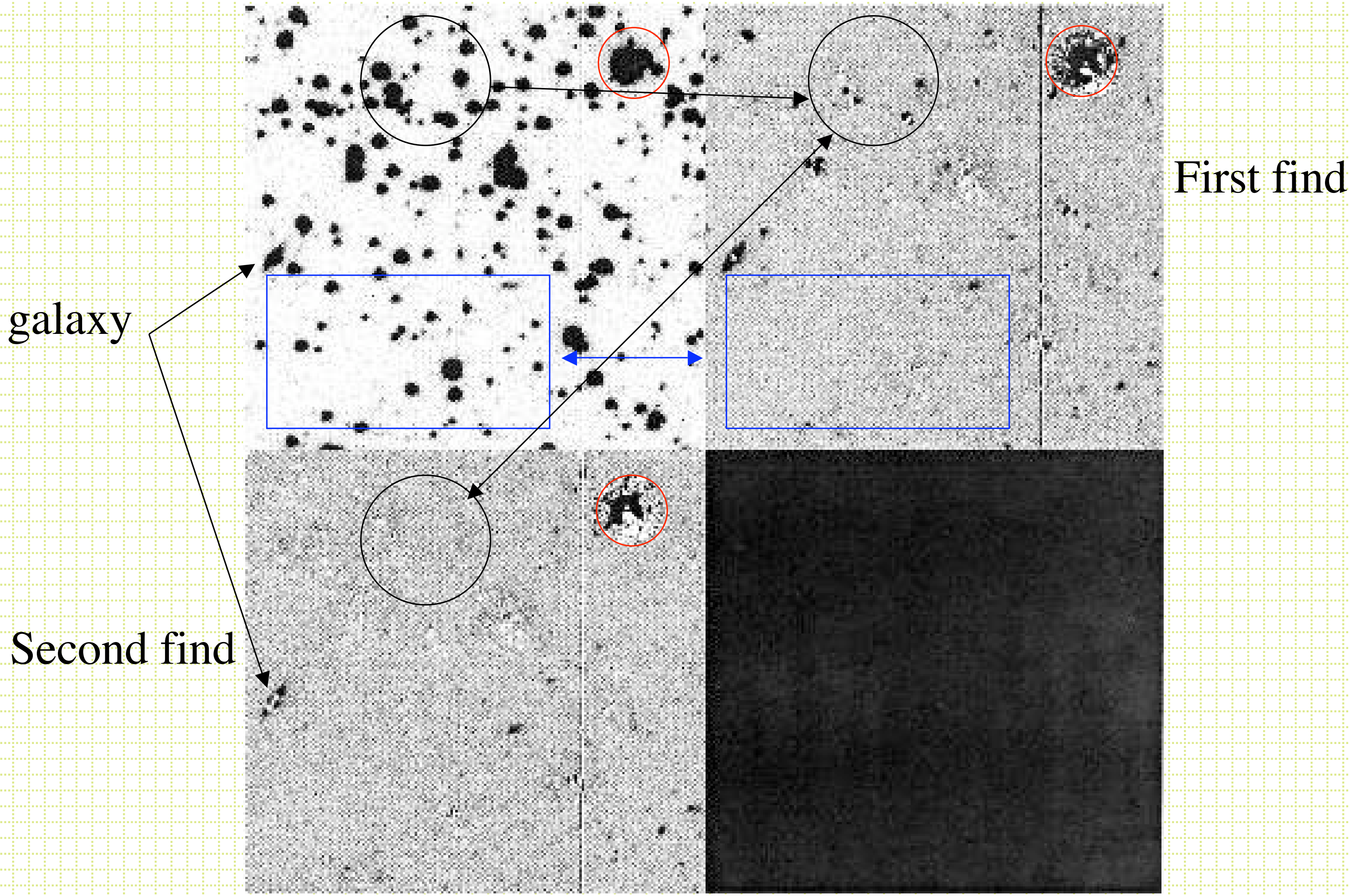


Star profile
+
PSF
residual after PSF fit
CHI~1
blend
CHI>1
galaxy
CHI>1

DAOPHOT run

Star-subtracted frame

1. Attach frame
2. find (frame.coo)
3. phot (frame.ap)
4. PSF loop (frame.psf)
5. Allstar (frame.als, frames.fits)
6. Attach subtracted frame
7. Find (frames.coo)
8. Phot (frames.ap)
9. Merge two lists
10. allstar


