

AY257: Modern Observational Techniques

- This class is mostly about data reduction techniques.
- BY FAR the most important thing to do this term is work through the homework problems
- A distant second in importance is the reference list.
- We will work in the IRAF environment. Not necessarily the best, but it is widely available and free.

Outline

- I. S/N calculations
- II. Planning an observing run
 - a) Proposal Writing
 - b) Aircharts
 - c) Calibration Frames
 - d) Checks during the run
- III. Data Reduction
 - i. Preliminary processing: overscan, bias, flat-fielding
 - ii. Photometry
 - a. Imaging cameras
 - b. Point Sources
 - c. Surface Photometry
 - d. Star-galaxy separation
 - e. calibration

Outline cont.

- iii. Spectral data
 - a. Spectrometer design
 - b. Formats
 - c. Extraction
 - d. Radial velocity measurements
 - e. Equivalent width measurements
 - f. Indices
- iv. IR (to 10μ)
- v. X-ray/gamma-ray astronomy

Homeworks

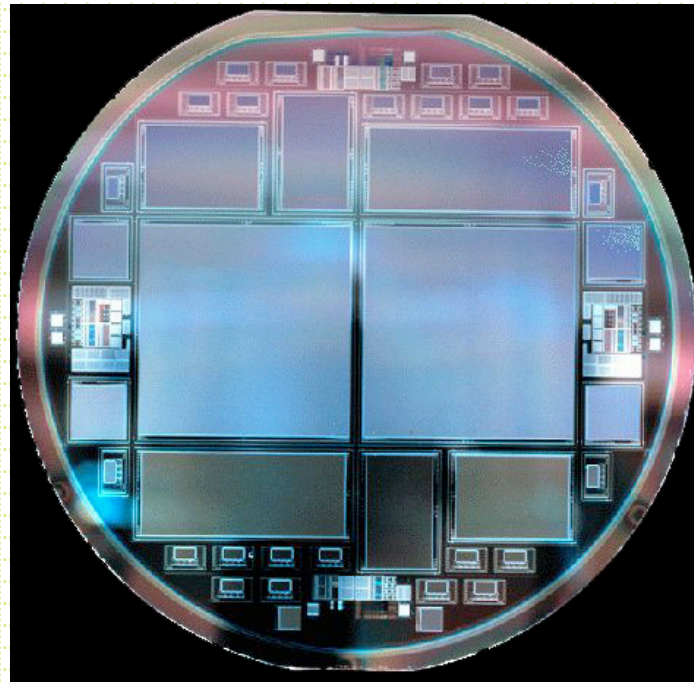
- Homework should be written up carefully using Latex with embedded figures. Purpose, ``howto'', results.
- Fine to work together, but everyone should do their writeups independently.
- Will need access to a computer with IRAF or IDL, Latex or Word, plotting package (e.g. SM) to do the homeworks and writeups.

Bolte Schedule

- Week 1: OK.
- Week 2: Hawaii (Thursday video-based class)
- Week 3: Mt. Hamilton + KAST (field trip?)
- Week 4: Little tricky
- Rest of term will hold all scheduled classes
- www.ucolick.org/~bolte/AY257/ay257.html
- bolte@ucolick.org

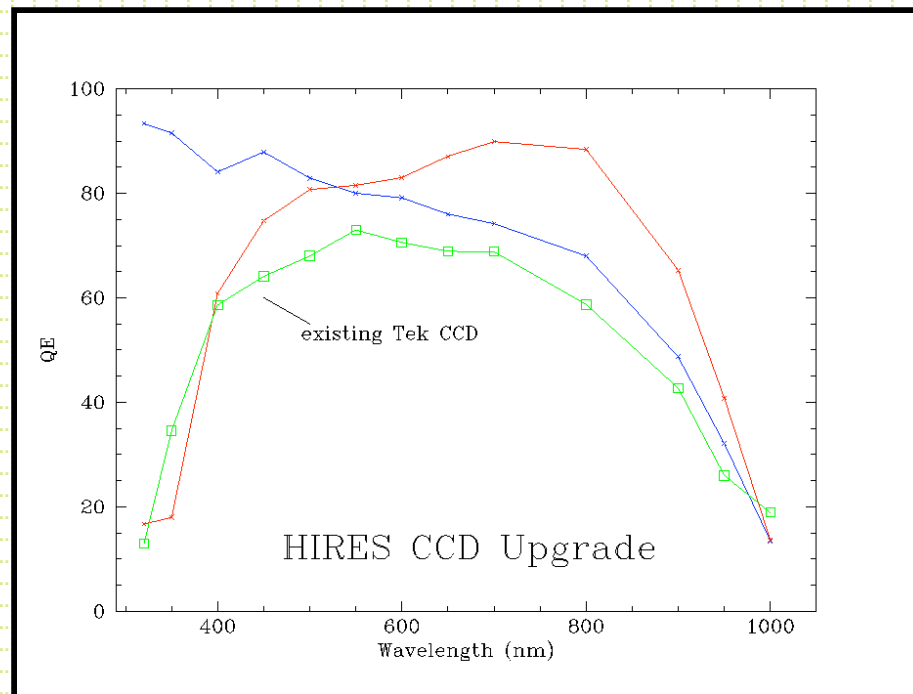
Digital Detectors

- By far the most common detector for wavelengths $300\text{nm} < \lambda < 1000\text{nm}$ is the CCD.



CCDs

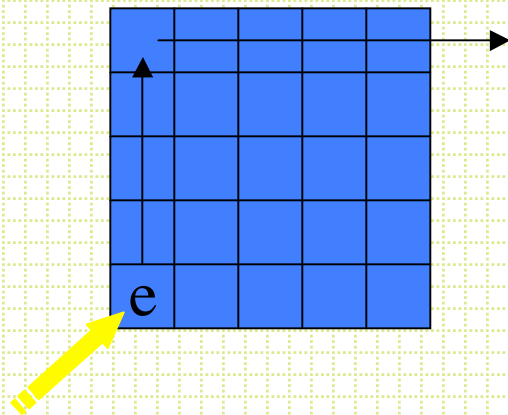
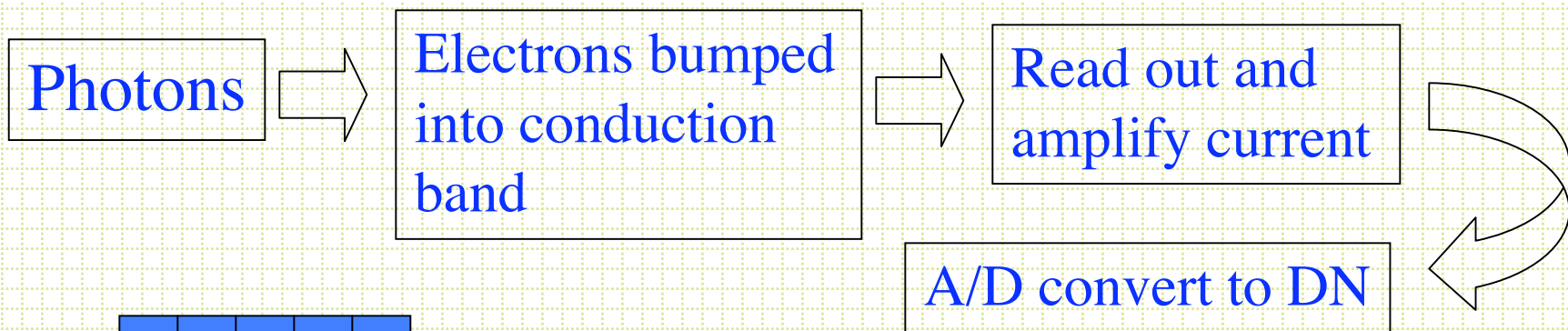
1. Quantum efficiency is more than an order of magnitude better than photographic plates.



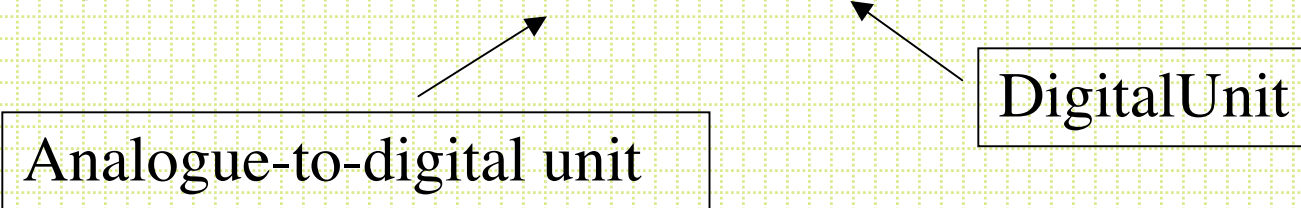
2. Linear Response

CCDs: How do they work?

- Silicon semiconductors with “gate” structure to produce little potential corrals.



“clock” parallel and serial registers
“CTE” > 0.99999

- ``Counts'' = ADU = DN


- DN is not the fundamental unit, the # of detected electrons is. The ``Gain'' is set by the electronics.

- Most A/D converters use 16 bits.

DN from: $0 \text{ to } (2^{16} - 1) = 65535$

for unsigned, long integers

- Signed integers are dumb: $-32735 \text{ to } +32735$
 $\pm(2^{15} - 1)$

What gain do you want?

Example: LRIS-R has a SITE 24μ -pixel CCD with pixel ``wells'' that hold $\sim 350,000$ e-

- 16-bit unsigned integer A/D saturates at 65525DN
- Would efficiently maximize dynamic range by matching these saturation levels:

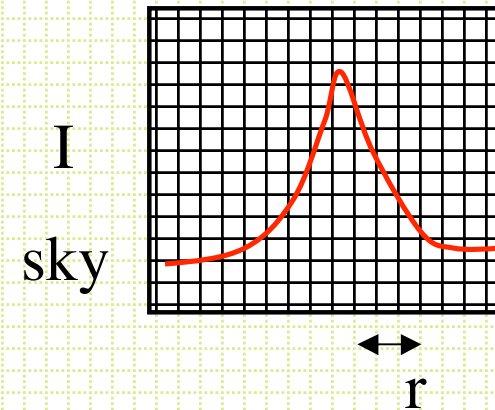
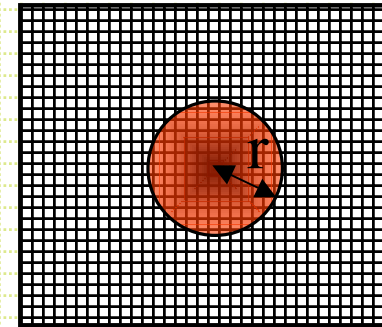
$$\frac{350,000}{65,535} = 5.3 \frac{e^-}{DN}$$

- Note, this undersamples the readout noise and leads to “digitization” noise.

