Data Reduction:
How to Make Your Own Light Curves

Jacob Bean
University of Chicago

Outline:

- Preliminaries
- Basic data reduction framework
- Questions

Outline:

- Preliminaries
- Basic data reduction framework
- Questions

Preliminaries

Data reduction golden rules:

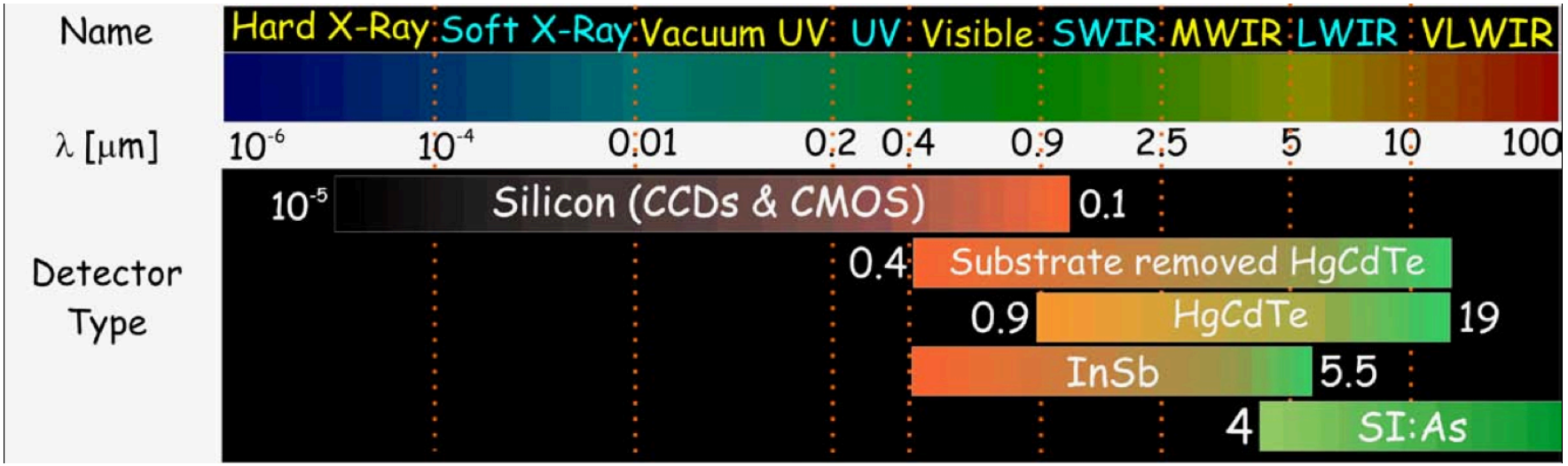
- Document, document, document.
- Do the best that you can to estimate your confidence intervals.
- Be willing to not publish bad data sets.

Preliminaries

Know your detector technology!

- What is the photo-sensitive material?
- What is the read-out circuit architecture?

Photo-sensitive materials:



Material Name	Symbol	E_g (eV)	λ_c (μm)
Silicon	Si	1.12	1.1
Indium-Gallium-Arsenide	InGaAs	0.73 – 0.48	1.68* – 2.6
Mer-Cad-Tel	HgCdTe	1.00 – 0.07	1.24 – 18
Indium Antimonide	InSb	0.23	5.5
Arsenic doped Silicon	Si:As	0.05	25

Image credit: James Beltic, Teledyne Imaging Sensors

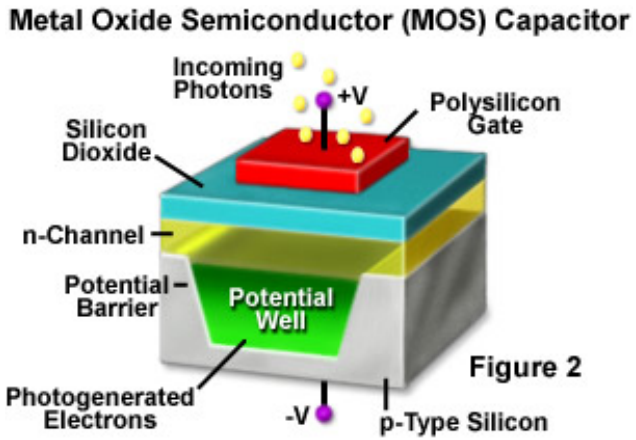
Preliminaries

Know your detector technology!

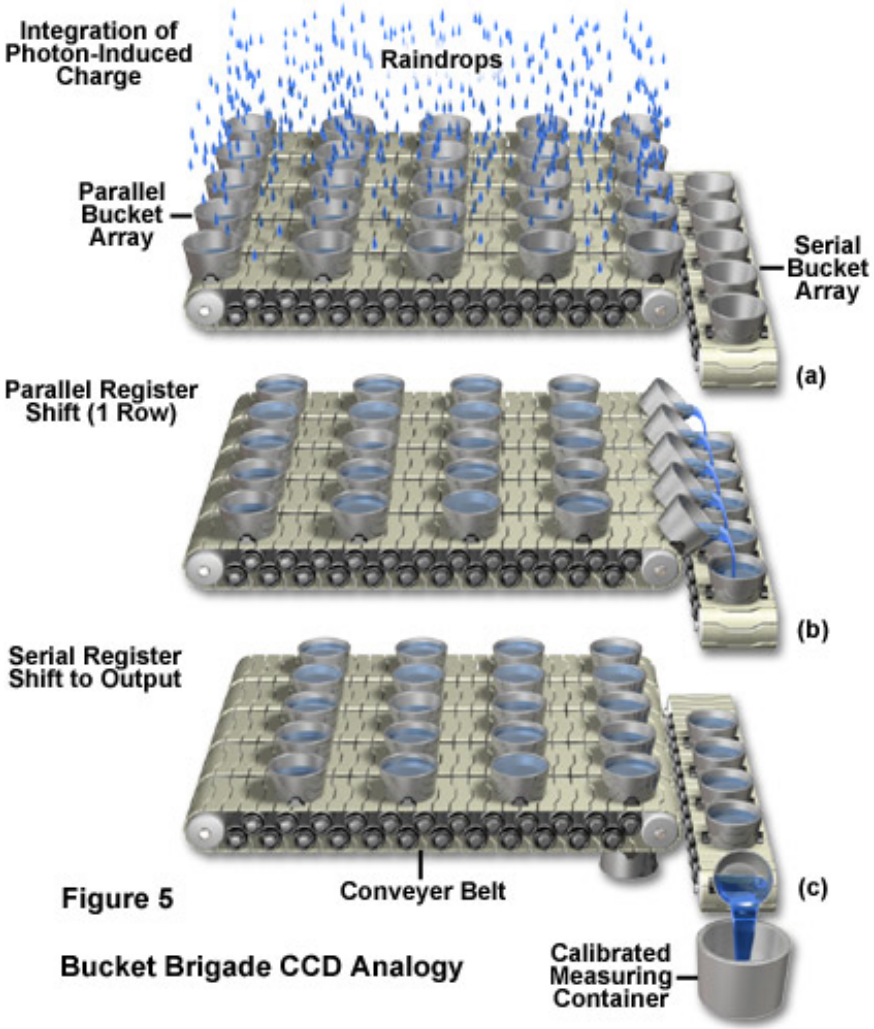
- What is the photo-sensitive material?
- What is the read-out circuit architecture?

