Observing Supernovae in the Infrared

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Overview

- Infrared challenges; general strategies
- IR imaging
  - Observations
  - Data processing
  - Calibrating & interpreting IR photometry of SNe
- IR spectroscopy
  - Observations
  - Data processing
  - Exotica

Some Plusses

- Better Seeing (at least in NIR)
- Less reddening
  - ~1/λ... in magnitudes!
- Less differential refraction
- Less atmospheric scattering
  - Bright time, dark time, twilight... (daylight?)
- New science

Poor Conditions

- High background
  - OH line emission
  - Thermal emission
- Variable transparency
  - H_2O, O_2, CO_2
- Rapidly varying conditions

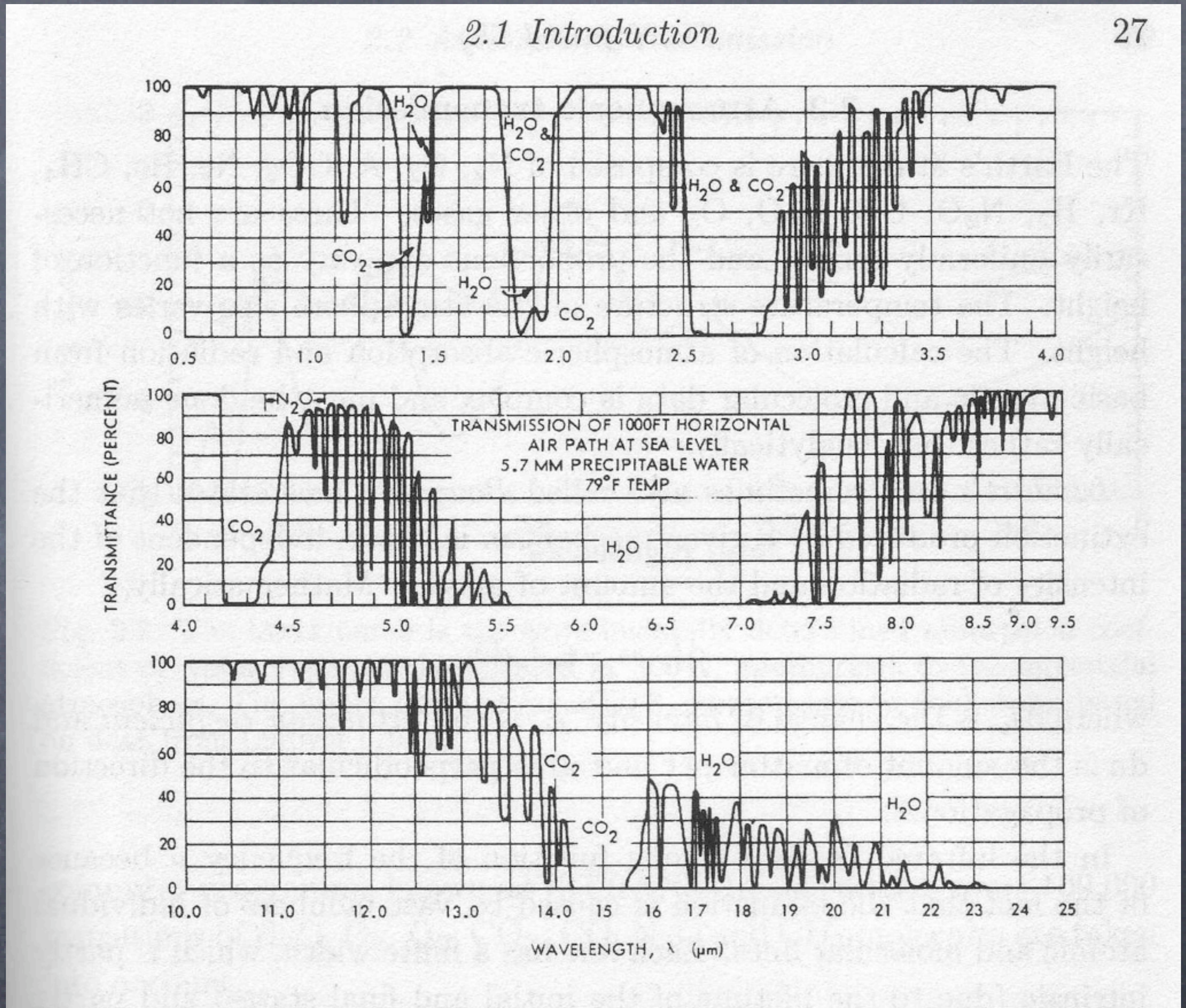
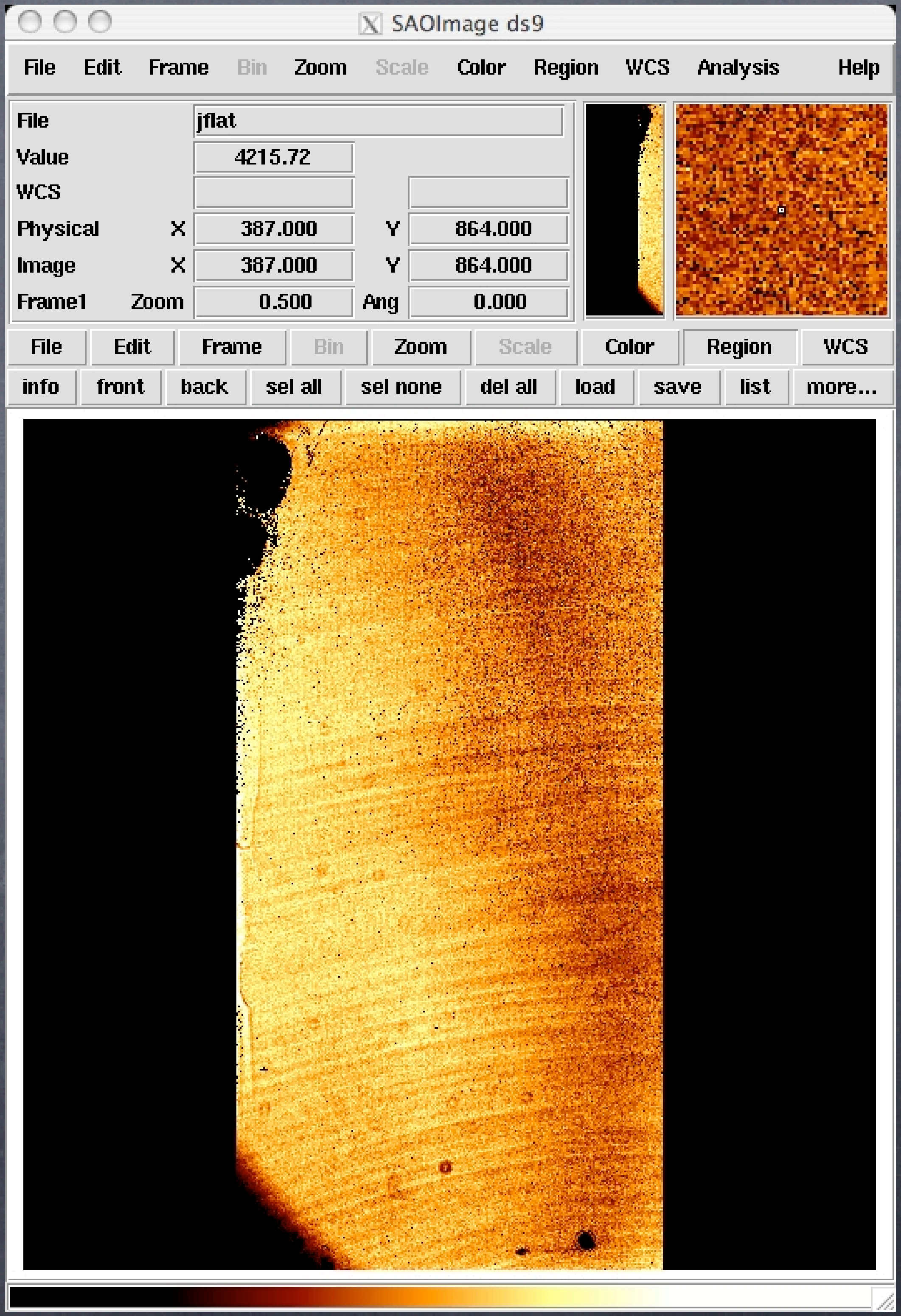


Fig. 2.1. Transmittance of 1000 feet horizontal air path at sea level containing 5.7 mm of precipitable water at 79 F (26 C). The omitted interval from 9.5–10 μm has transmittance = 100%. (Image is courtesy of Raytheon Infrared Center of Excellence, formerly SBRC.)