Signal-to-Noise (S/N)

- $\text{Signal} = R_* \cdot t$
 ↑ ↙
 ↕ time
 ↕
 detected e-/second

- Consider the case where we count all the detected e- in a circular aperture with radius r.



- Noise Sources:

$$\sqrt{R_* \cdot t} \quad \square \quad \text{shot noise from source}$$

$$\sqrt{R_{sky} \cdot t \cdot \square r^2} \quad \square \quad \text{shot noise from sky in aperture}$$

$$\sqrt{RN^2 \cdot \square r^2} \quad \square \quad \text{readout noise in aperture}$$

$$\sqrt{\left[RN^2 + (0.5 \square \text{gain})^2 \right] \cdot \square r^2} \quad \square \quad \text{more general RN}$$

$$\sqrt{\text{Dark} \cdot t \cdot \square r^2} \quad \square \quad \text{shot noise in dark current in aperture}$$

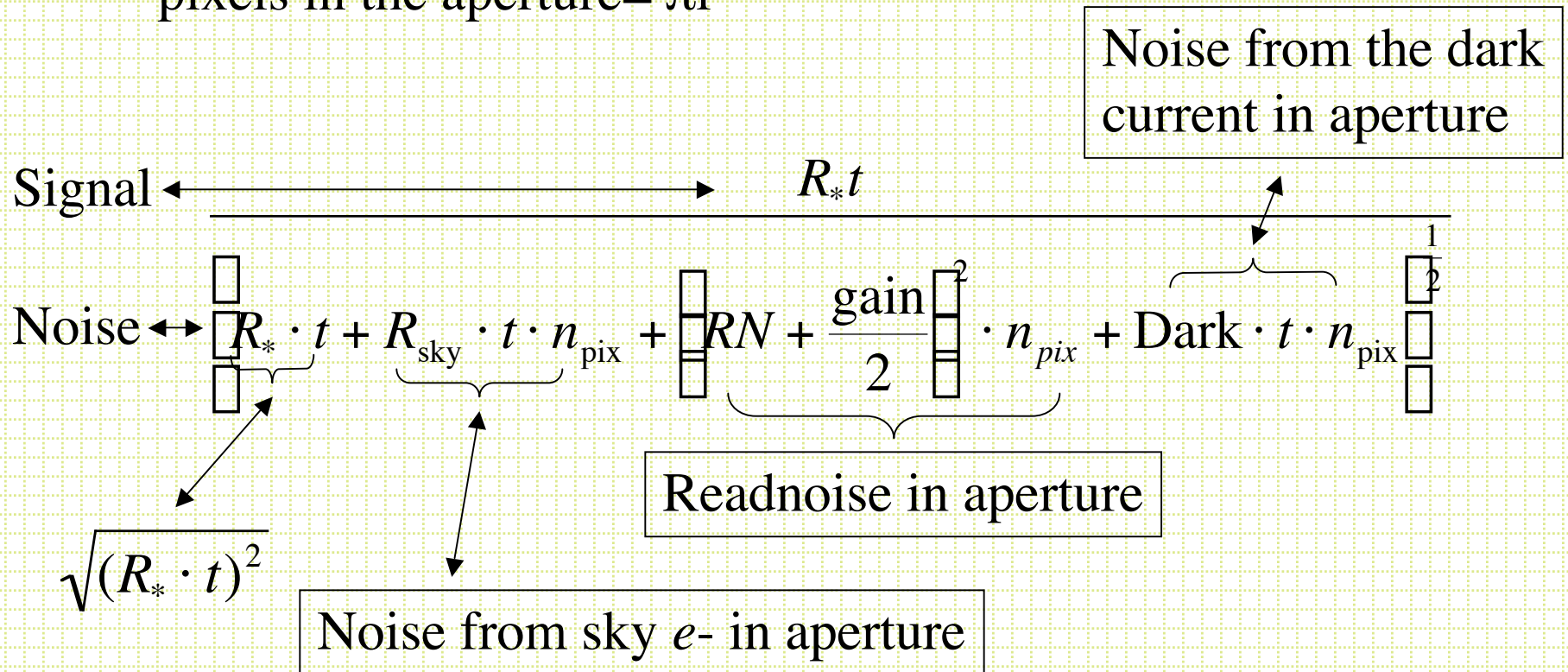
$R_* = e^-/\text{sec}$ from the source

$R_{sky} = e^-/\text{sec}/\text{pixel}$ from the sky

$RN = \text{read noise}$ (as if $RN^2 e^-$ had been detected)

$\text{Dark} = e^-/\text{second}/\text{pixel}$

S/N for object measured in aperture with radius r : $n_{\text{pix}} = \#$ of pixels in the aperture $= \pi r^2$



All the noise terms added in quadrature
Note: always calculate in e^-

S/N Calculations

- So, what do you do with this?
 - Demonstrate feasibility
 - Justify observing time requests
 - Get your observations right

Side Issue: S/N \leftrightarrow Δ mag

$$\begin{aligned}
 m \pm \Delta(m) &= c_o \pm 2.5 \log(S \pm N) \\
 &= c_o \pm 2.5 \log\left[S\left(1 \pm \frac{N}{S}\right)\right] \\
 &= c_o \pm \underbrace{2.5 \log(S)}_m \pm \underbrace{2.5 \log\left(1 \pm \frac{N}{S}\right)}_{\Delta m}
 \end{aligned}$$

$$\Delta(m) \approx 2.5 \log\left(1 + \frac{1}{S/N}\right)$$

Note: in log +/- not symmetric

$$= \frac{2.5}{2.3} \left[\frac{N}{S} \pm \frac{1}{2} \left(\frac{N}{S}\right)^2 + \frac{1}{3} \left(\frac{N}{S}\right)^3 \pm \dots \right]$$

$$\approx 1.087 \left(\frac{N}{S}\right)$$

Fractional error

This is the basis of people referring to +/- 0.02mag error as “2%”

$$S/N \leftrightarrow \sigma_{\text{mag}}$$

S/N	σ_{mag}
2	0.44
10	0.10
100	0.01

How do you get values for some of these parameters?

- Dark Current: CCD@-120°C < 2e-/pix/hour
Insb: ~2e-/pix/sec
- RN: CCD: 2 - 6 e-/pix
Insb: 10 - 25 e-/pix
- R_{*}: for a given source brightness, this can be calculated for any telescope and total system efficiency.
- In practice: *Go to the facility WWW site for everything!*

Source Count Rates

Example: LRIS on Keck 1

for a B=V=R=I=20mag object @ airmass=1

B	1470 e-/sec
V	1521 e-/sec
R	1890 e-/sec
I	1367 e-/sec

To calculate R_* for a source of arbitrary brightness only requires this table and a bit of magnitude math.

Source Count Rates

$$m_1 = c_o \square 2.5 \log(I_1) \dots \dots \dots (1)$$

$$m_2 = c_o \square 2.5 \log(I_2) \dots \dots \dots (2)$$

$$m_1 \square m_2 = \square 2.5 [\log(I_1) \square \log(I_2)] \dots \dots \dots (1) \square (2)$$

$$m_1 \square m_2 = \square 2.5 \log\left(\frac{I_1}{I_2}\right)$$

$$\frac{I_1}{I_2} = 10^{\square\left(\frac{m_1 \square m_2}{2.5}\right)}$$

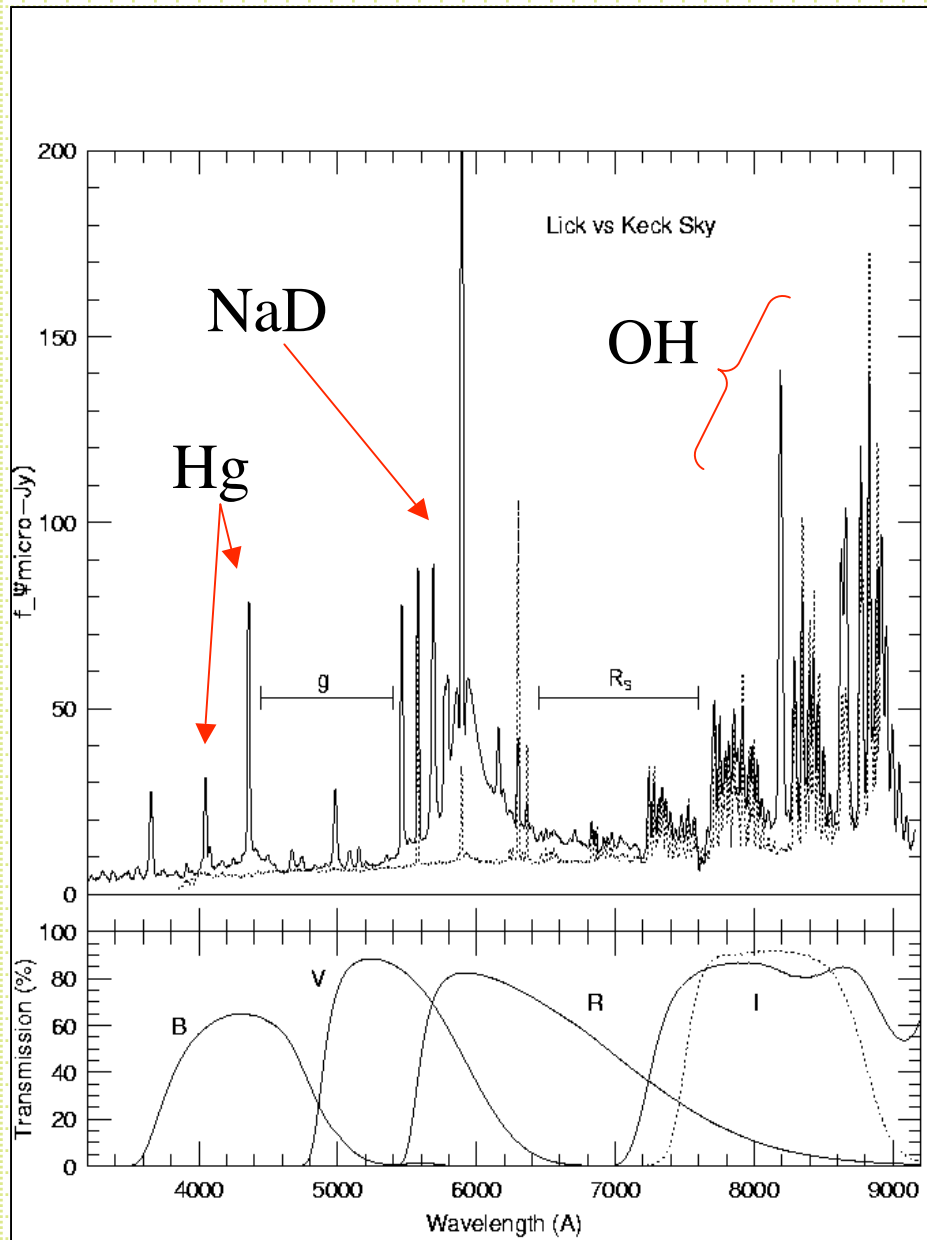
Let I_2 be the intensity for the fiducial $m=20$ object

$$I_1 = R_*(m_1) = I_{20} \cdot 10^{\square\left(\frac{m_1 \square 20}{2.5}\right)}$$