Read-out Circuit Architectures:

CCD (charge-coupled device)

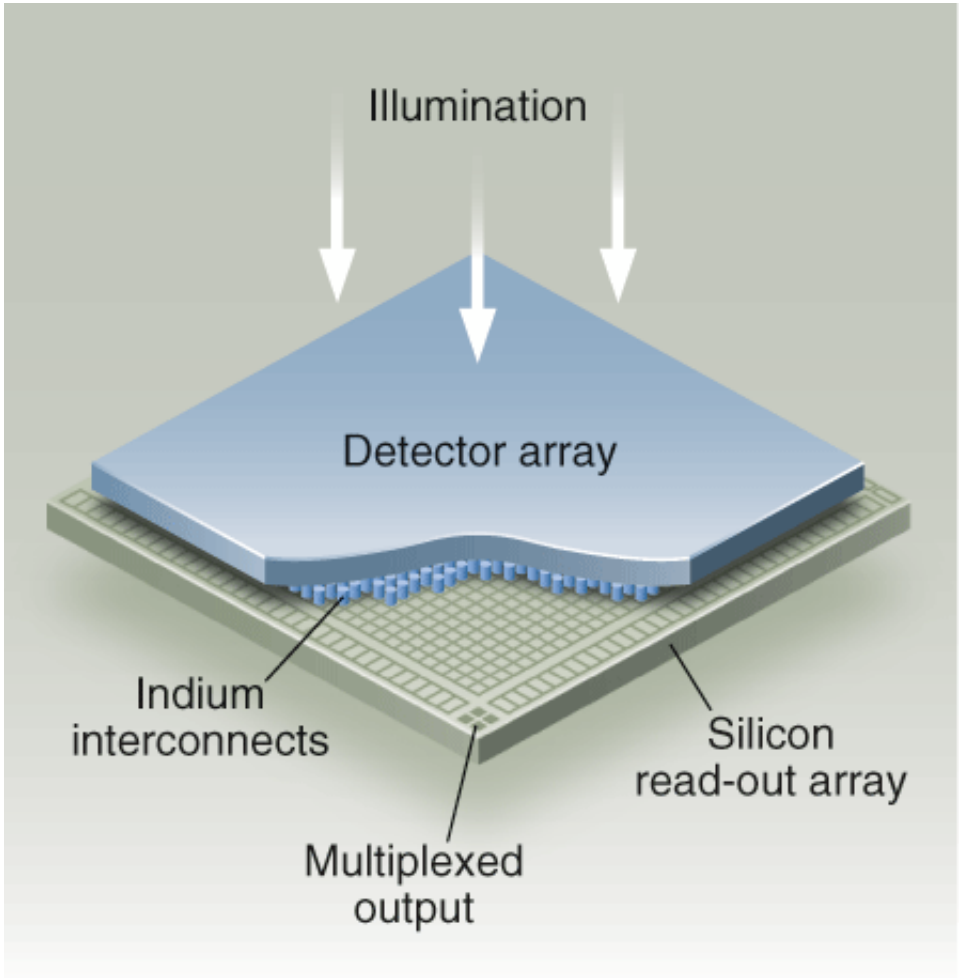


- serial voltage generation
- only destructive reads



Read-out Circuit Architectures:

Hybrid CMOS (complementary metal–oxide–semiconductor)



- voltage generation at the pixel level (parallel)
- non-destructive reads
- higher read noise

Image credit: Ian McLean

Preliminaries

Question standard techniques!

Example: dithering/nodding for ground-based NIR observations to remove sky background

Preliminaries

Basic terms/concepts:

"full-well" = number of free photoelectrons that a pixel can hold

Typical values on order of 100,000 electrons, range 70,000 – 200,000

IR detectors generally lower, optical detectors generally higher

Preliminaries

Basic terms/concepts:

"gain" = electrons per data number for analog-to-digital conversion

Typical value on order of 1, range 0.5 – 5

Large values correspond to low gain, small values to high gain

Be wary of different modes that are not supported

Preliminaries

Basic terms/concepts:

"saturation" = when output digital signal no longer responsive to more incident light

Can occur at the pixel level (full-well depth exceeded),

Or at the analog-to-digital converter (ADC saturated)

Note: ADCs are typically 16 bit devices, so are limited to 2^16 - 1 = 65535

Saturation in CCDs leads to blooming, but flux can be conserved

Saturation in IR arrays can be mitigated with up-the-ramp sampling

Preliminaries

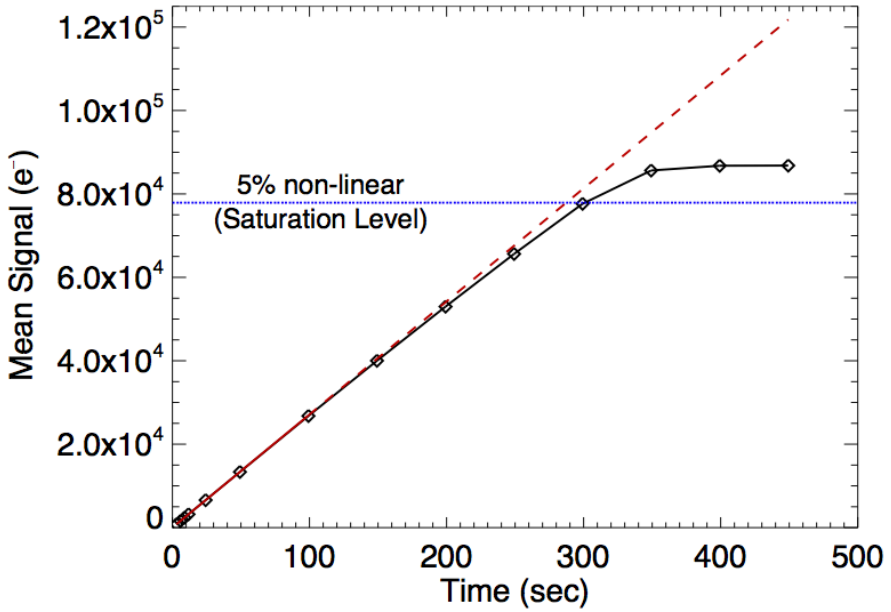
Basic terms/concepts:

"non-linearity" = deviation from a one-to-one correspondence of incident photons and generated photoelectrons

CCDs very linear up to near the saturation level (at least 50k DN)

IR detectors are strongly non-linear.

Non-linearity can (must) be calibrated, but there is a point where the corrections break down. Typically this is well below saturation.



HST/WFC3 instrument manual for IR channel

Outline:

- Preliminaries
- Basic data reduction framework
- Questions

Outline:

- Preliminaries
- Basic data reduction framework
- Questions

Basic data reduction framework

Goal: Measure stellar flux as a function of time (and wavelength)

Limitations:

- Noise inherent in the data =

shot noise (star + background) + read noise + uncertainty in the processing

- Time and/or wavelength varying systematics =

instrumental + Earth's atmosphere + stellar variability

Task: Extract maximum possible information from the data and minimize systematics

Basic data reduction framework

Typical steps (not a recipe):

- Remove detector systematics
- Extract flux and separate star from background
- Record diagnostics of data acquisition and reduction
- Calibrate data
- Remove light curve systematics

Estimate and propagate uncertainties at every step!