From Handbook of Infrared Astronomy, I.S. Glass

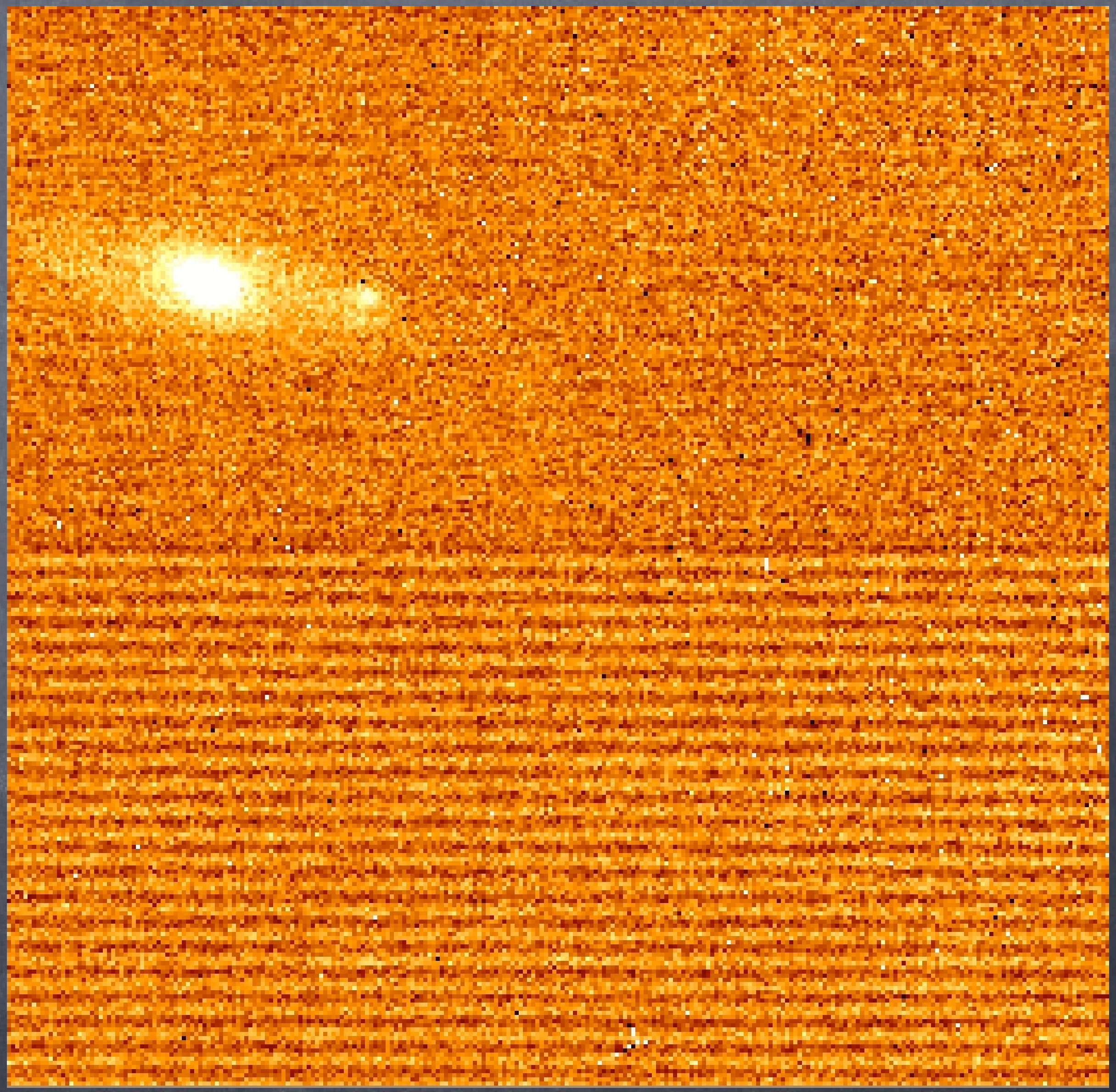
Quirky Detectors

- Small arrays
- Shallow wells
  - NIR detectors typically linear to about 10K counts
- Poor cosmetics
  - Lots of bad pixels
  - Ugly flat-field
  - Cracks, blobs, "quadrants", etc...
- Know your instrument!



Quirky Detectors

- Shutterless cameras
  - Double read, typically ~1 sec.
  - Not simultaneous
- Noisy, unstable electronics
  - Bias drift, variable pattern noise
- Residuals, often about 0.5 to 1 %



IR Detectors

- InSb, HgCdTe, etc
- Not charge transfer devices
  - Double read
  - ~1s readout time
- Readnoise ~30e
  - MNDR? particularly for spectroscopy