R_{sky}

Signal from the sky background is present in every pixel of the aperture. Because each instrument generally has a different pixel scale, the sky brightness is usually tabulated for a site in units of $\text{mag}/\text{arcsecond}^2$.

$(\text{mag}/\text{arc}^2)$



Lunar age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

Scale \square "/pix

(LRIS - R : 0.218" /pix)

Area of 1 pixel = (Scale)²

(LRIS \square R : 0.0475"²)

this is the ratio of flux/pix to flux/"

In magnitudes :

$$I_{\text{pix}} = I_{\text{''}} \text{Scale}^2$$

I \square Intensity (e⁻/sec)

$$\square 2.5 \log(I_{\text{pix}}) = \square 2.5 [\log(I_{\text{''}}) + \log(\text{Scale}^2)]$$

$$m_{\text{pix}} = m_{\text{''}} \square 2.5 \log(\text{Scale}^2)$$

(for LRIS - R : add 3.303mag)

and

$$R_{\text{sky}}(m_{\text{pix}}) = R(m = 20) \square 10^{(0.4 \square m_{\text{pix}})}$$

Example, LRIS in the R - band :

$$R_{\text{sky}} = 1890 \square 10^{0.4(20 \square 24.21)} = 39.1 \text{ e}^- / \text{pix} / \text{sec}$$

$$\sqrt{R_{\text{sky}}} = 6.35 \text{ e}^- / \text{pix} / \text{sec} \square \text{RN in just 1 second}$$

S/N - some limiting cases. Let's assume CCD with Dark=0, well sampled read noise.

$$\frac{R_* t}{\left[R_* \cdot t + R_{\text{sky}} \cdot t \cdot n_{\text{pix}} + (RN)^2 \cdot n_{\text{pix}} \right]^{\frac{1}{2}}}$$

Bright Sources: $(R_* t)^{1/2}$ dominates noise term

$$S/N \approx \frac{R_* t}{\sqrt{R_* t}} = \sqrt{R_* t} \quad t^{\frac{1}{2}}$$

Sky Limited ($\sqrt{R_{\text{sky}} t} > 3 \square RN$): $S/N \approx \frac{R_* t}{\sqrt{n_{\text{pix}} R_{\text{sky}} t}} \sqrt{t}$

Note: seeing comes in with n_{pix} term

What is ignored in this S/N eqn?

- Bias level/structure correction
- Flat-fielding errors
- Charge Transfer Efficiency (CTE)
0.99999/pixel transfer
- Non-linearity when approaching full well
- Scale changes in focal plane
- A zillion other potential problems

Writing Proposals

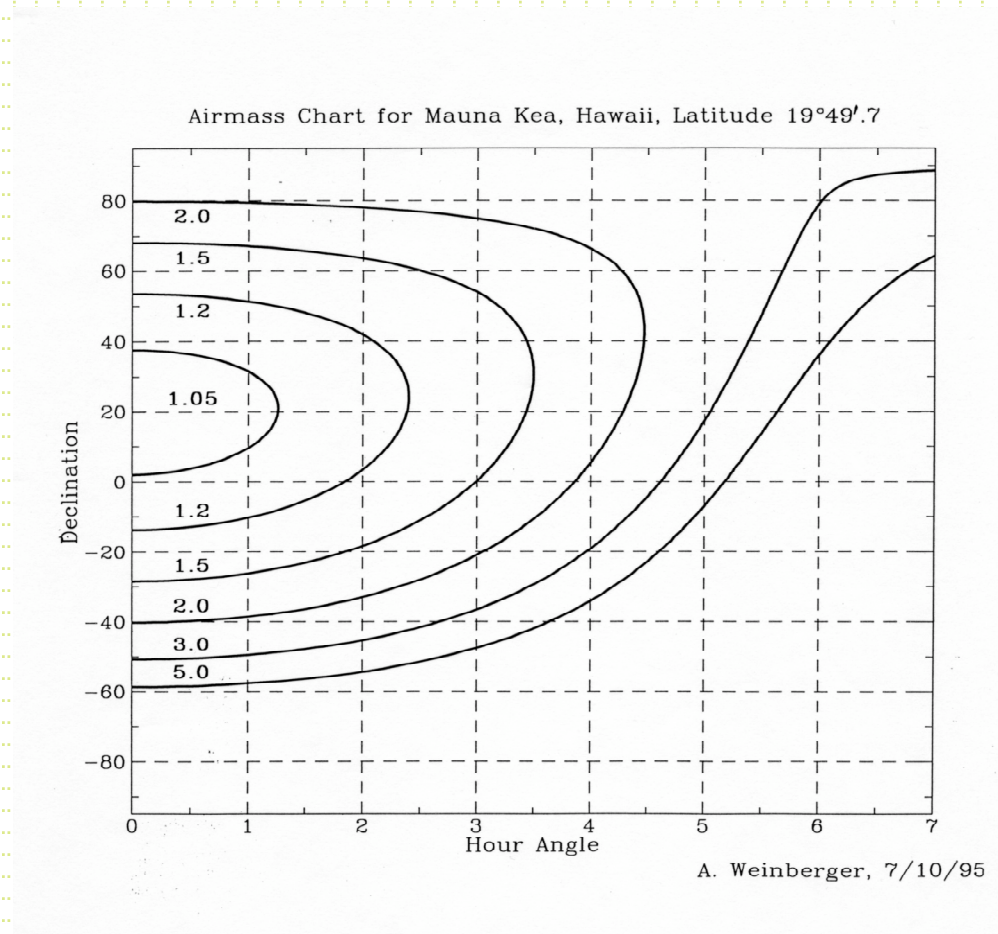
- First and foremost: Scientific Justification!
 - Give context
 - Clearly state what unanswered questions are to be addressed
 - Clearly state what you will do new or better
- Look Competent and Smart
 - Do S/N and exposure time calculations
 - Defend choice of filters/spectral resolution sample size etc.

Observing

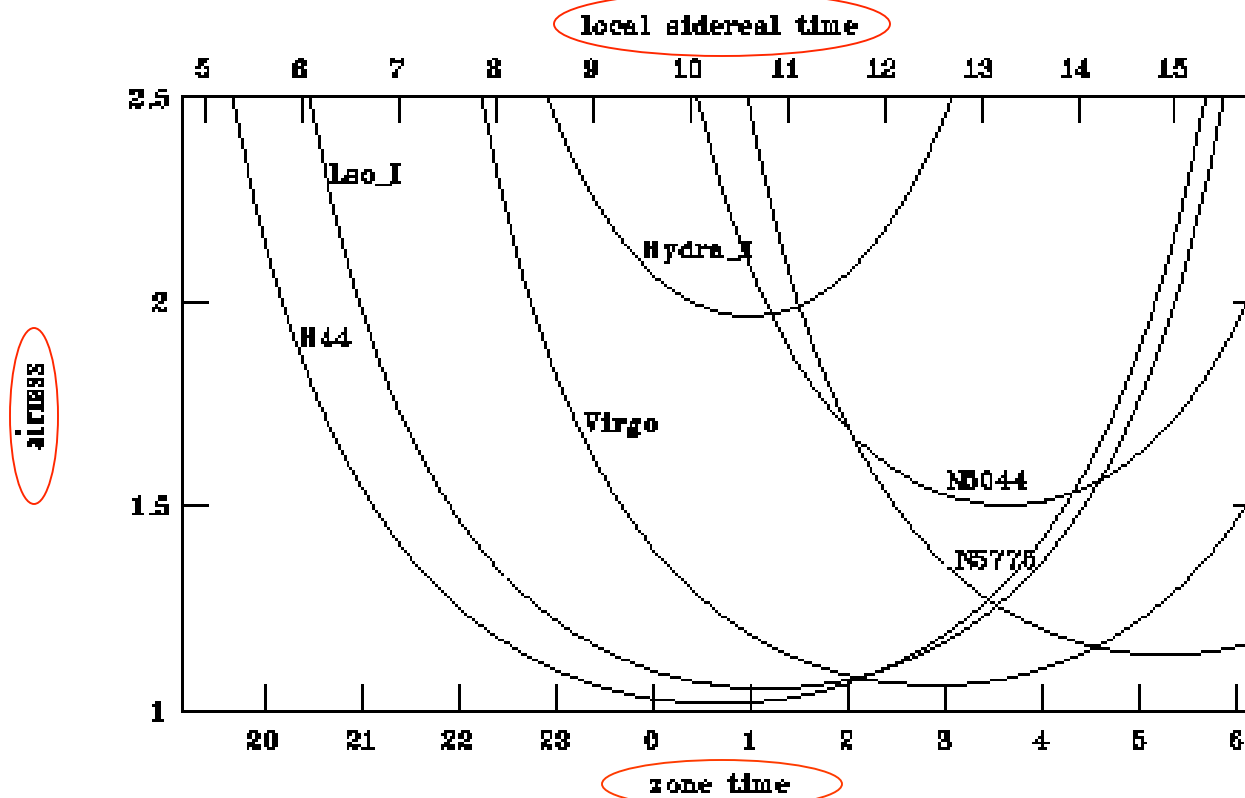
- Rule #1 -- keep collecting photons!
- Know your S/N targets
- Plan the night out carefully ahead of time
- Useful tools:
 - Aircharts