Basic data reduction framework

Remove detector systematics

Possible steps:

- Remove bias/pedestal
- Remove dark current
- Collapse data cubes
- Apply flat field correction
- Apply non-linear corrections

Basic data reduction framework

Remove detector systematics

Possible steps:

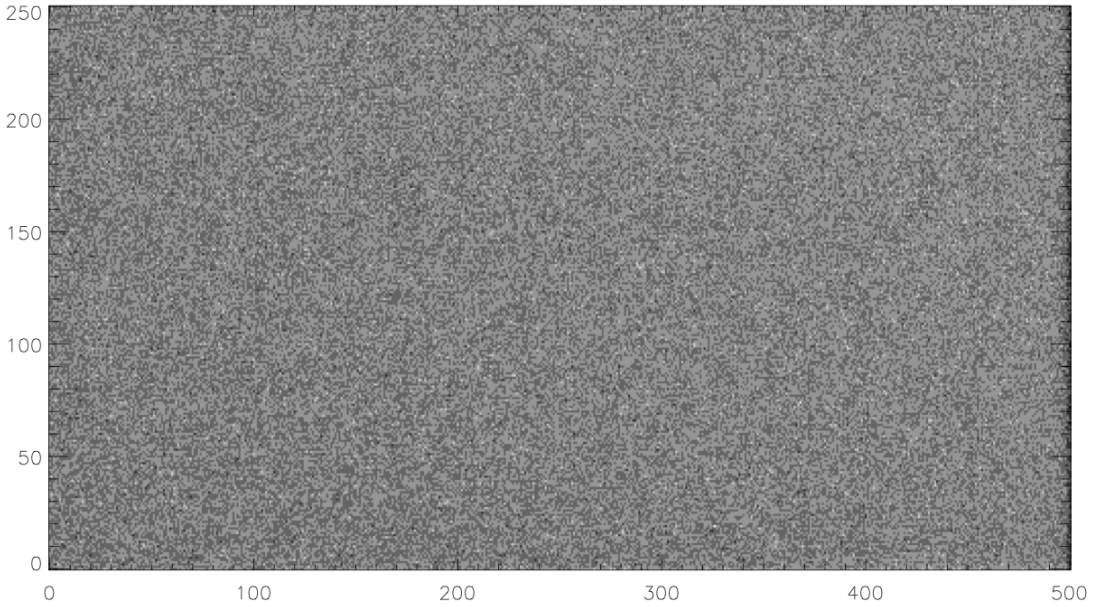
- Remove bias/pedestal → subtract bias frame
- Remove dark current
- Collapse data cubes
- Apply flat field correction
- Apply non-linear corrections

Basic data reduction framework

Remove detector systematics

Example CCD bias frame (Gemini + GMOS)

min to max is 5 DN



Basic data reduction framework

Remove detector systematics

Possible steps:

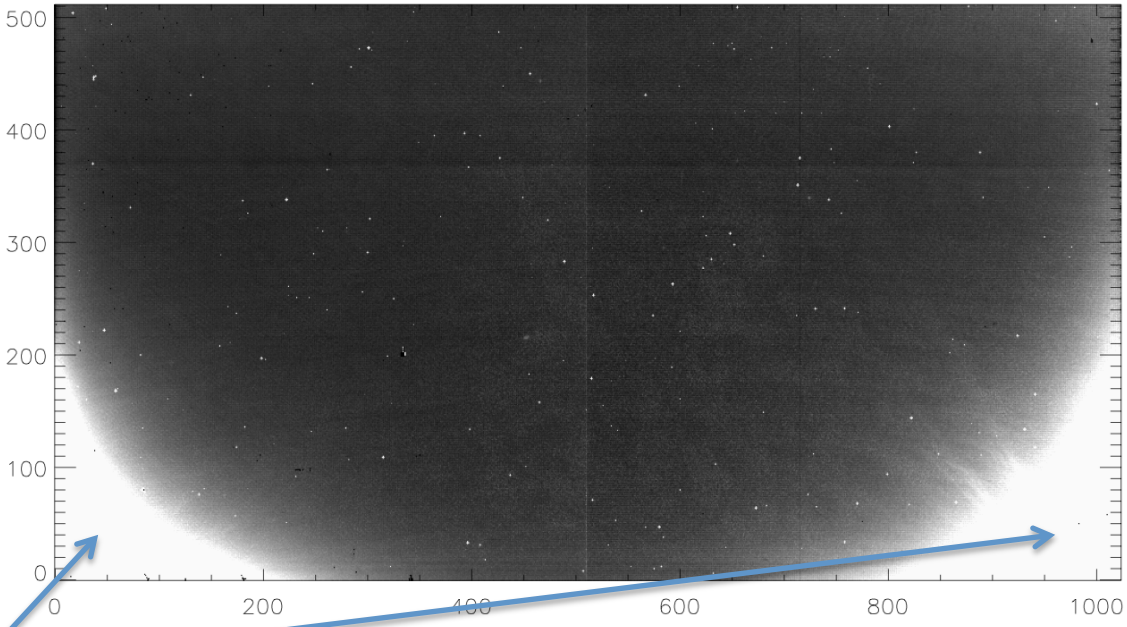
- Remove bias/pedestal → subtract bias frame
- Remove dark current → subtract dark frame
- Collapse data cubes
- Apply flat field correction
- Apply non-linear corrections

Basic data reduction framework

Remove detector systematics

Example 300s InSb dark frame (VLT + CRIRES)

Scale is 0 – 50 DN



amplifier glow

Basic data reduction framework

Remove detector systematics

Possible steps:

- Remove bias/pedestal → subtract bias frame
- Remove dark current → subtract dark frame
- Collapse data cubes → only for IR detectors
- Apply flat field correction
- Apply non-linear corrections

Basic data reduction framework

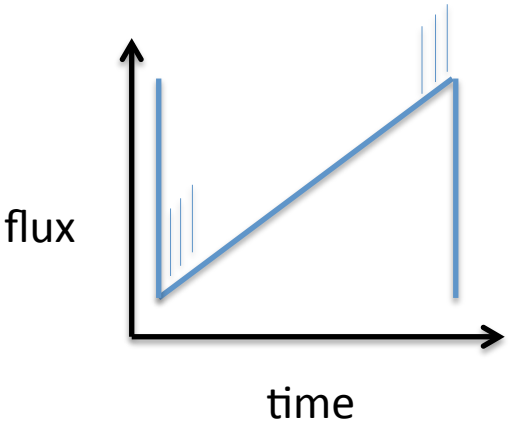
Remove detector systematics

IR detector read modes

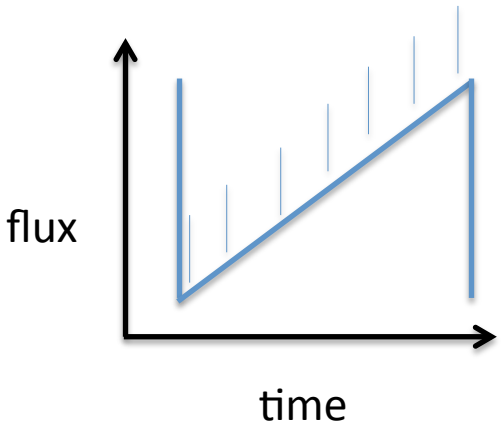
Advantages:

- Both remove variable pedestal
- Both reduce read noise
- Up-the-ramp can allow rejection of cosmic rays and use of saturated pixels