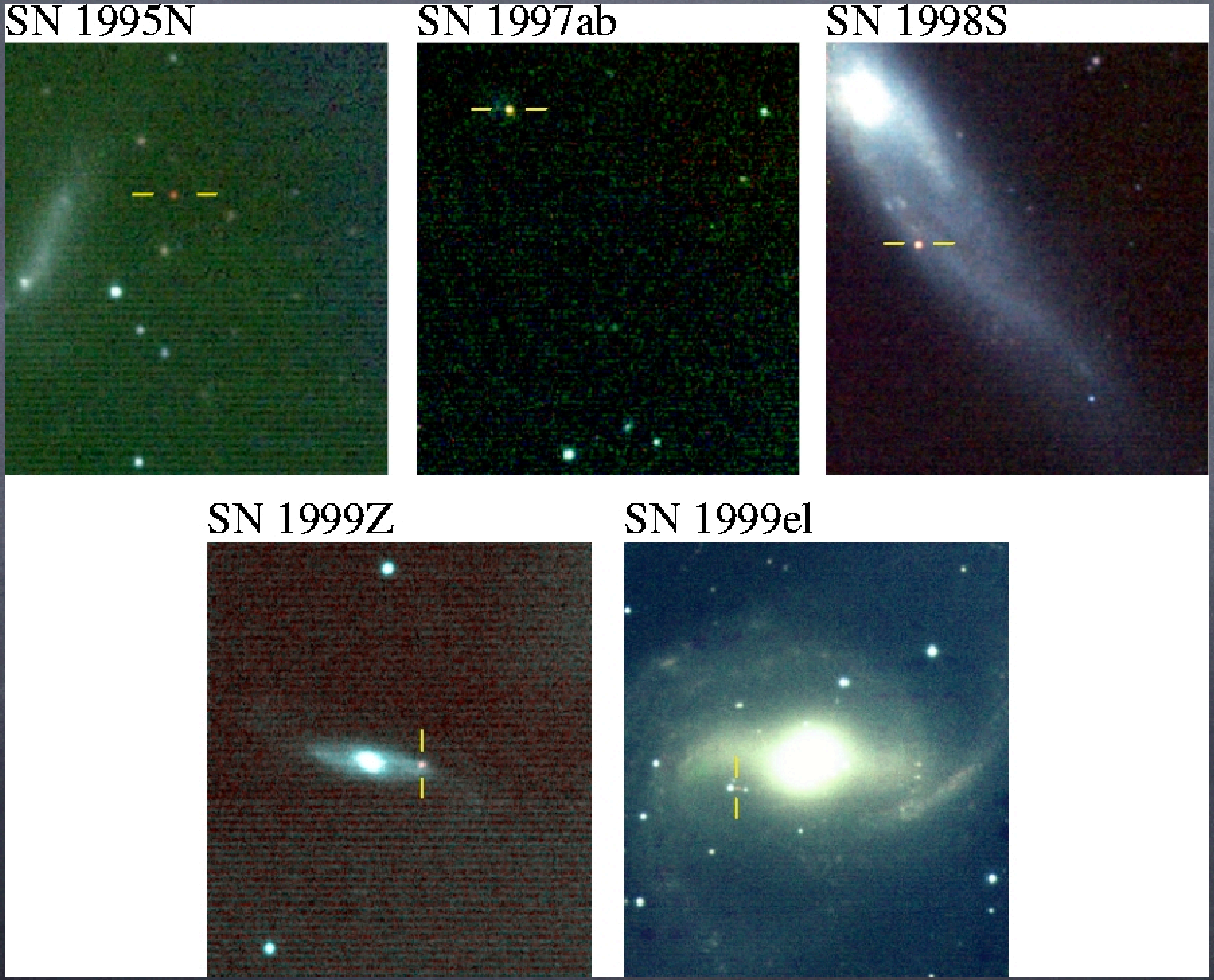
Infrared Strategies

- Cold instruments, thermal masks, blocking filters
- Short Exposures... lots of ‘em
- Dither, Nod, Chop
  - Sky subtraction (also bias, dark, & thermal, and some bad pixels)
  - Sample the detector in different locations
- Visit standards often

Working in the IR

- Large overheads
  - Short exposures, lots of telescope business, lots of calibration data
- Large datasets
  - Get a big disk and learn to program
- Large telescopes
  - Rule of thumb: upgrade by 1 generation of telescope aperture when moving into the NIR
- Trailblazing; bring a machete!
  - May need to build tools & get creative

Infrared Imaging



What's in an image?

Astrophysical Flux   Sky Flux   Filter   Inst. Resp   Exp. Time   "flatfield"

$$N_{tot} = \left(\int_0^\infty \{f_{ast}(\lambda) + f_{sky}(\lambda) + f_{th}(\lambda)\}\phi(\lambda)\eta(\lambda)\tau(\lambda)d\lambda \right) T\phi_{ff} + N_b + n_d T$$

Thermal Glow   Atm. Trans.   Bias   Dark Current

Why Sky Subtraction?

$$N_{obj} = \left(\int_0^\infty \{f_{ast}(\lambda) + f_{sky}(\lambda) + f_{th}(\lambda)\} \phi(\lambda)\eta(\lambda)\tau(\lambda) d\lambda \right) T\phi_{ff}$$

$$+N_b + n_d T$$

-

$$N_{no\_obj} = \left(\int_0^\infty \{f_{sky}(\lambda) + f_{th}(\lambda)\} \phi(\lambda)\eta(\lambda)\tau(\lambda) d\lambda \right) T\phi_{ff}$$

$$+N_b + n_d T$$

=

$$N_{ssub} = \int_0^\infty f_{ast}(\lambda)\phi(\lambda)\eta(\lambda)\tau(\lambda) d\lambda T\psi_{ff}$$

Biases & Darks

- Typically not needed unless using sky frames for FF, or can't make "off" flats
  - 1 set of "daylight" darks and/or bias frames might be useful for building bad-pixel masks
- No overscan: make biases by taking "0" sec exposures with a dark setup
  - Not usually needed if you're taking darks
- Darks should be same length as exposure
- Both Bias level and DC rate can drift during the night.
  - Bracket observations with dark frames

Taking Flats

- On/Off flats
  - Subtraction removes bias, dark & thermal
- Dome flats/ "comp-lamp" flats
  - Illumination?
  - Too bright -> ND filters -> different setup
- Twilight flats
  - Do each filter twice for On/Off
  - Not really possible longward of K-band
- Sky flats
  - No Off: take darks, hard to make a "thermal"