Hour angles and airmass

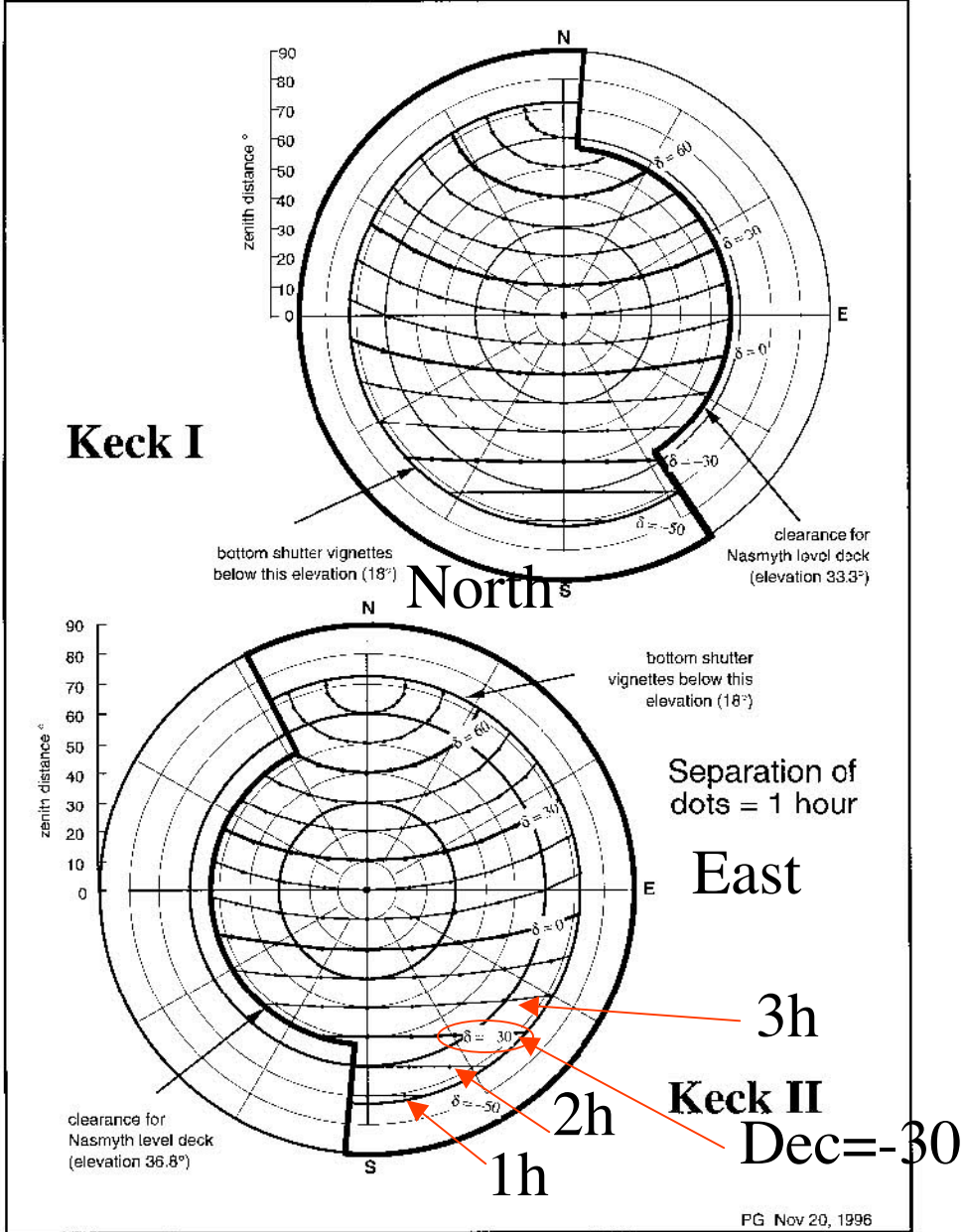
- The *sidereal time* gives the right ascension that is passing through the meridian. My index point is 12h is overhead at local midnight on March 21. Sky advances 2 hours per month.
- The *hour angle* is the time before or after a particular RA is at the meridian.
 $HA = LST - RA$
- *Airmass* is a combination of the HA and the difference between the telescope latitude and the pointing declination.
 $Airmass \sim \sec(\text{zenith angle})$



NOAO/IRAF V2.11EXPORT bolte@mojave.nao.berkeley.org Tue 10:22:59 06-Apr-9
Airmass chart for UT date SAT February 21, 1996 at KPN0 (time zone = 7
→ evening ast. twilight = 19:30 morning ast. twilight = 5:43
moon: ra = 17:24 dec = -17:59 rise = 2:24 set = 19:14 ill. frac. =



- IRAF Airchart in the mtools packages is very handy.
- Typically observe with airmass= $X < 2$
- Atmospheric dispersion can be a problem for $X > 1.5$

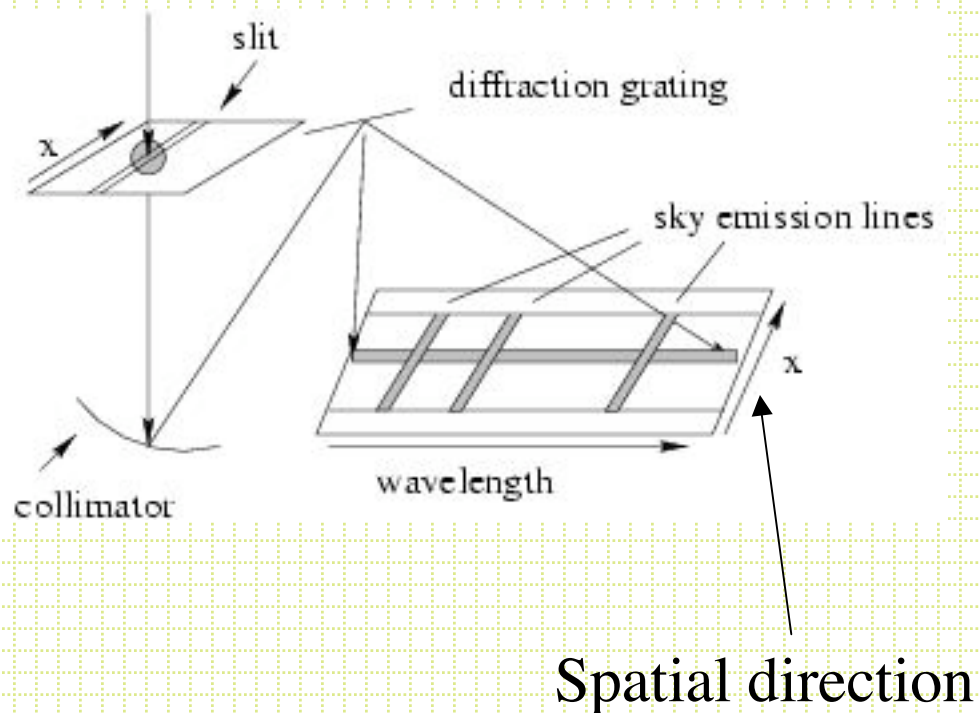


There are often other limits that govern where you can point in the sky.

Decisions before observing

- Sometimes, the gain in e^-/DN for the system
- On-chip binning?
 - Smaller files (not important)
 - Faster readout time (can be important)
 - Less readout noise per area detector (can be important)
- For direct imaging in broadband filters, readnoise is very rarely an issue. You want to have the FWHM of point sources to be at least 2.5 pixels to properly sample the PSF. If you are oversampled, that doesn't usually have any dire consequences. The readout time can be a deciding factor.

Binning for spectra



- Sometimes, RN is a significant component of the noise. Having fewer pixels under the spectrum reduces the noise in a resolution element.

- Binning in *Spectral* direction can reduce resolution

- Binning in the spatial direction can compromise fitting the sky lines

Observing Checklist: Afternoon

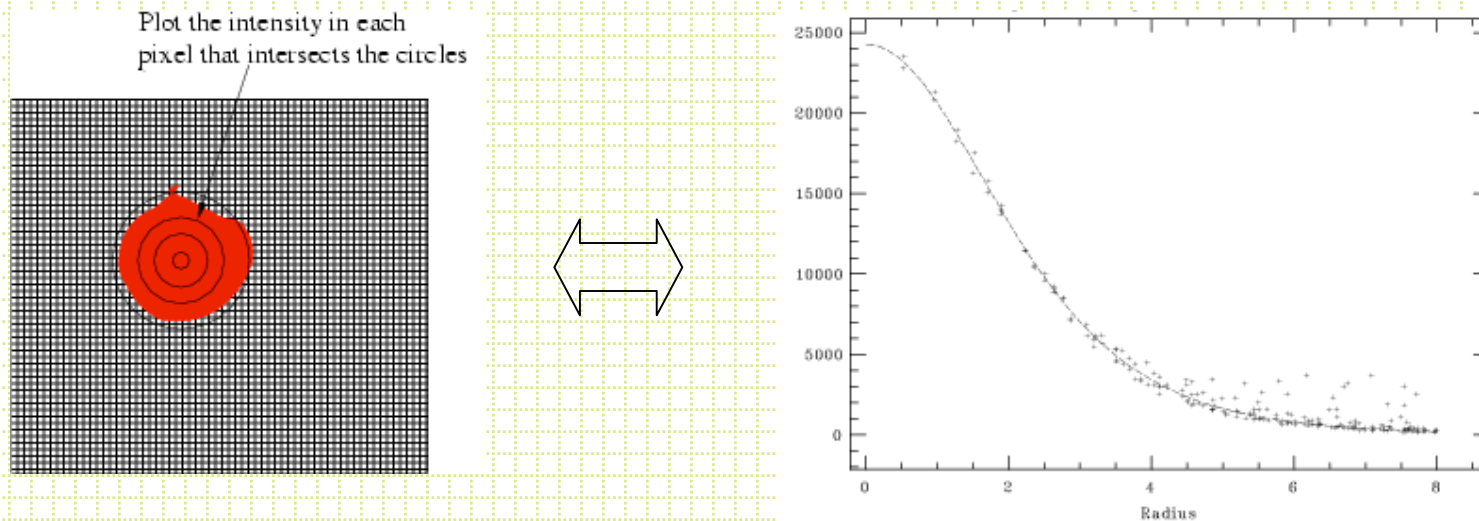
- Bias frames - should be boring! WWW site for instrument should have an example to compare to.
 - Move filterwheels, gratings, telescope, dome during readout to see if it will be safe to do so during the night
- Dome Flats
 - Is the shutter opening?
 - Shutter timing observations
- For spectra, check the grating tilts for proper wavelength range
- Things are working- take flats, arcs, biases, darks
- Get quick-look reduction procedures in place