First find
galaxy
Second find

Post-DAOPHOT

- You usually want to combine photometry in each filter and match up stars in different filters to determine colors.
- First, need to determine the coordinate transformation between frames. You can do this and combine *photometry* or *images*.
- In IRAF, use a list of a matched stars and *geotrans* and *geomap*.
- There are standalone Stetson programs to combine DAOPHOT-format photometry files

DAOMATCH

- DAOMATCH uses the Method of Matching Triangles. Triangle side length ratios are invariant under rotation, translation, scale change and ``flip''. Groth, 1986, AJ, 91, 1244. (note: #triangles goes like n!/[3!(n-3)!])
- Check bright stars in two files, identify matching triangles, solve for coefficients in:

$$x_1 = A + Cx_2 + Dy_2$$
$$y_1 = B + Ex_2 + Fy_2$$

DAOMATCH

- For dithered frames:
  - A,B - x,y offsets
  - C,F ~ 1 (scale changes in x and y)
  - D,E ~ 0 (cross-terms are non-zero for rotations)
- Use this with .als files and produce a .mch file with the coordinate transformations. This is usually used as the first guess, to be fed into DAOMASTER

DAOMASTER

- DAOMASTER takes the DAOMATCH .mch files with transformations and a list of .als files and (1) refines the transformations using all matched stars, (2) derives robust photometric offsets between frames and (3) *correctly* averages measurements (remember to never average magnitudes!)

Photometric Calibration

- The photometric standard systems have tended to be zero-pointed arbitrarily. Vega is the most widely used and was original defined with V= 0 and all colors = 0.
- Hayes & Latham (1975, ApJ, 197, 587) put the Vega scale on an absolute scale.
- The AB scale (Oke, 1974, ApJS, 27, 21) is a physical-unit-based scale with:

$$m(AB) = -2.5\log(f) - 48.60$$

where f is monochromatic flux is in units of $erg/sec/cm^2/Hz$. Objects with constant flux/unit frequency interval have zero color on this scale

Photometric calibration

1. *Instrumental* magnitudes

Counts/sec

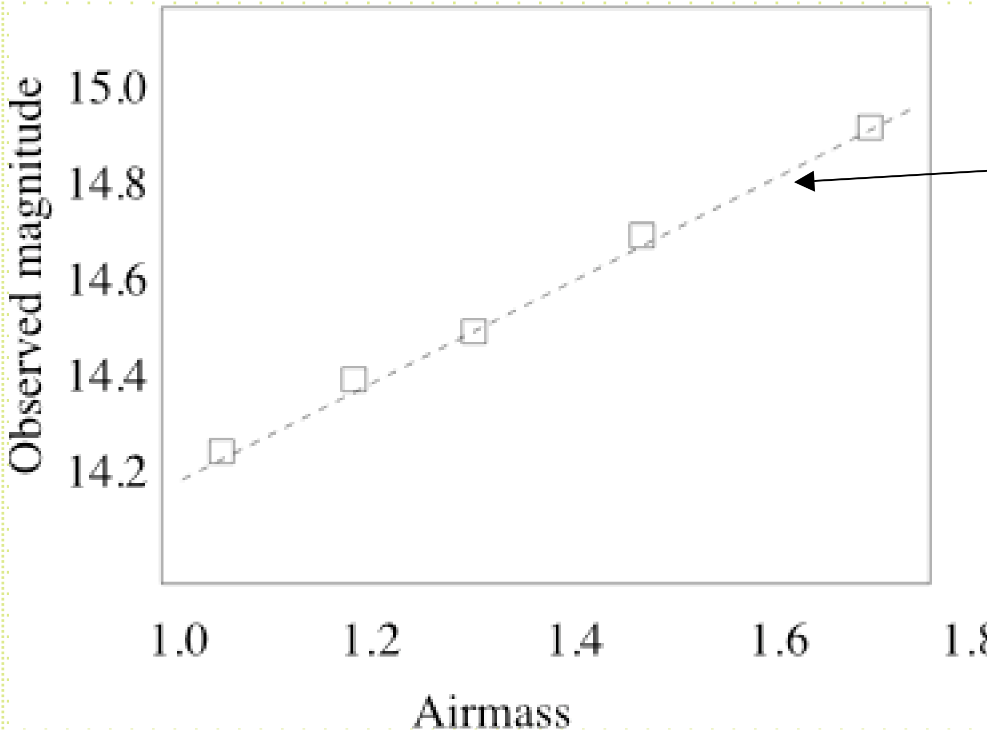
$$m = c_0 - 2.5\log(I \bullet t)$$
$$= \underbrace{c_0 - 2.5\log(I)}_{m_{instrumental}} - 2.5\log(t)$$