Double-correlated (Fowler) sampling



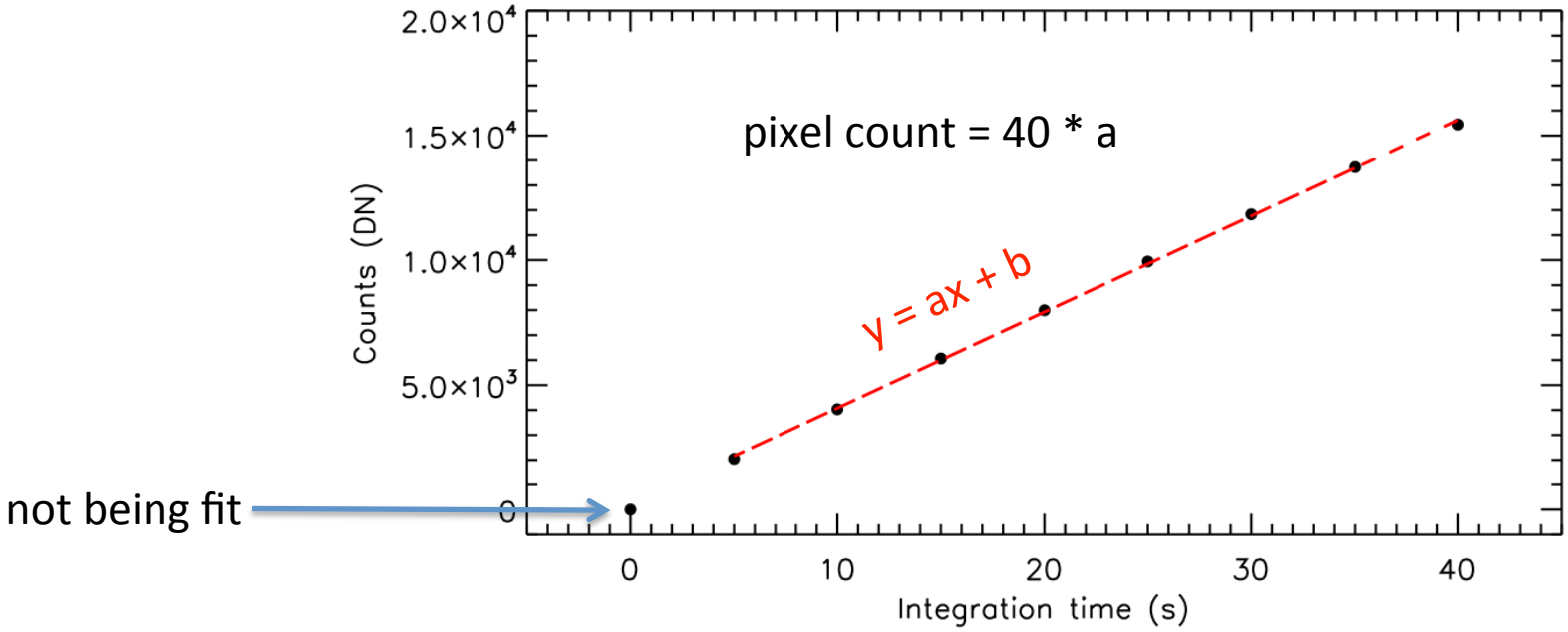
Sample up-the-ramp



Basic data reduction framework

Remove detector systematics

Example up-the-ramp fit (Magellan + MMIRS)



Basic data reduction framework

Remove detector systematics

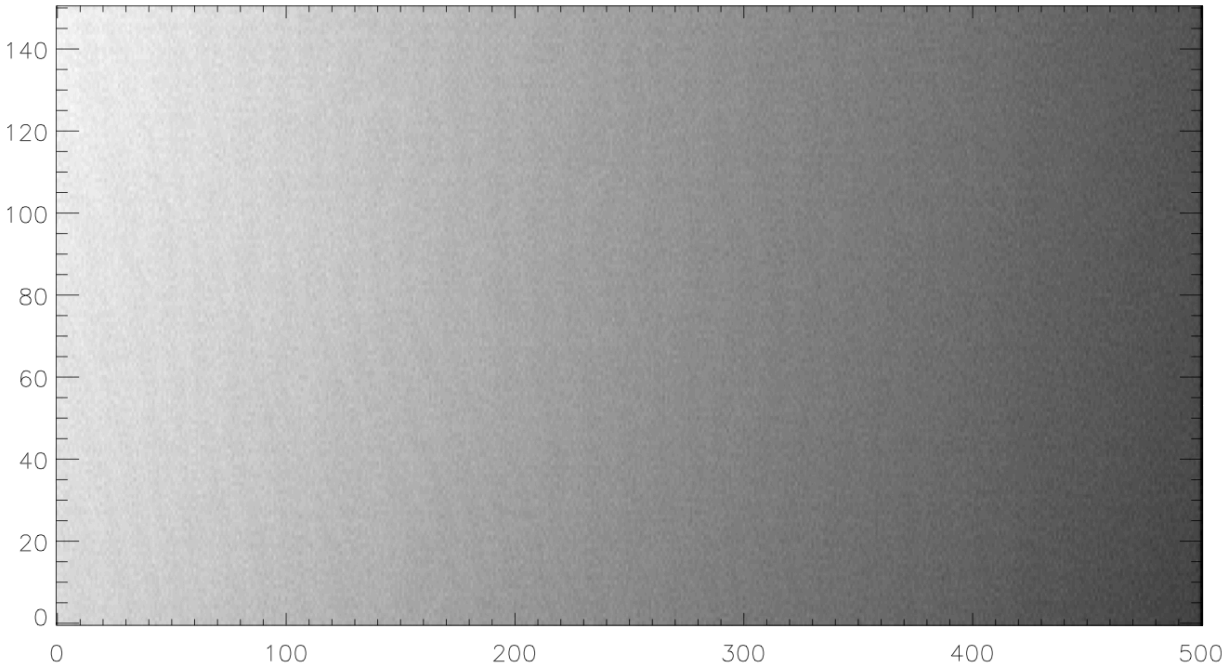
Possible steps:

- Remove bias/pedestal → subtract bias frame
- Remove dark current → subtract dark frame
- Collapse data cubes → only for IR detectors
- Apply flat field correction → divide by flat field frame
- Apply non-linear corrections

Basic data reduction framework

Remove detector systematics

Example CCD spectroscopic flat (Gemini + GMOS)