At Night

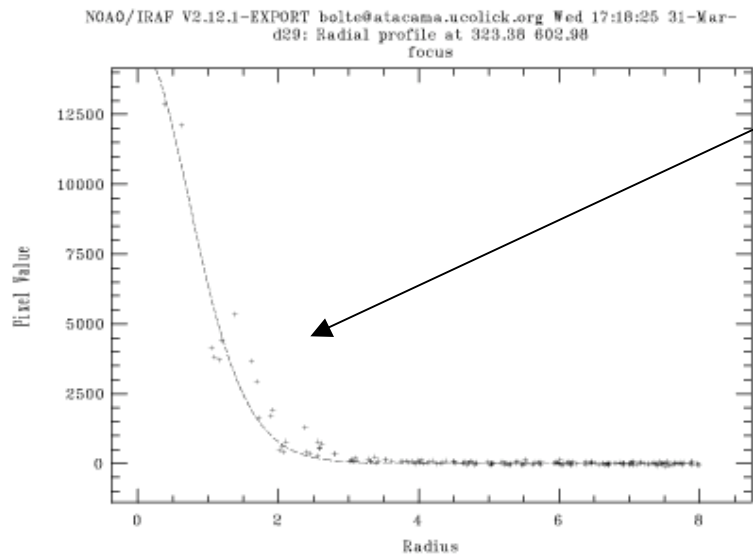
- Efficiency is everything!
 - Have the shutter open
 - Know your S/N goals
 - Have targets queued up
 - Check focus
 - Have the shutter open
- Be looking at your data in near real time including flat-fielding and bias subtraction

Telescope Focus

- Whether you focus yourself or the telescope operator does it for you, you need to always be checking *radial profiles*.

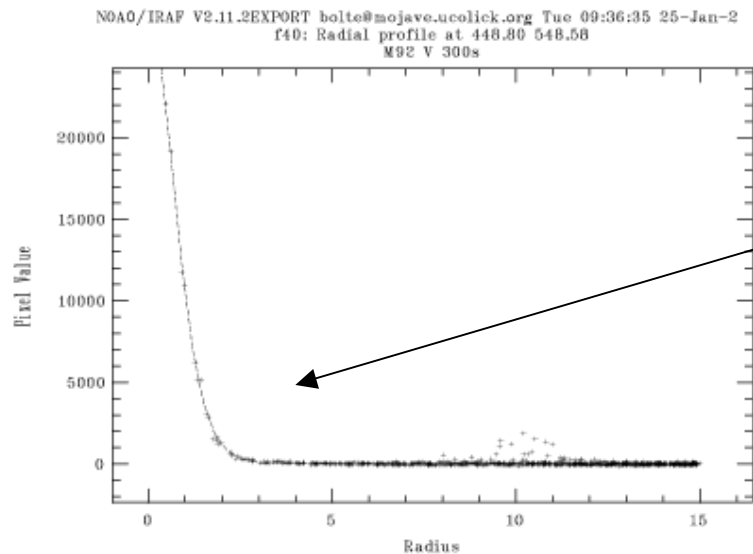


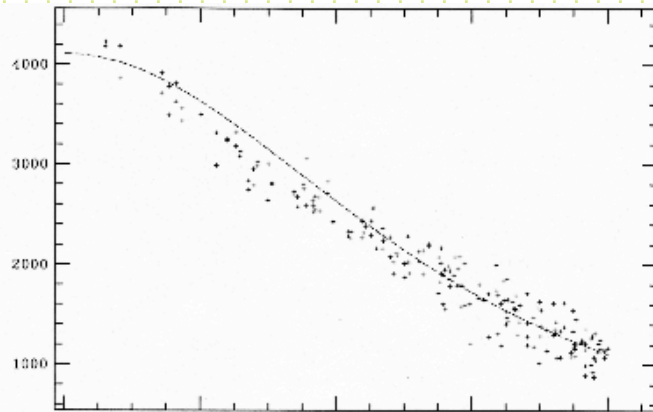
Poor focus (scatter is lack of roundness and probably astigmatism)



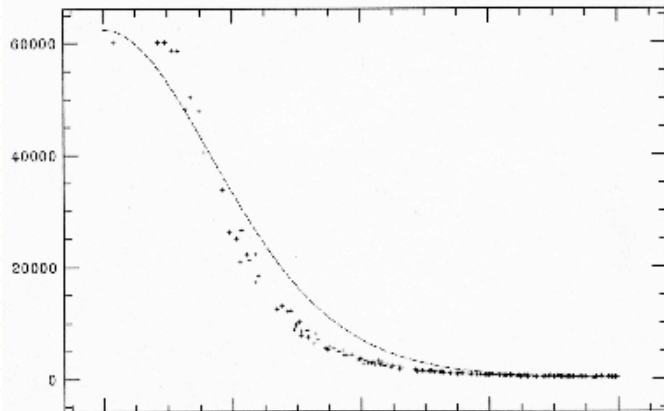
- Using the ``r'' command in IRAF's *imexam*, you can produce radial profiles for any object in a frame. `:.snap eps` in the graphics window will output an `.eps` file.