Photometric Calibration

- To convert to a *standard* magnitude you need to observe some standard stars and solve for the constants in an equation like:

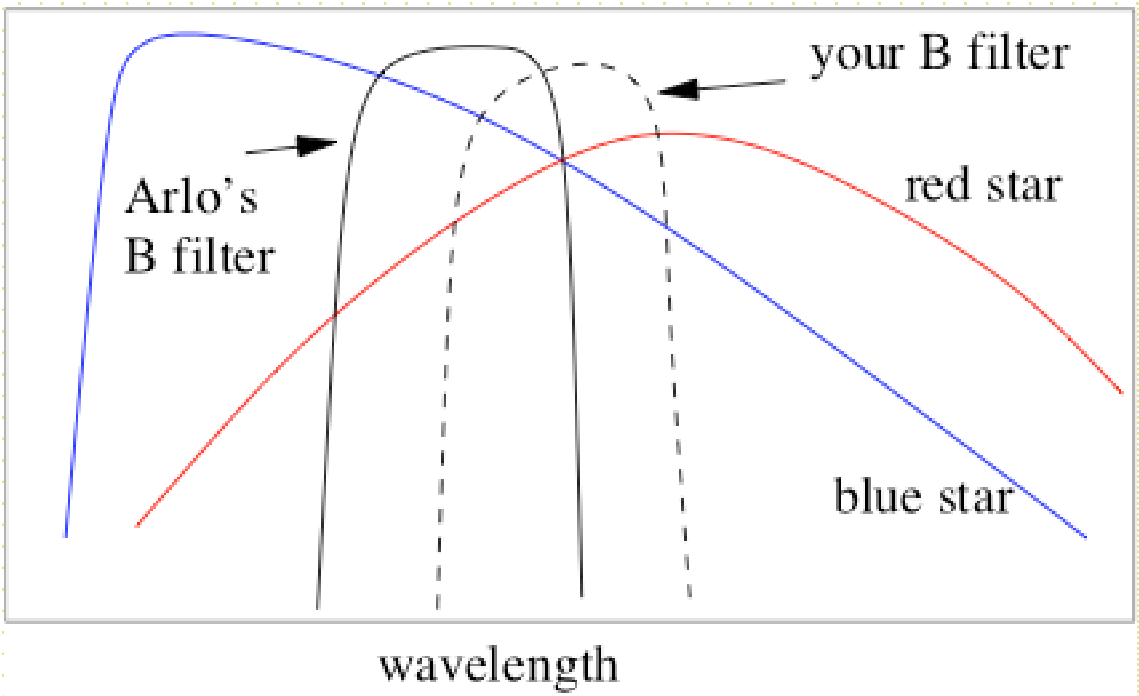
$$\underbrace{m_{inst}}_{\text{Stnd mag}} = \underbrace{M}_{\text{Instr mag}} + \underbrace{c_0}_{\text{zpt}} + \underbrace{c_1}_{\substack{\text{Extinction coeff}\\ \text{(mag/airmass)}}}\underbrace{X}_{\text{airmass}} + \underbrace{c_2(\text{color})}_{\text{Color term}} + c_3(\text{UT}) + c_4(\text{color})^2 + \ldots$$