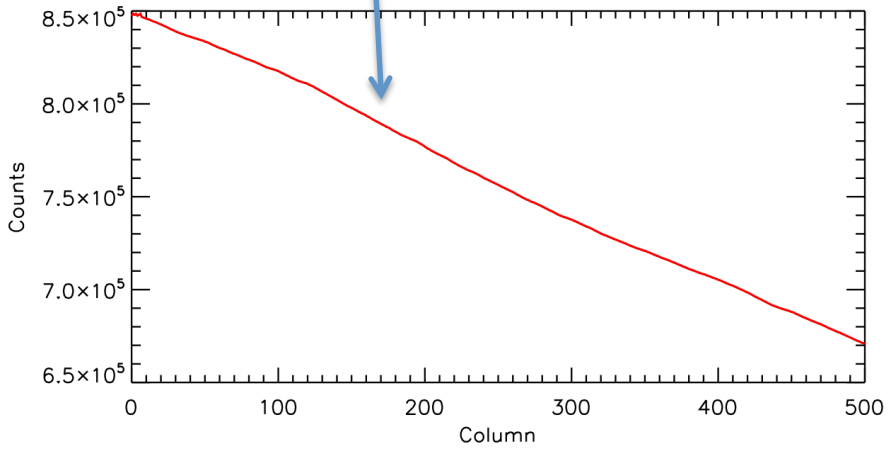


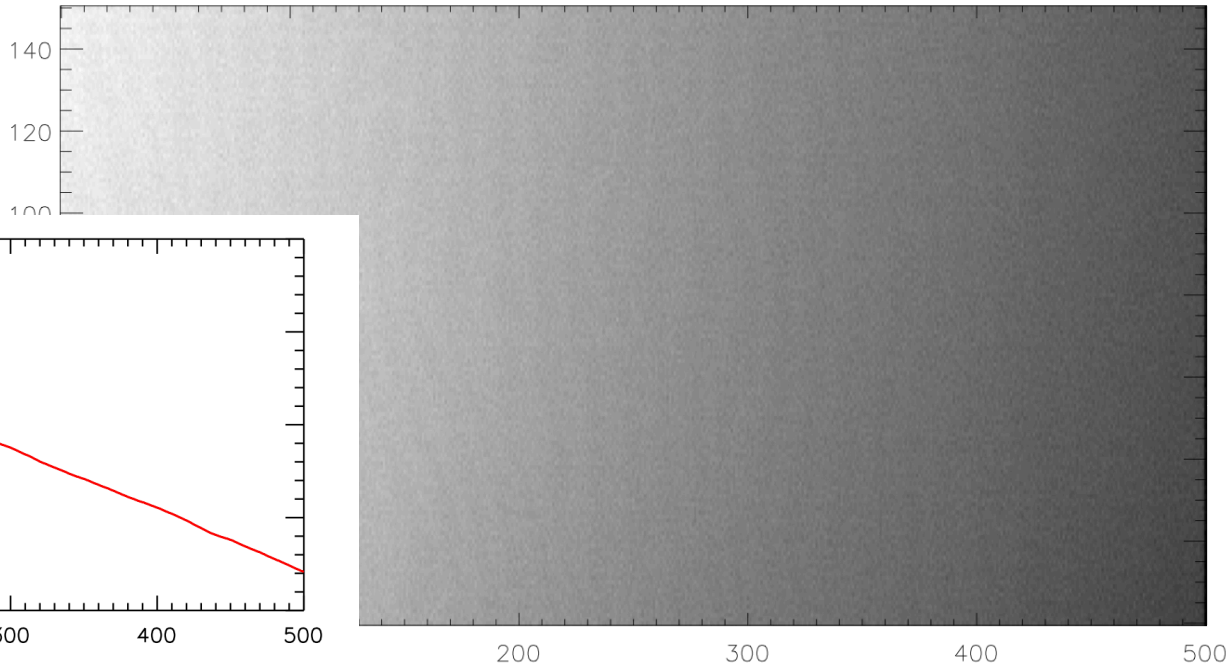
Basic data reduction framework

Remove detector systematics

Example CCD spectroscopic flat (Gemini + GMOS)

Need to divide by spectroscopic function





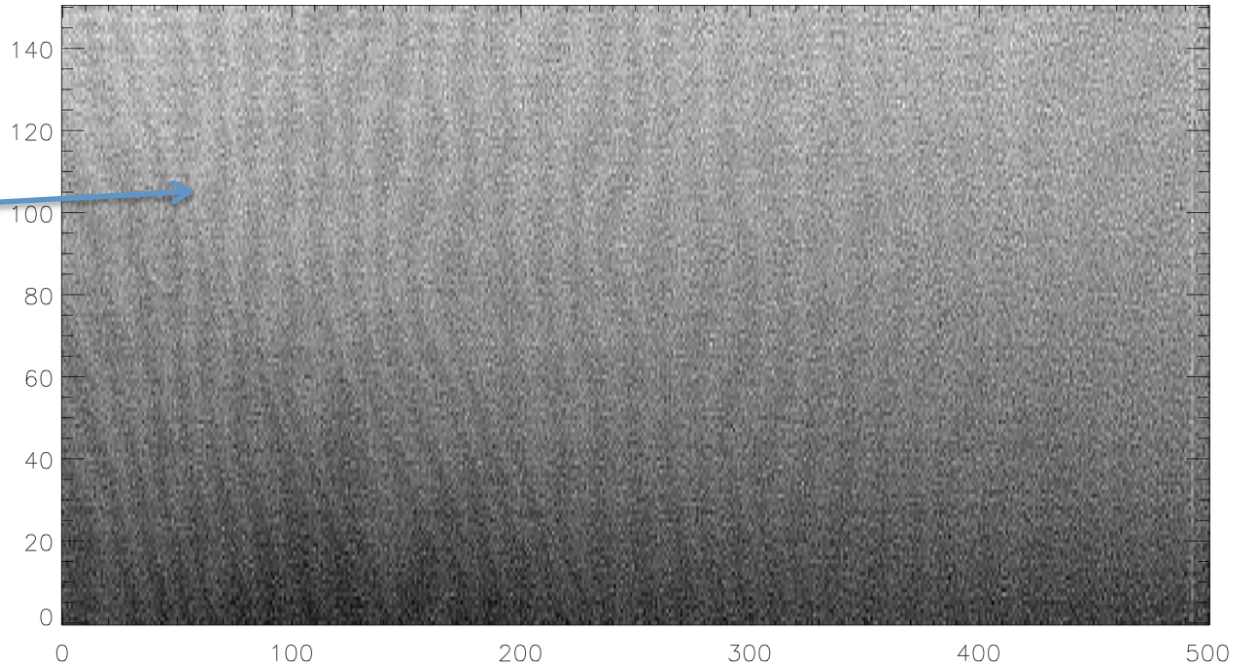
Basic data reduction framework

Remove detector systematics

Example CCD spectroscopic flat (Gemini + GMOS)

Fringing from internal reflections inside detector at wavelengths approaching silicon bandgap

variations are ± 5%



Basic data reduction framework

Remove detector systematics

Possible steps:

- Remove bias/pedestal → subtract bias frame
- Remove dark current → subtract dark frame
- Collapse data cubes → only for IR detectors
- Apply flat field correction → divide by flat field frame
- Apply non-linear corrections → based on calibration data

Basic data reduction framework

Typical steps (not a recipe):

- Remove detector systematics ✔
- Extract flux and separate star from background
- Record diagnostics of data acquisition and reduction
- Calibrate data
- Remove light curve systematics

Estimate and propagate uncertainties at every step!

Basic data reduction framework

Extract flux and separate star from background

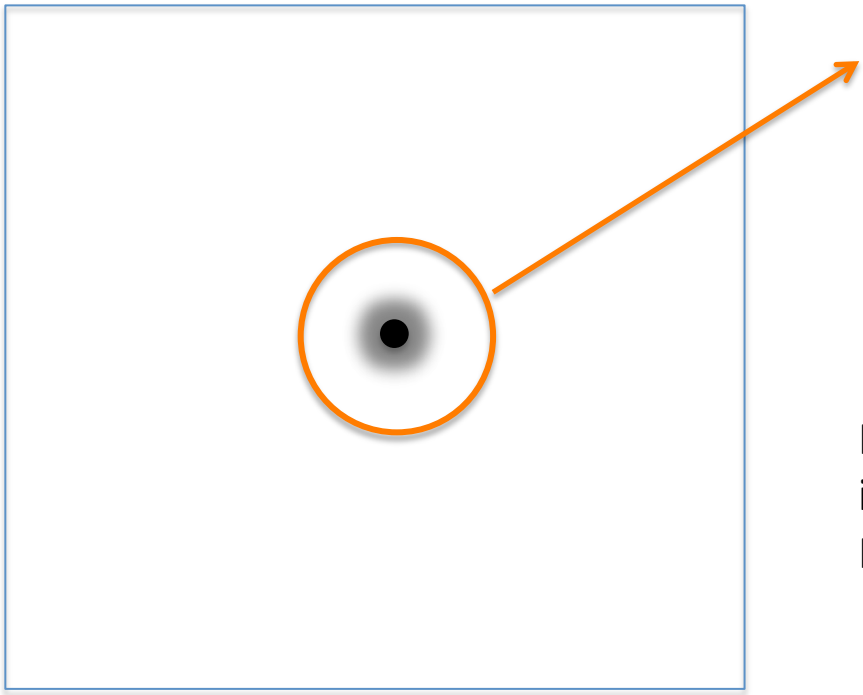
- Imaging = aperture photometry

Many standard routines for this in IRAF, IDL, and probably Python, etc too.

Basic data reduction framework

Extract flux and separate star from background

- Imaging = aperture photometry

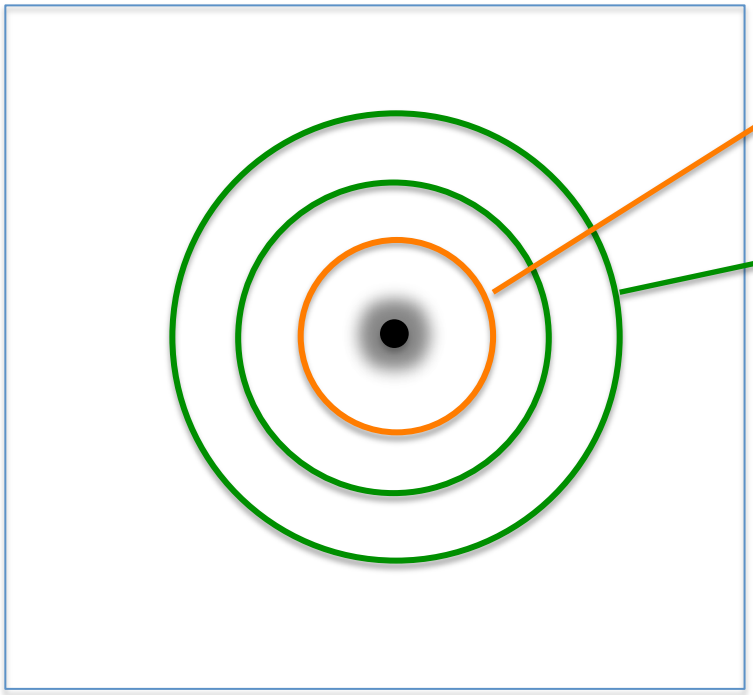


Many standard routines for this in IRAF, IDL, and probably Python, etc too.