Excellent focus. Very round (and dangerously sharp) image

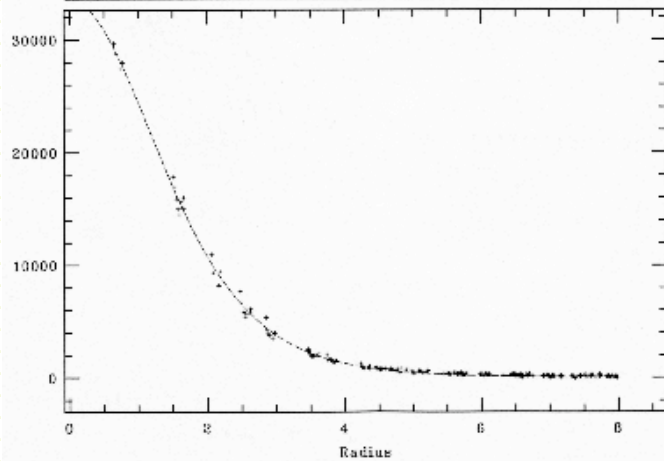




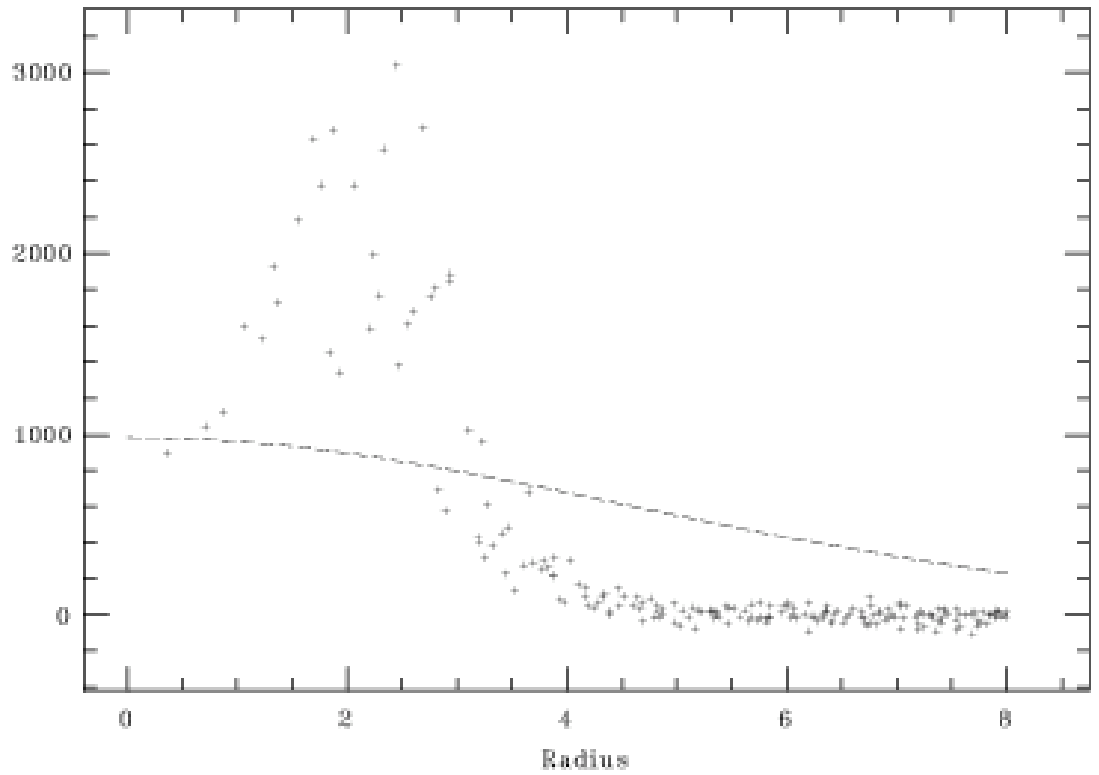
Galaxy



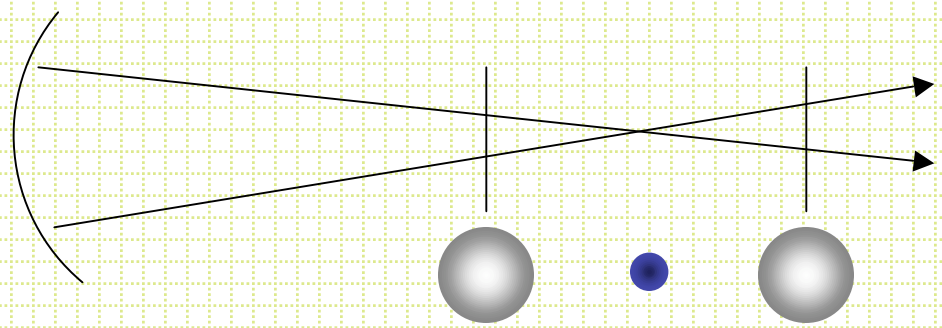
Saturated star



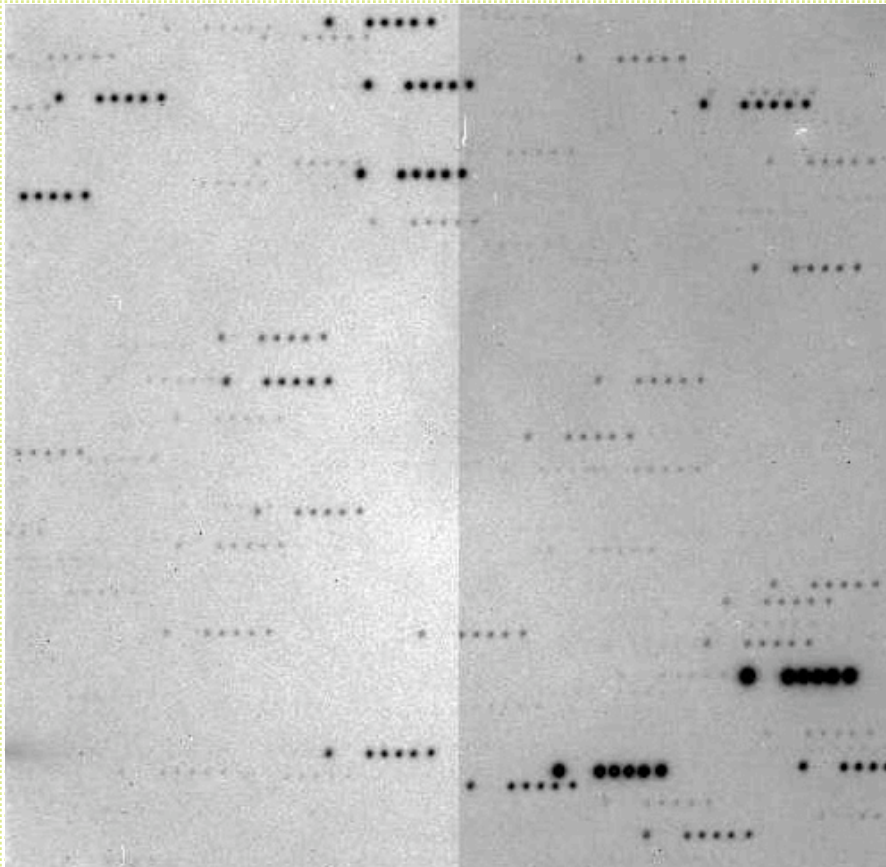
Well focussed star



Way out of focus (donut).



Focus frames



1. Set focus, start exposure.
2. Pause exposure, move telescope, change focus
3. Repeat
4. Make a double telescope move on the last focus value, then read out

Splitting Exposures

- How long to expose? Once in the sky-limited regime, the S/N only depends on the total exposure time. There is only the CCD readout time penalty to be paid by splitting long exposures into multiple shorter exposure.
- Why do shorter exposures?
 - Cosmic ray rejection
 - Increase dynamic range
 - ``in-field dithering'' along slit or on the sky can help with flat fielding
 - Reduce risk

Preliminary Processing

- There are two types of instrumental signature to remove:

- Additive:

- Bias Level
- Bias Structure
- Dark Counts
- ``charge skimming``

Constant # of counts added independent of the brightness of the source(s).

- Multiplicative:

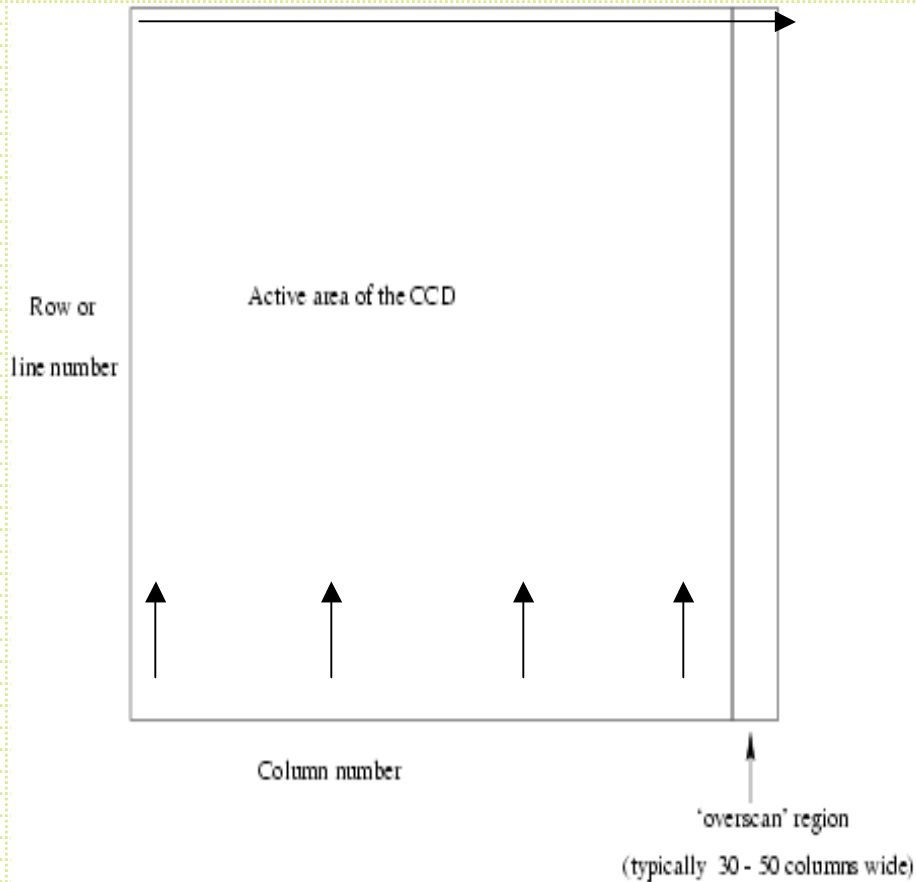
- Q.E. variations on all scales

Constant *fractional* effect

Bias Correction

- Bias level and any y (along columns) gradient is taken out via *overscan* subtraction.
- Bias structure is taken out by subtracting a *zero-level* frame.
- In IRAF *ccdproc* takes care of both.

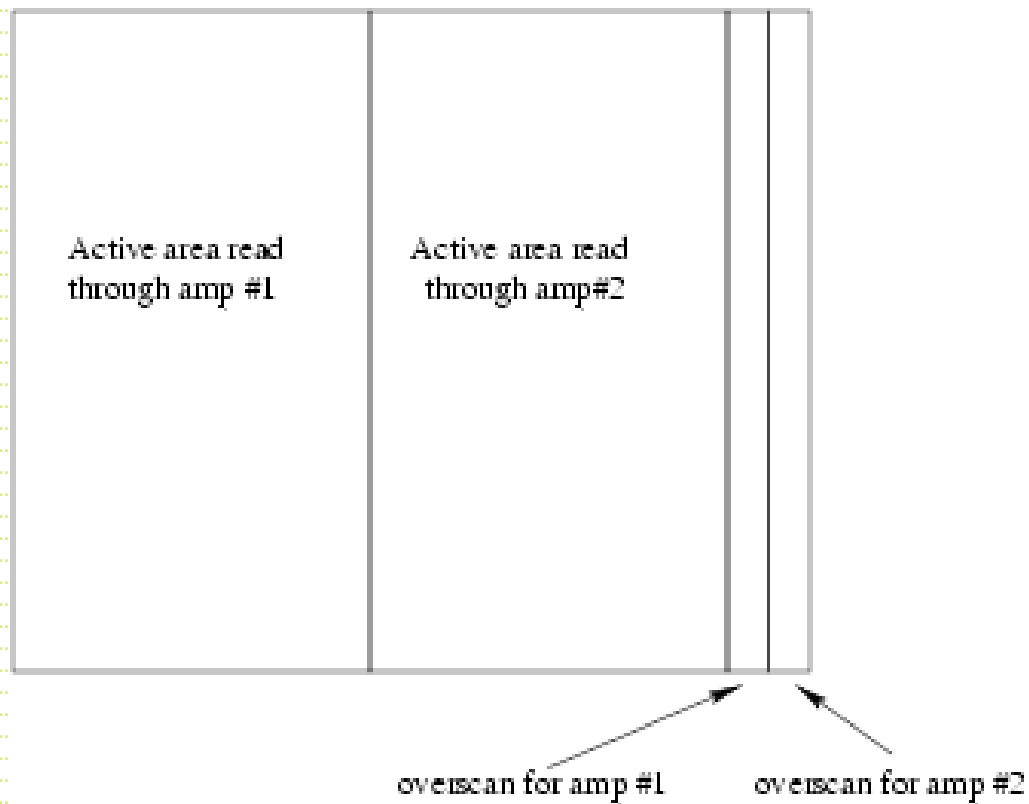
Overscan

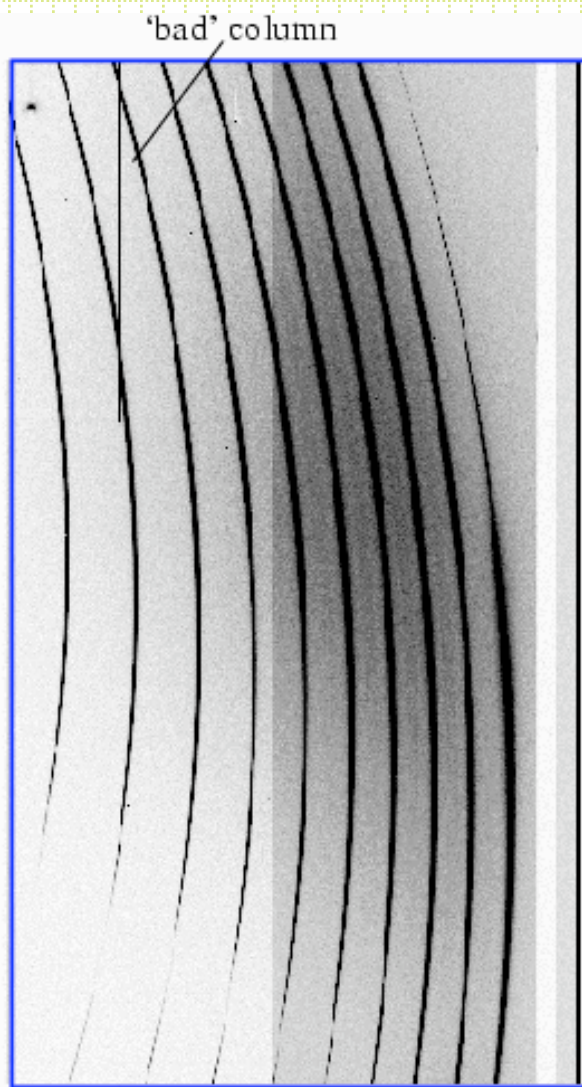


After reading out the CCD `real' pixels, you can continue to read out virtual pixels and record the bias level and read noise of the amplifiers. These virtual pixels are called the overscan region