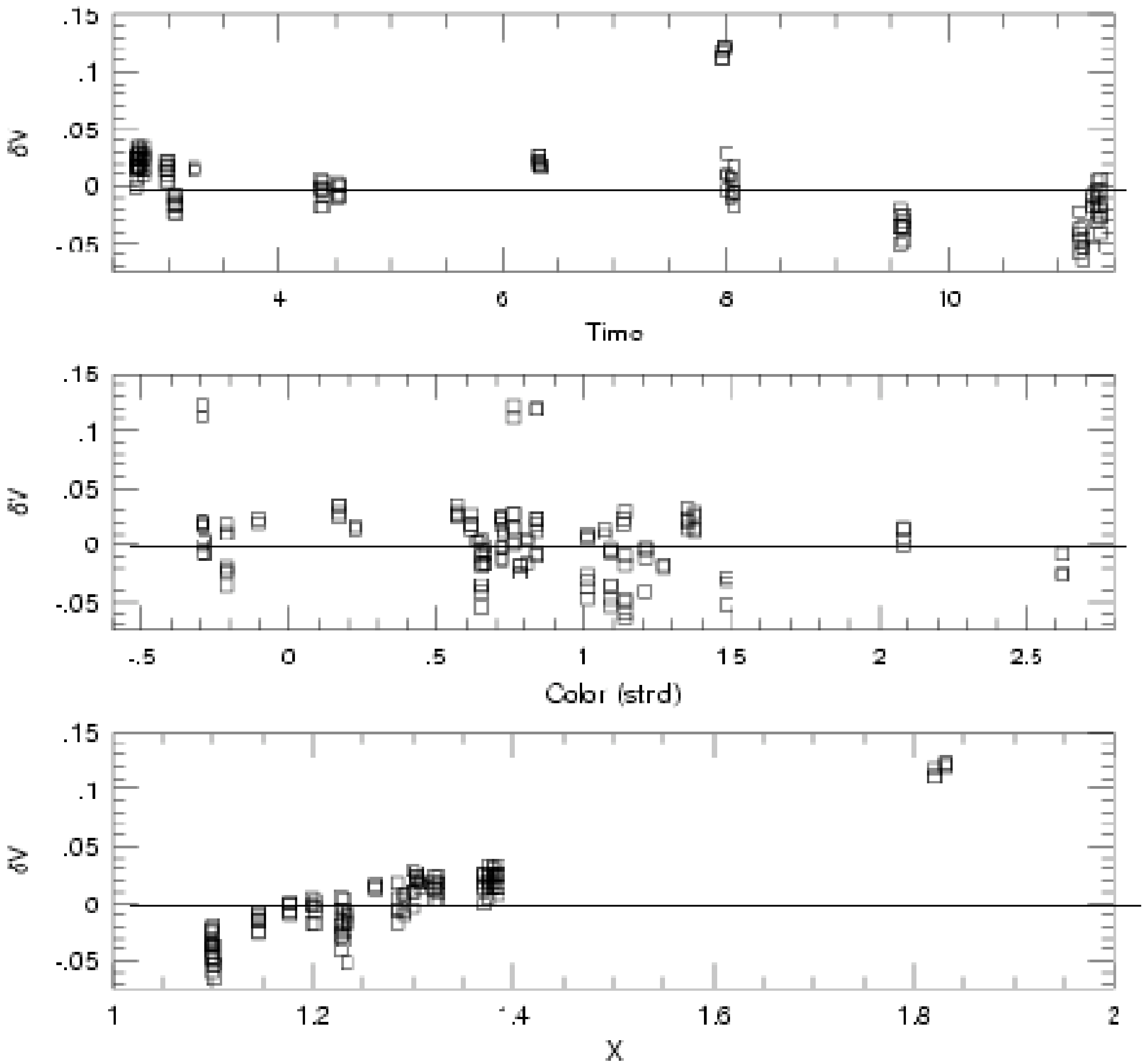
- Extinction coefficients:
  - Increase with decreasing wavelength
  - Can vary by 50% over time and by some amount during a night
  - Are measured by observing standards at a range of airmass during the night