Basic data reduction framework

Extract flux and separate star from background

- Imaging = aperture photometry



star flux aperture, sum total flux

–

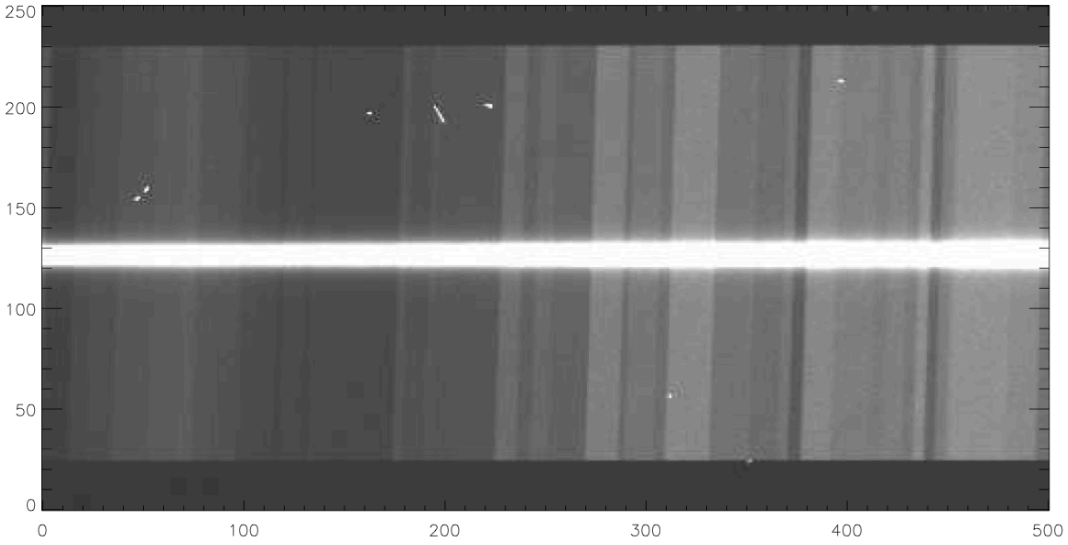
background annulus,
background per unit area

Many standard routines for this in IRAF, IDL, and probably Python, etc too.

Basic data reduction framework

Extract flux and separate star from background

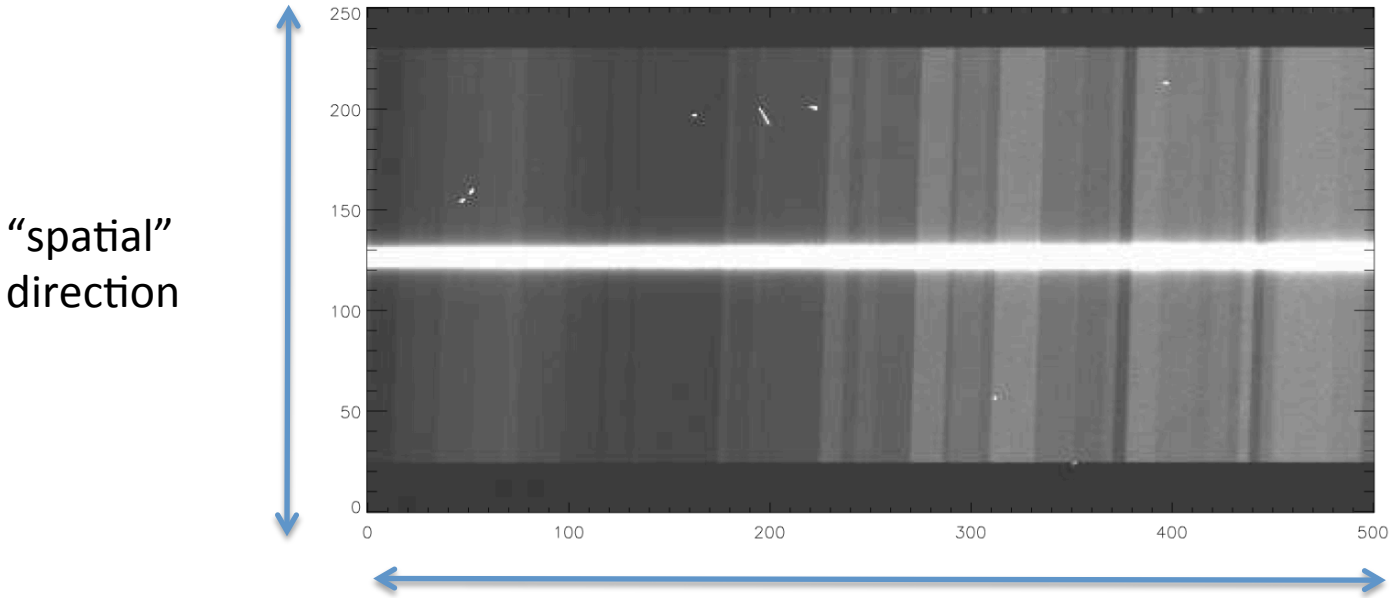
- Imaging = aperture photometry
- Spectroscopy = spectrum extraction