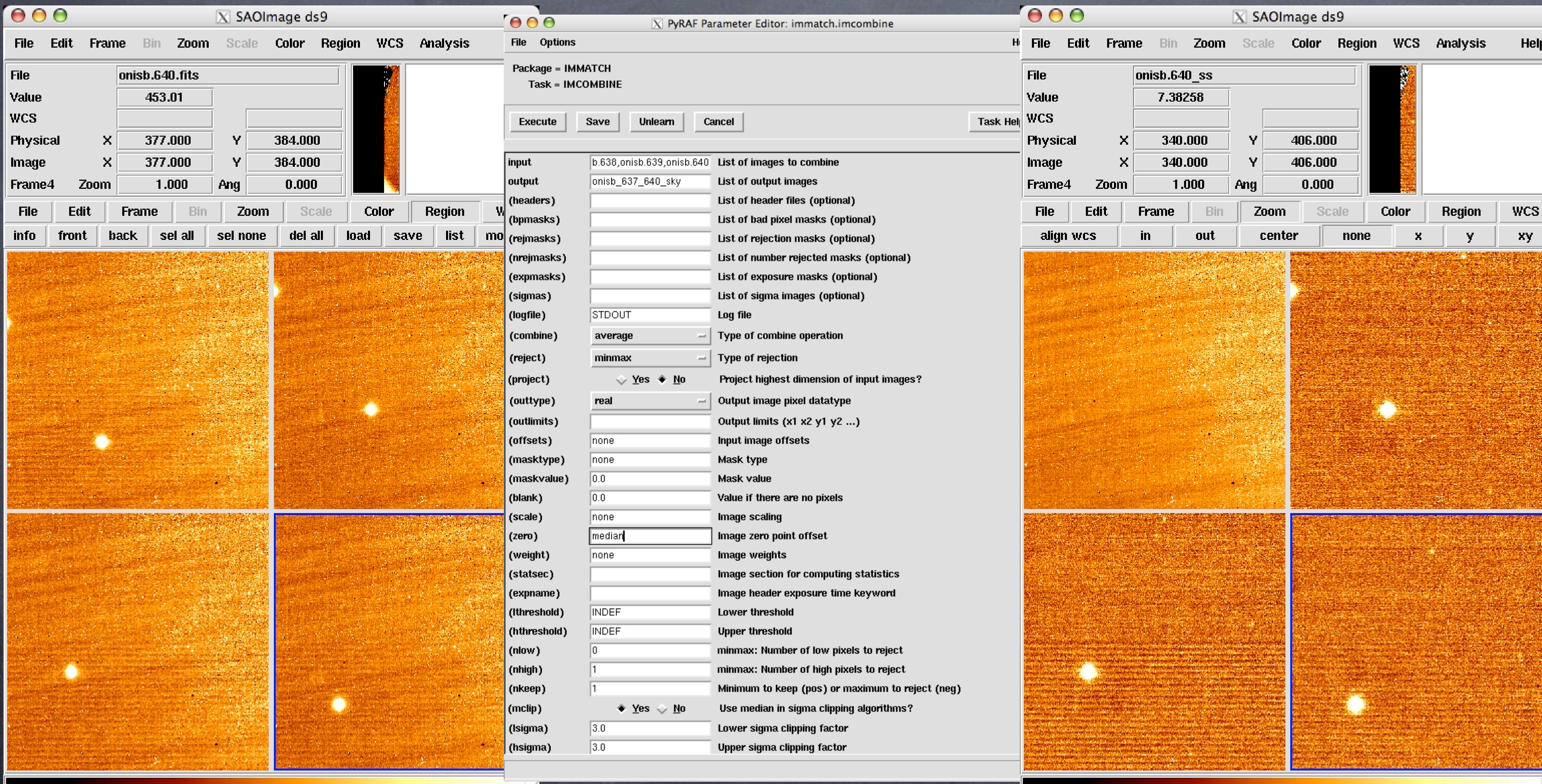
IR Imaging Reduction

- Dome or Twilight flats
  - Build On/Off flats and difference (Illum. Corr.?)
  - FF all images
  - Build Sky frames, subtract
  - Register and stack images
- Sky flats
  - Combine darks & subtract from images
  - Build sky images & combine to make flat
  - FF object & sky frames
  - Sky subtract, register, & stack images

Building Sky Frames

- Combine dithered pointings.
  - For clean Sky-sub, at least 3 pointings
  - Combine images with high-pixel rejection to remove sources (e.g. imcombine.reject=minmax)
    - Matching median image levels may make a cleaner sky (e.g. imcombine.zero=median)
  - Avoid sources overlapping in multiple dither positions as these will leave residuals in the sky frame
  - For crowded fields use more positions, large dither steps, or off-target fields
  - Beware of residuals from bright field stars