Two amplifier overscan

Dual amplifier readout

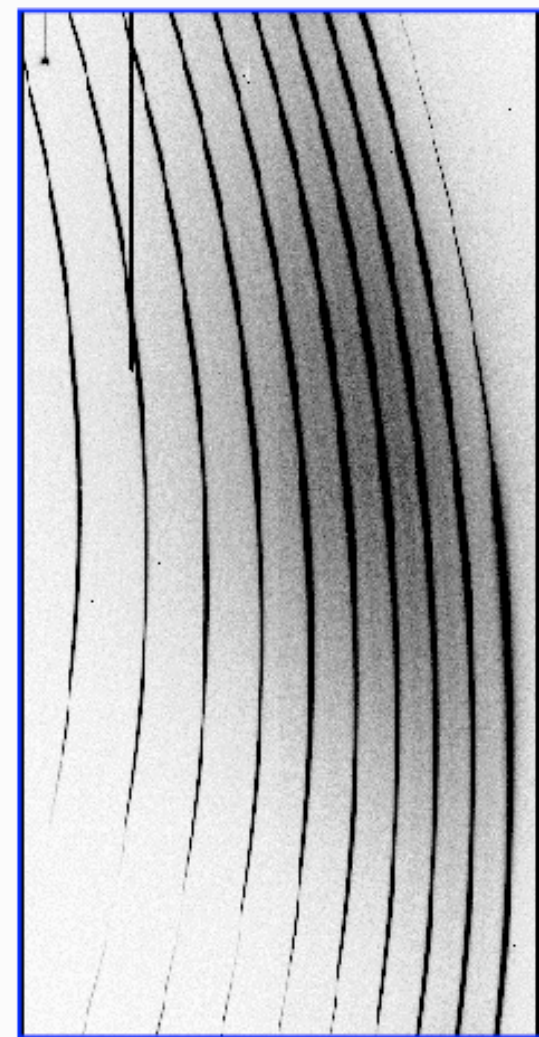




RAW FRAME

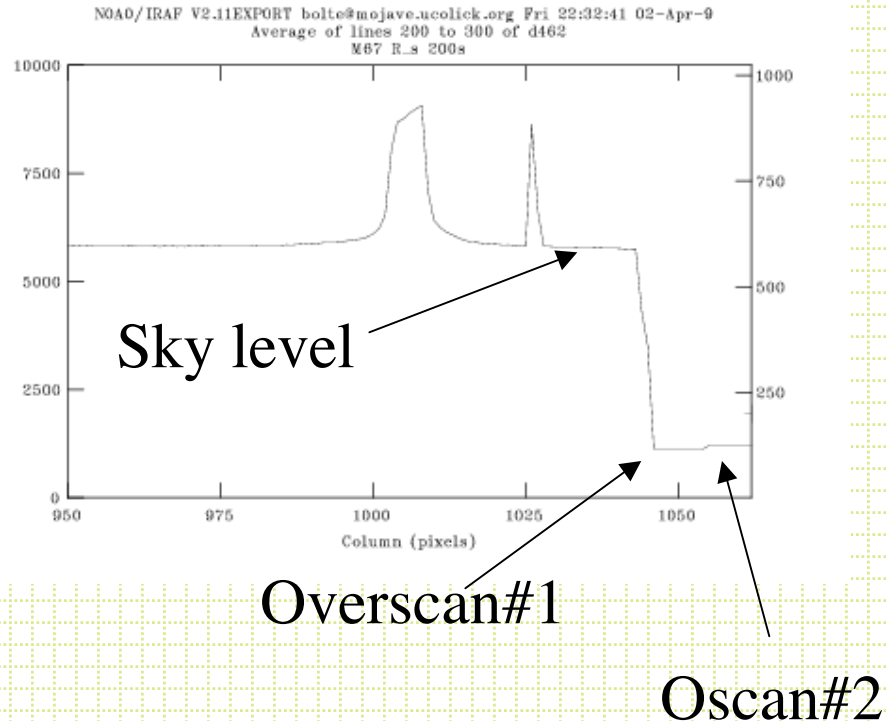
overscan for Amp#1

overscan for Amp#2



OVERSCAN CORRECTED/TRIMMED

Overscan subtraction

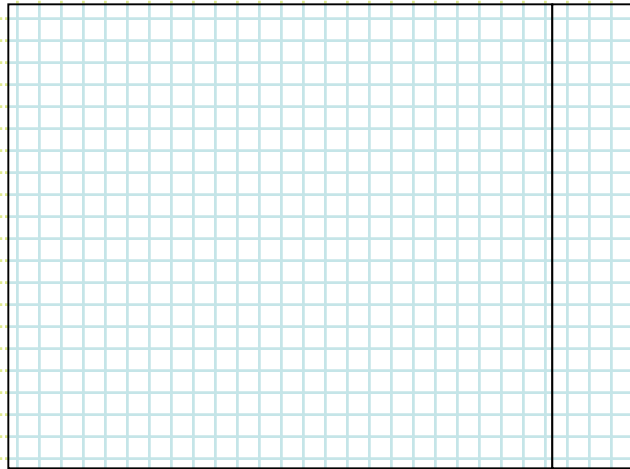


- First you need to identify the relevant columns.
- In IRAF use the format:
 $[x1,x2:y1,y2]$

In IRAF, plots like this are made using *implot*

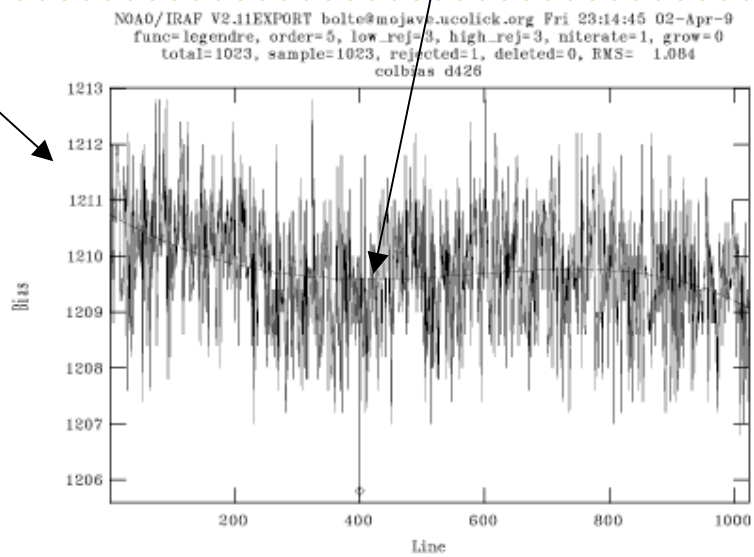
Colbias

- The overscan subtraction is accomplished by fitting a smooth function to the average of several columns in the overscan region.
- The value of the fitted curve is subtracted from each row. This accounts for a mean bias level and any gradient in along columns.



Average
several

Smooth fit is subtracted
from each row



Flat Fielding

- There are pixel-to-pixel QE variations and lower spatial frequency QE variations in all electronic detectors. The goal of flat-fielding is to multiply every pixel by the correct normalizing factor to eliminate these QE differences.
- Ideally, illuminate the detector with a source that is as flat on the sky as the background and collect at least a million e- per pixel. Then could flat-field to $\frac{\sqrt{10^6}}{10^6} = 0.001 = 0.1\%$.

Flat Fielding

- If you could illuminate the CCD uniformly, then normalize the mean to 1, this image could be divided into every frame.
- For direct imaging, usually use a combination of:
 - Dome Flats
 - Twilight Flats
 - Dark Sky Flats

Dome Flats

- Put some quartz (hot, continuum source) lamps on the telescope and illuminate a white screen or spot on the dome.
- These often don't work very well for two reasons:
 - The lamps are always too cool (red)
 - The dome is not even close to infinity and usually illuminates the primary differently than the sky
- But, you can collect a lot of photons during the day

Twilight Flats

- These often work pretty well
- The Sun is pretty hot, the scattering surface illuminates the telescope just like the dark night sky
- Doesn't use dark time