Slope of this line is c_1

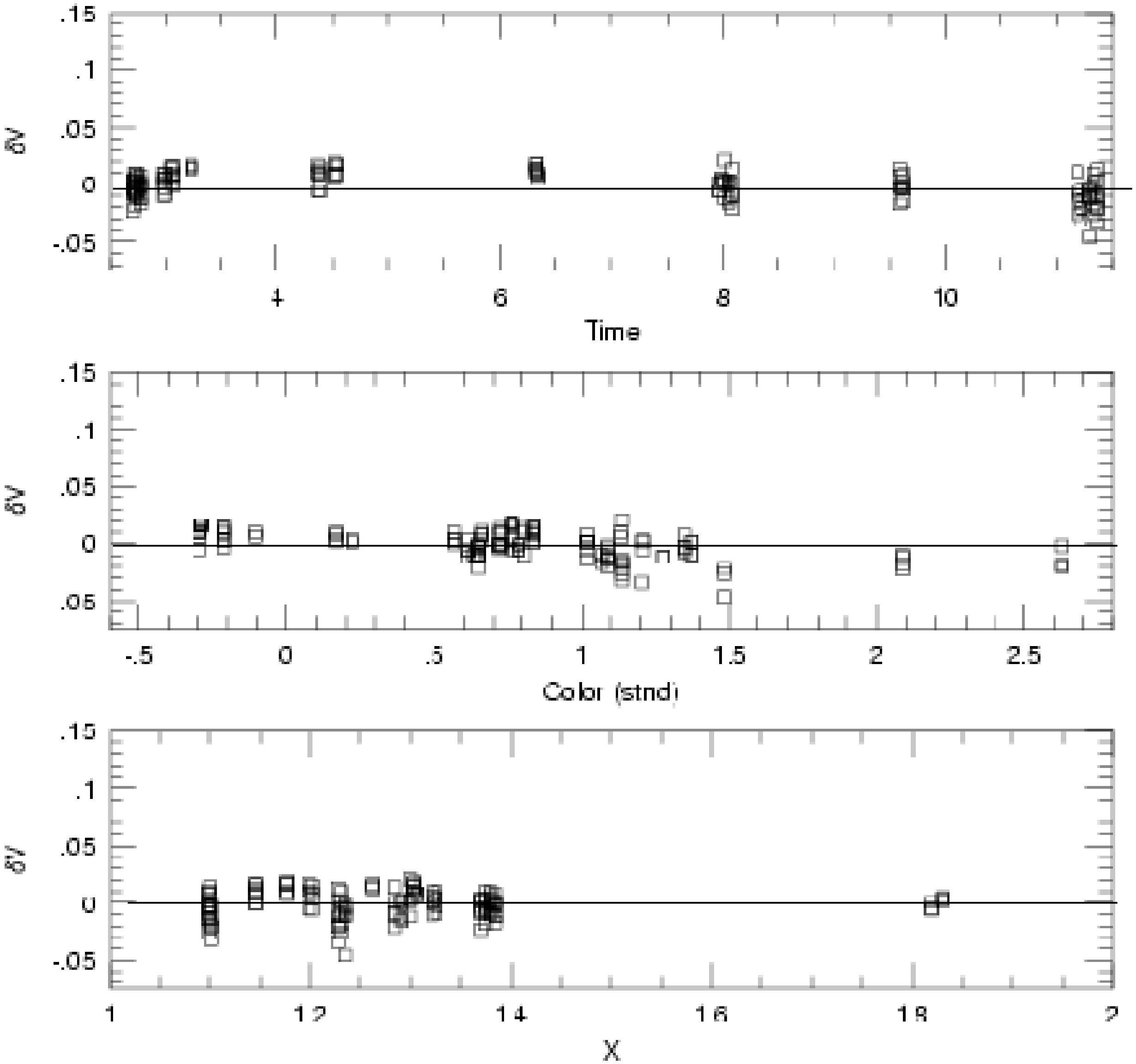
- The *color terms* come about through mismatches between the effective bandpasses of your filter system and those of the standard system. Objects with different spectral shapes have different offsets.