Basic data reduction framework

Extract flux and separate star from background

- Imaging = aperture photometry
- Spectroscopy = spectrum extraction

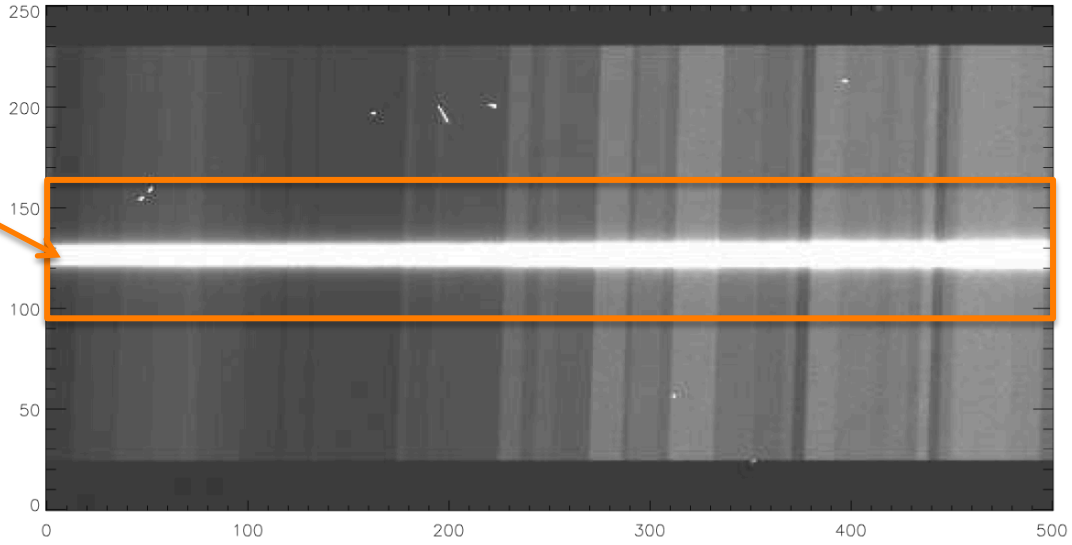


Basic data reduction framework

Extract flux and separate star from background

- Imaging = aperture photometry
- Spectroscopy = spectrum extraction

Stellar spectrum



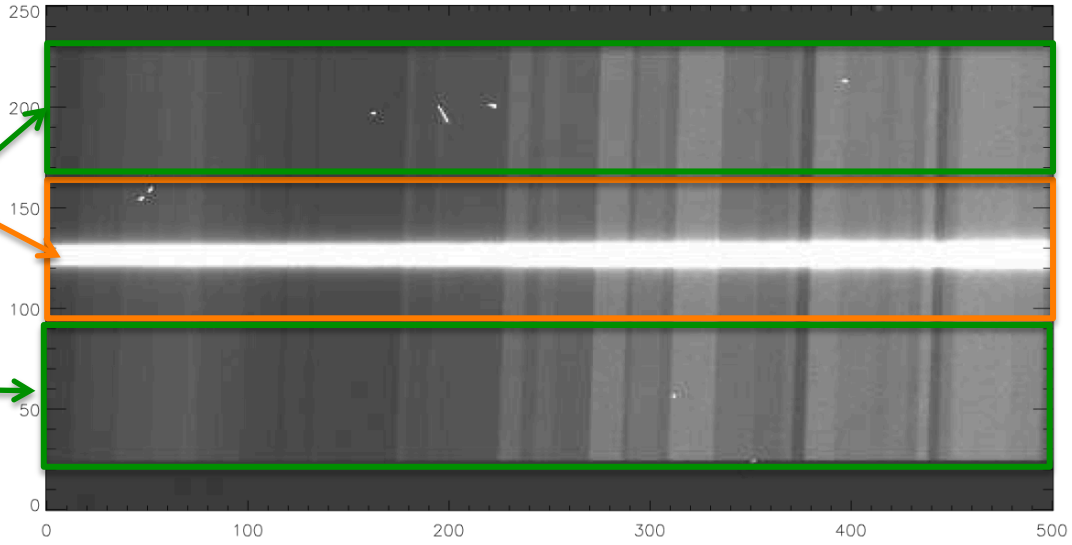
Basic data reduction framework

Extract flux and separate star from background

- Imaging = aperture photometry
- Spectroscopy = spectrum extraction

Stellar spectrum

Background (continuum + line)

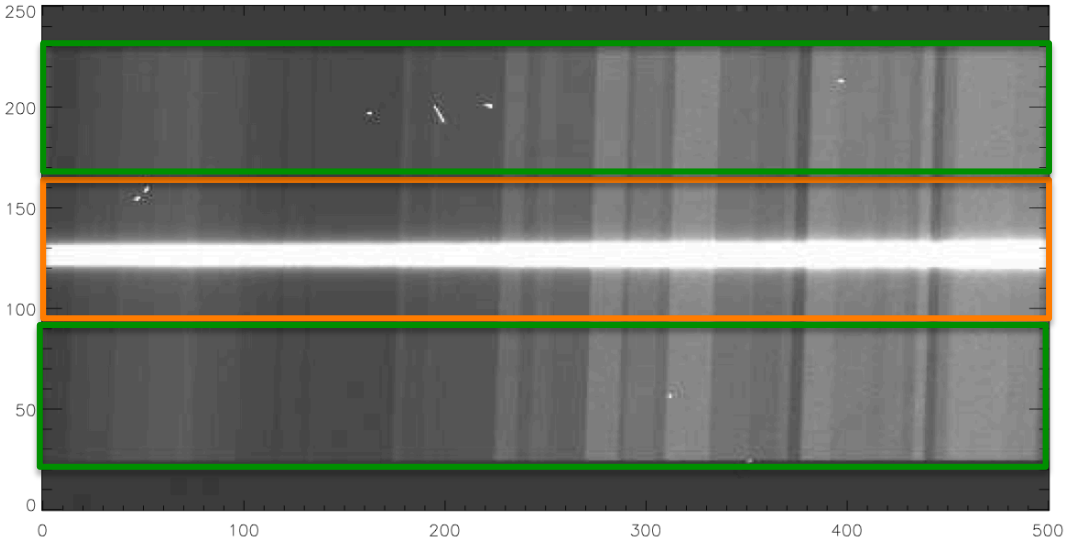


Basic data reduction framework

Extract flux and separate star from background

- Imaging = aperture photometry
- Spectroscopy = spectrum extraction

Step 1:
Estimate background as a function of wavelength (note slit tilt/curvature)



Basic data reduction framework

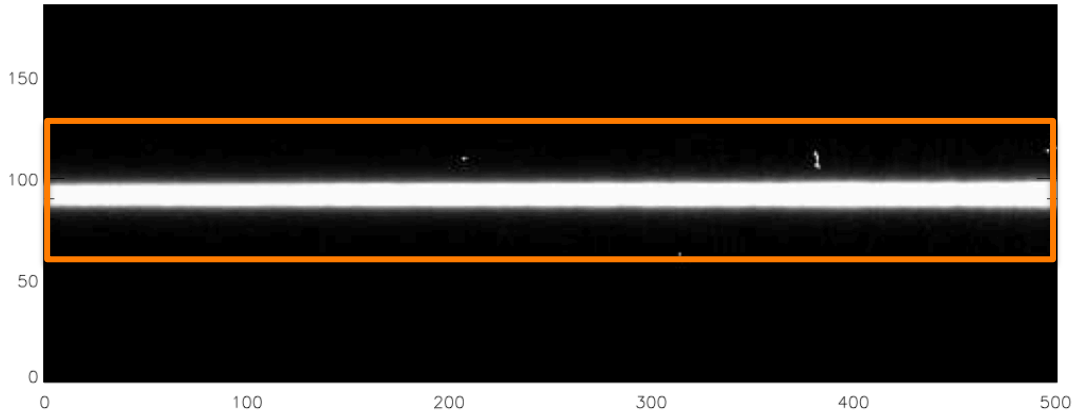
Extract flux and separate star from background

- Imaging = aperture photometry
- Spectroscopy = spectrum extraction

Step 2:
Extract spectrum

Two options:

- "box" extraction = sum up the pixels
- "optimal" extraction (Horne 1986)

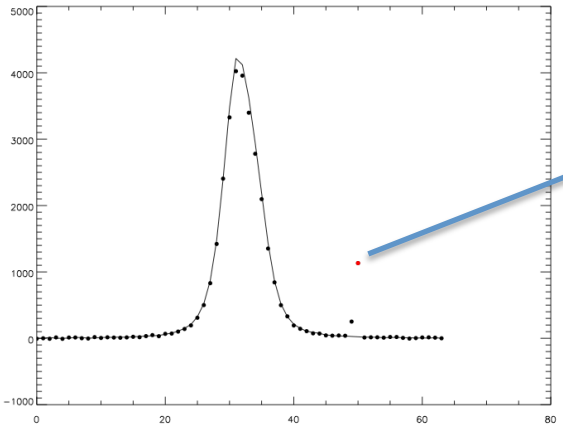


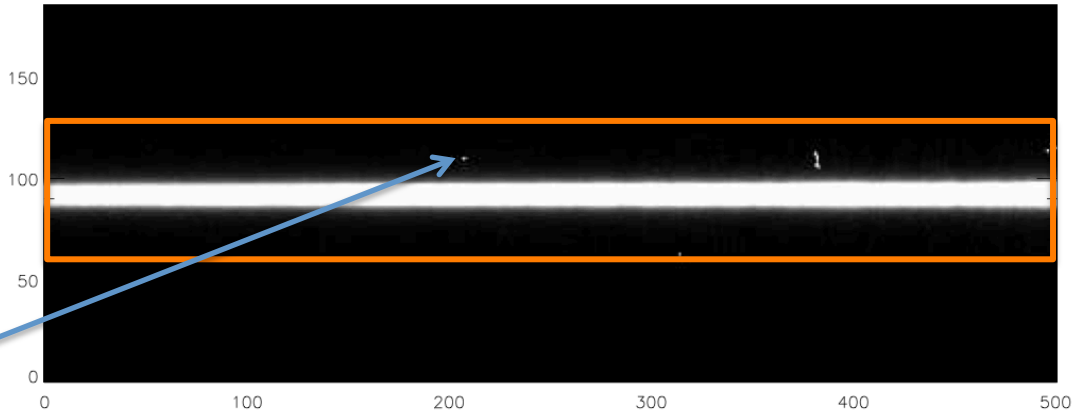
Basic data reduction framework

Extract flux and separate star from background

- Imaging = aperture photometry
- Spectroscopy = spectrum extraction

Optimal extraction:
Use estimate of spatial profile to identify and mask cosmic rays, and to weight the extraction.