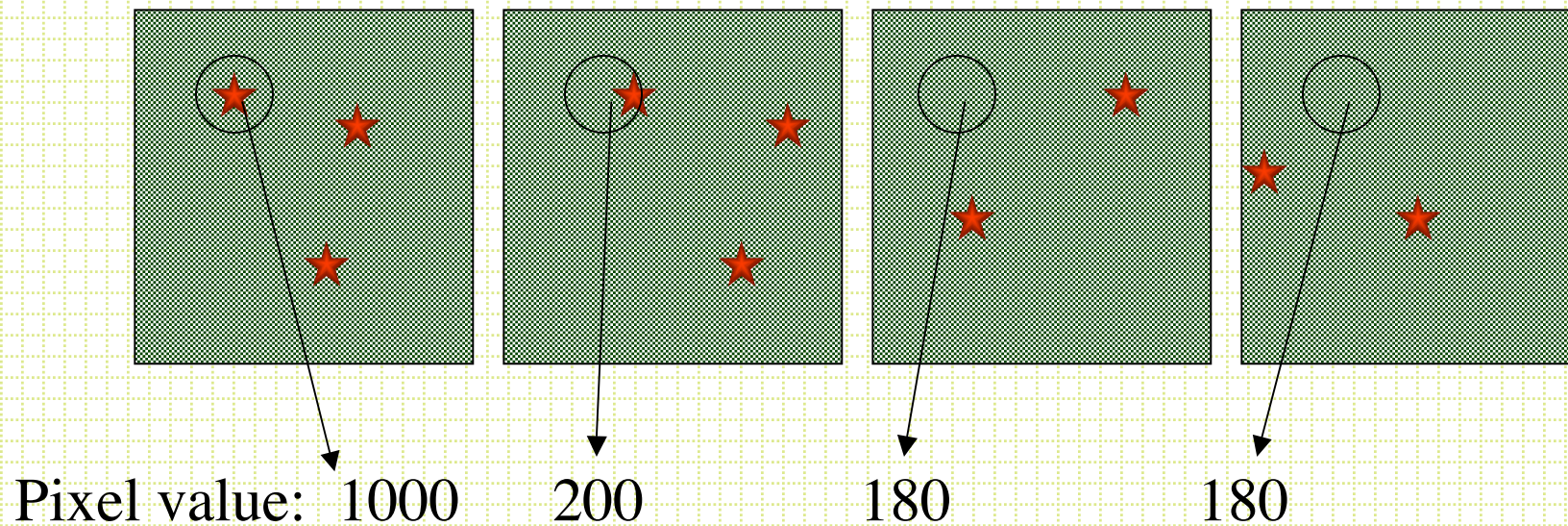
Dark-sky Flats

- These tend to work very well. They match the sky perfectly
- They sometimes require useful dark time
- They sometimes contain fringes

Stars and Galaxies

- For twilight and dark sky flats you have a problem in that they contain stars and galaxies. The usual trick is to move the telescope between exposures and then do a non-registered stack of the frames in each filter.
- Median or better yet *minmax* rejection (for example, in the frame combining can effectively eliminate all the stars and galaxies in the combined flat.

Minimax rejection



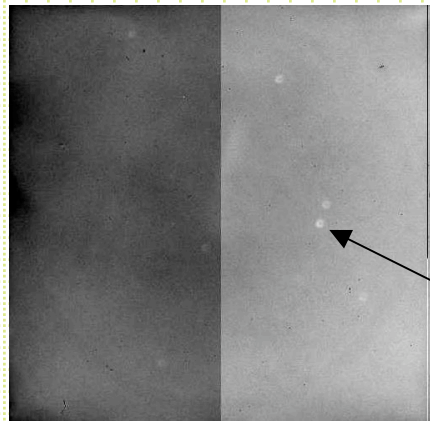
Average with minmax rejection, reject 2 highest value averaging lowest two will give the sky value. NOTE! Must normalize frames to common mean or mode before combining! Sometimes it is necessary to pre-clean the frames before combining.

Combining Frames

- In IRAF, *imcombine* is the task to combine frames.
 - combine=average
 - reject=minmax
 - scale=mode
 - nlow=0
 - nhigh=2

Flat fielding tricks

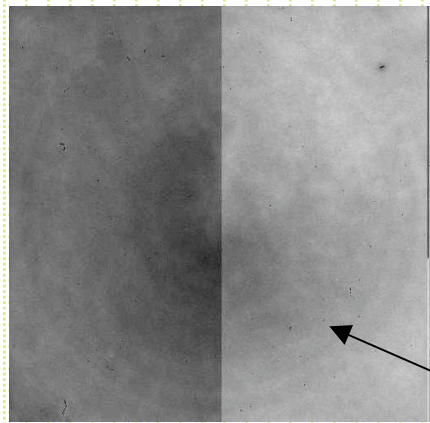
- Combine domes (high counts, bad illumination) with dark sky flats (low counts, excellent illumination).
 1. Spatially smooth (or fit low-order surface to) both combined dome and combined dark sky. $> sDome, sDark$
 2. Remove dome low-spatial-frequency pattern: $Dome/sDome$
 3. $sDark$ is the sky flat with the low-f pattern already removed.
 4. Best of both worlds is $(Dome/sDome) \times sDark$



I-band

PFCam flat fields

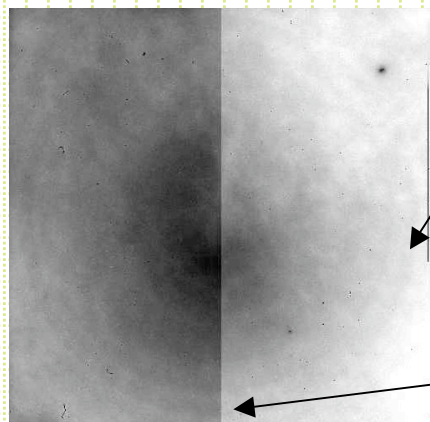
Dust on filter



V-band

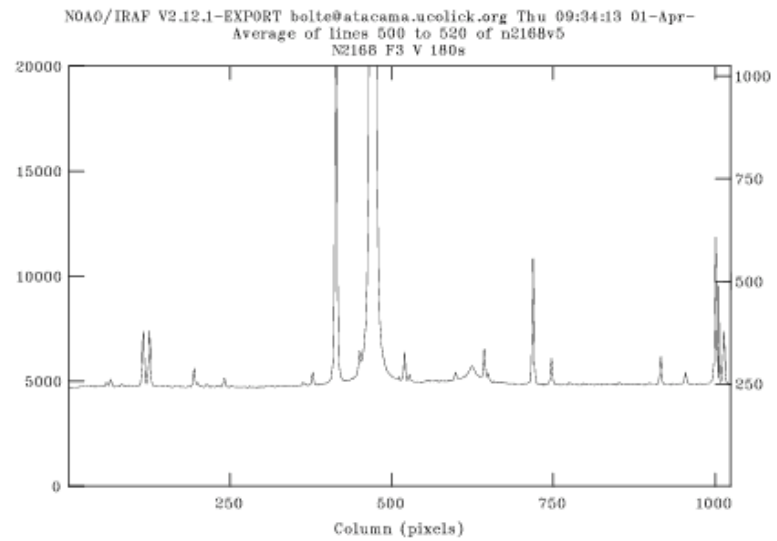
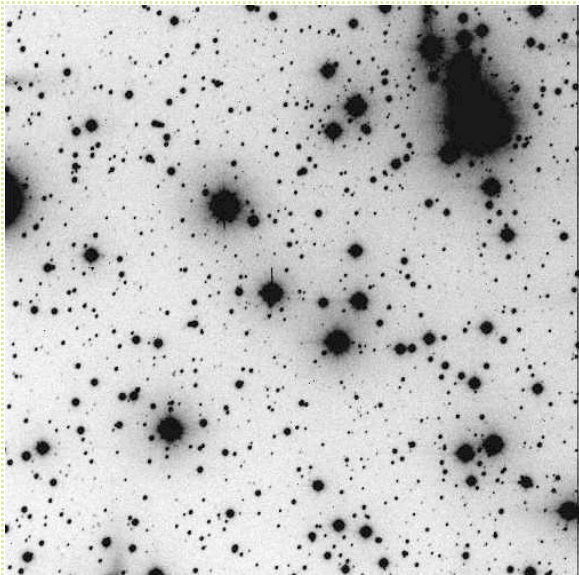
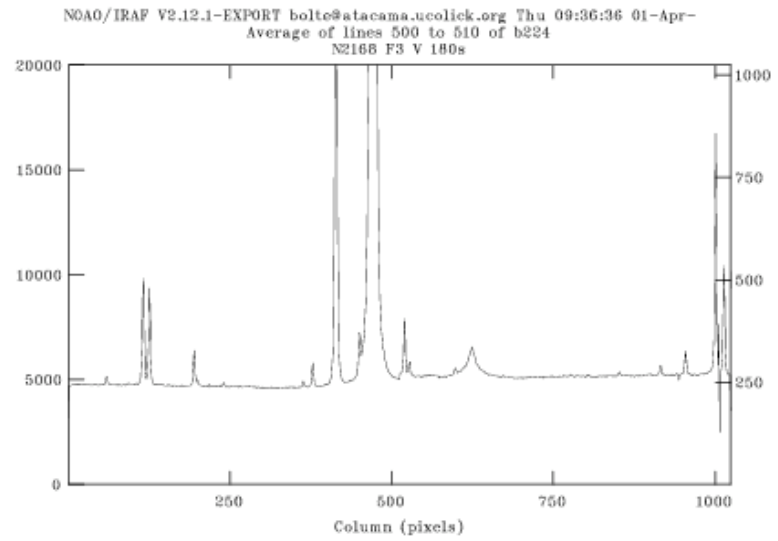
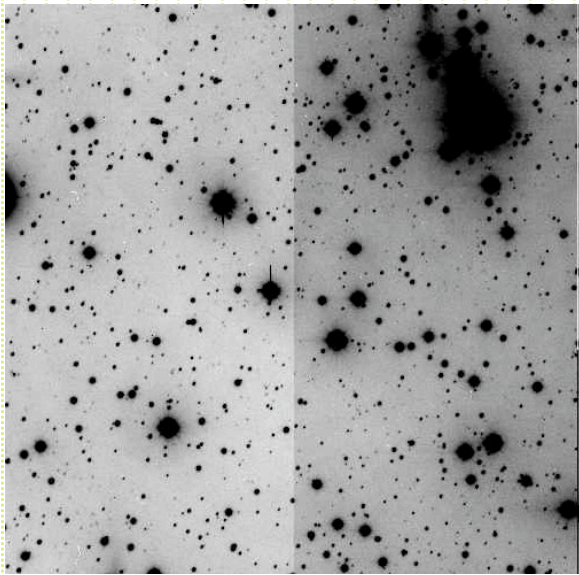
Note differences with color.
This means that objects with
different spectra will be flat-
fielded slightly incorrectly.

Rings due to non uniform thinning



U-band

Two amplifier readout



Flat-field tests

1. Take cuts through your flat-fielded frames and make sure the sky is flat (check corners). IRAF *implot*
2. In blank areas, make sure the pixel-to-pixel variations are consistent with shot noise from the sky level. IRAF *imexam* and the `m' key.