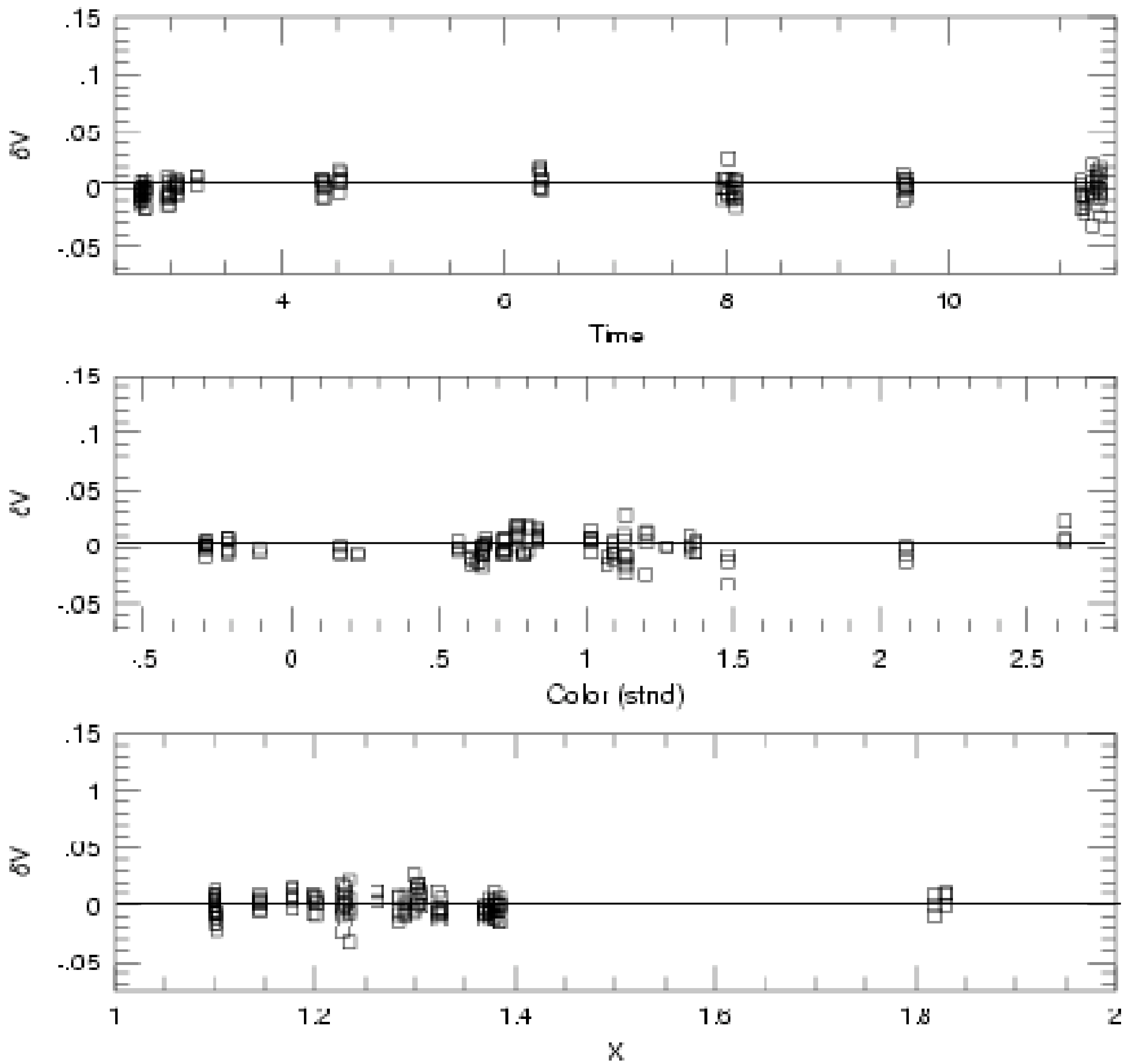
$V = v_1 + a_0$

RMS=0.055



$$V = v_{inst} + c_0 + c_1 X$$

RMS=0.032



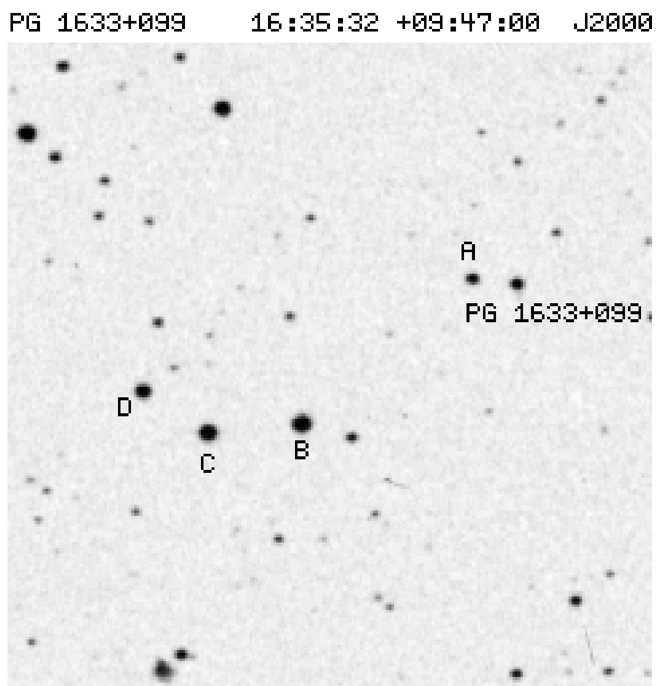
$$V = v_{inst} + c_0 + c_1 X + c_2 (B-V)$$

RMS=0.021

Photometric Standards

- Landolt (1992, AJ, 104, 336)
- Stetson (2000, PASP, 112, 995)
- Fields containing several well measured stars of similar brightness and a big range in color. The blue stars are the hard ones to find and several fields are center on PG sources.
- Measure the fields over at least the the airmass range of your program objects and intersperse standard field observations throughout the night.

Example Landolt Field



Transfer of the Stnd Transformation

- Usually observe standard fields on a night

  ………………… program fields …………
  - Standards measured with growth-curve aperture photometry to estimate the `total' light
  - Program stars measured via frame-dependent PSF scaling factors
- For each program field you need to find the magnitude difference between the PSF and `total' light -- this is called the *aperture correction*

Aperture correction procedure

- After finding and PSF fitting stars on a frame, subtract the fitted PSFs for all but 20 or 30 relatively isolated objects (after the subtraction, they are hopefully very isolated)
- Do growth-curve photometry on the frame and find:

$$\overline{\Delta} = \sum_{1}^{n} (\mathrm{mag}_{\mathrm{PSF}} - \mathrm{mag}_{\mathrm{aperture}})/n$$

- This gets added to all the PSF-based magnitudes on the frame.
- Note: check for position-base trends