Some freely available routines, but none that are particularly good.

Basic data reduction framework

Typical steps (not a recipe):

- Remove detector systematics ✔
- Extract flux and separate star from background ✔
- Record diagnostics of data acquisition and reduction
- Calibrate data
- Remove light curve systematics

Estimate and propagate uncertainties at every step!

Basic data reduction framework

Record diagnostics of data acquisition and reduction

- Atmospheric conditions:

  airmass, water vapor, etc.

- Instrument state:

  detector temperature, orbital phase, focus and filter wheel position, rotator angle, etc.

- Position and width of image/spectrum

- Background flux

Basic data reduction framework

Typical steps (not a recipe):

- Remove detector systematics ✔
- Extract flux and separate star from background ✔
- Record diagnostics of data acquisition and reduction ✔
- Calibrate data
- Remove light curve systematics

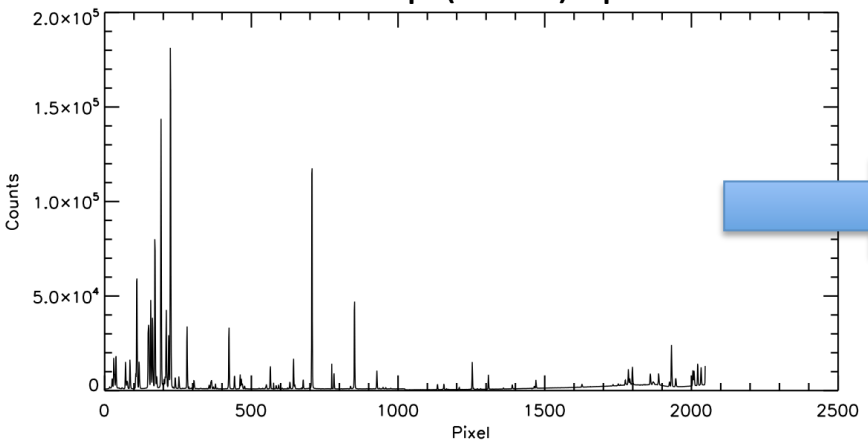
Estimate and propagate uncertainties at every step!

Basic data reduction framework

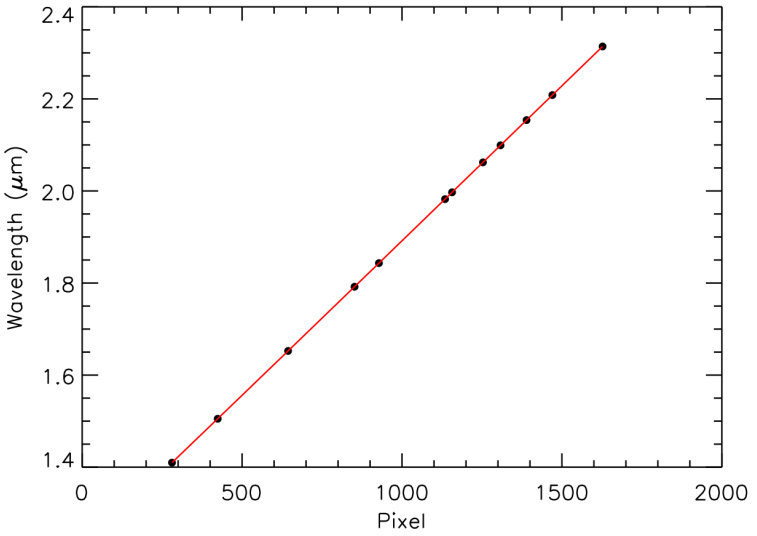
Calibrate data

Spectroscopy: wavelength calibration

Emission lamp (“arc”) spectrum



“wavelength solution”



Basic data reduction framework

Typical steps (not a recipe):

- Remove detector systematics ✔
- Extract flux and separate star from background ✔
- Record diagnostics of data acquisition and reduction ✔
- Calibrate data ✔
- Remove light curve systematics

Estimate and propagate uncertainties at every step!

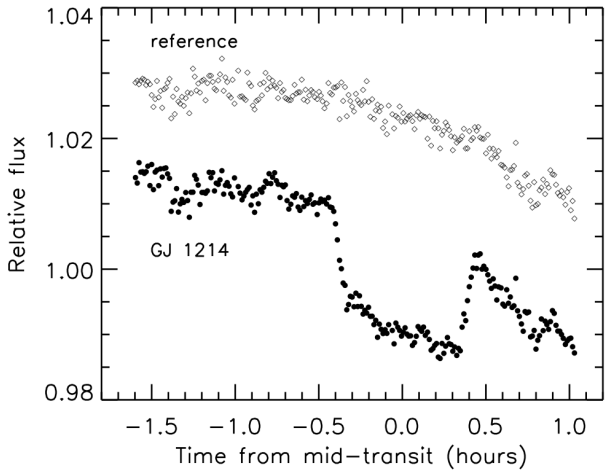
Basic data reduction framework

Remove light curve systematics

(simultaneous with light curve fitting!)

Division by reference flux and/or decorrelation function

ground-based near-infrared

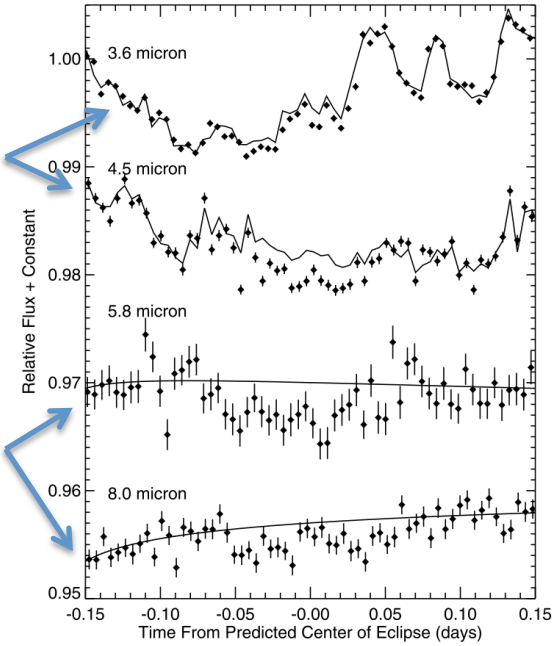


Bean et al. 2011

Spitzer infrared

Image position decorrelation

Decorrelation against time



Knutson et al. 2008

Basic data reduction framework

Typical steps (not a recipe):

- Remove detector systematics ✔
- Extract flux and separate star from background ✔
- Record diagnostics of data acquisition and reduction ✔
- Calibrate data ✔
- Remove light curve systematics ✔

Estimate and propagate uncertainties at every step!

Outline:

- Preliminaries
- Basic data reduction framework
- Questions

Outline:

- Preliminaries
- Basic data reduction framework
- Questions