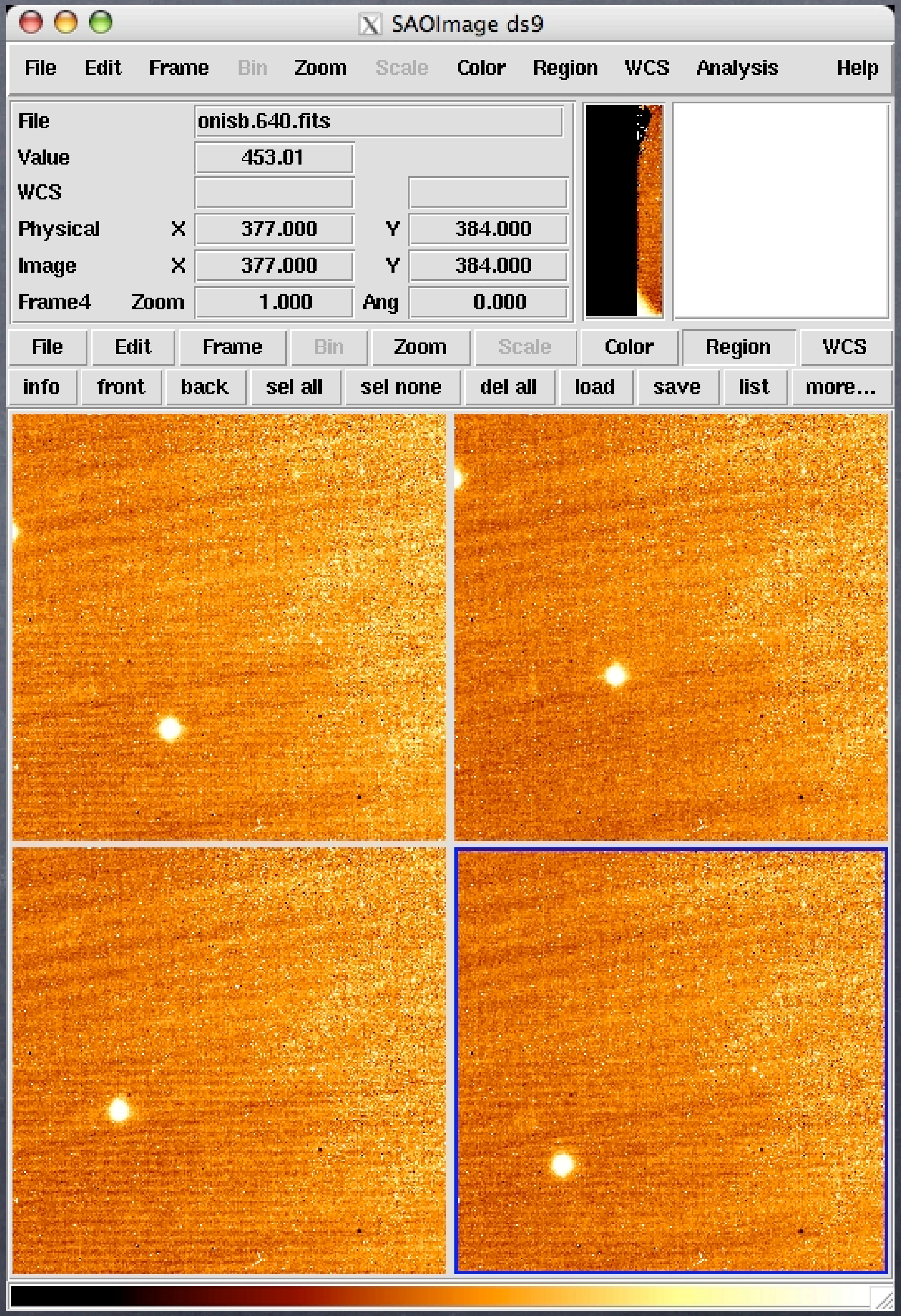
Building Sky Frames



- Beware of residuals from bright field stars

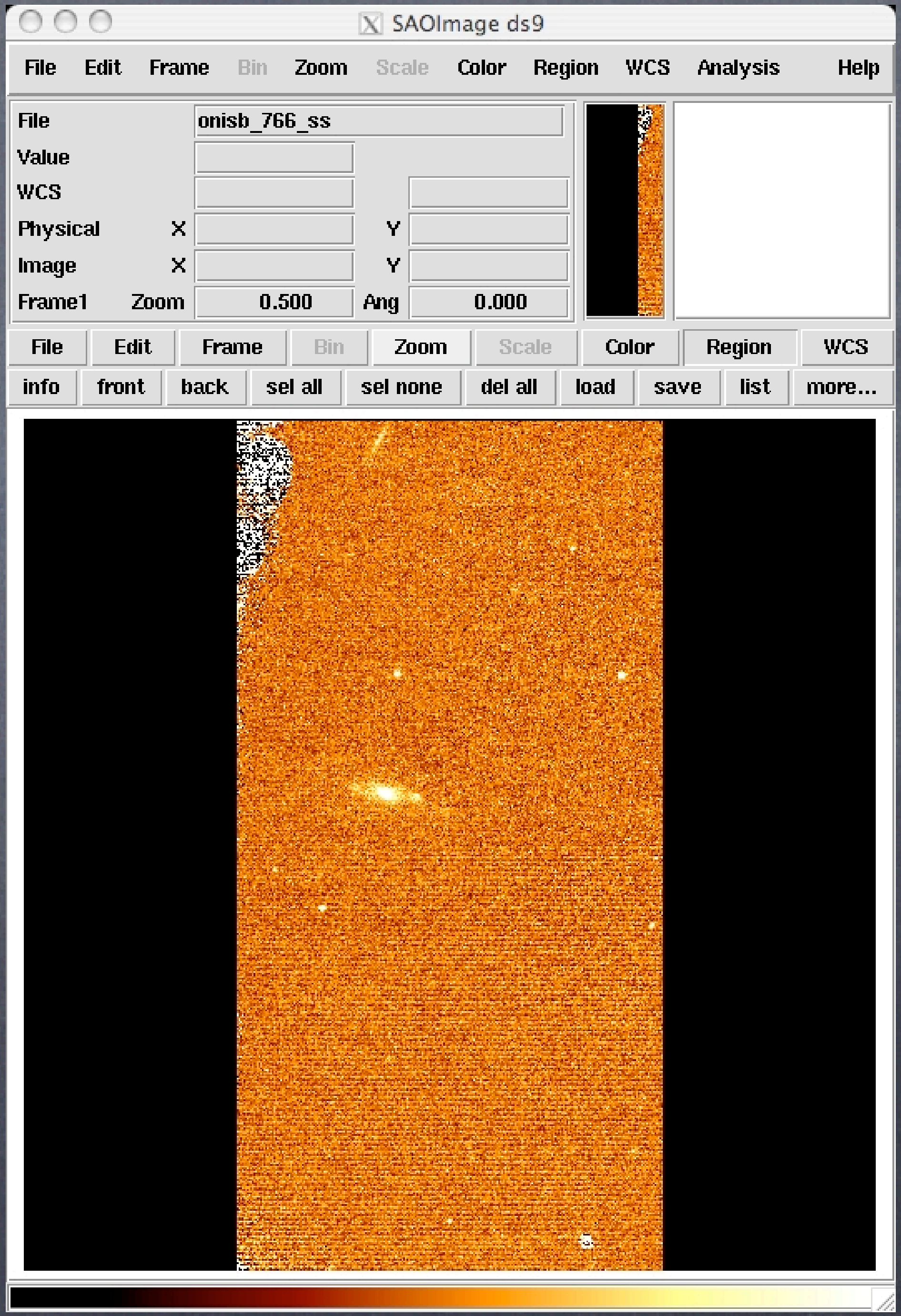
Dithering (small steps)

- For point sources in uncrowded fields (e.g. std. stars)
- Make dither step large enough to avoid PSF overlap
- Sky & Object frames simultaneous
- General note: typically unguided
  - Short exposures: GS re-acq. => large overhead



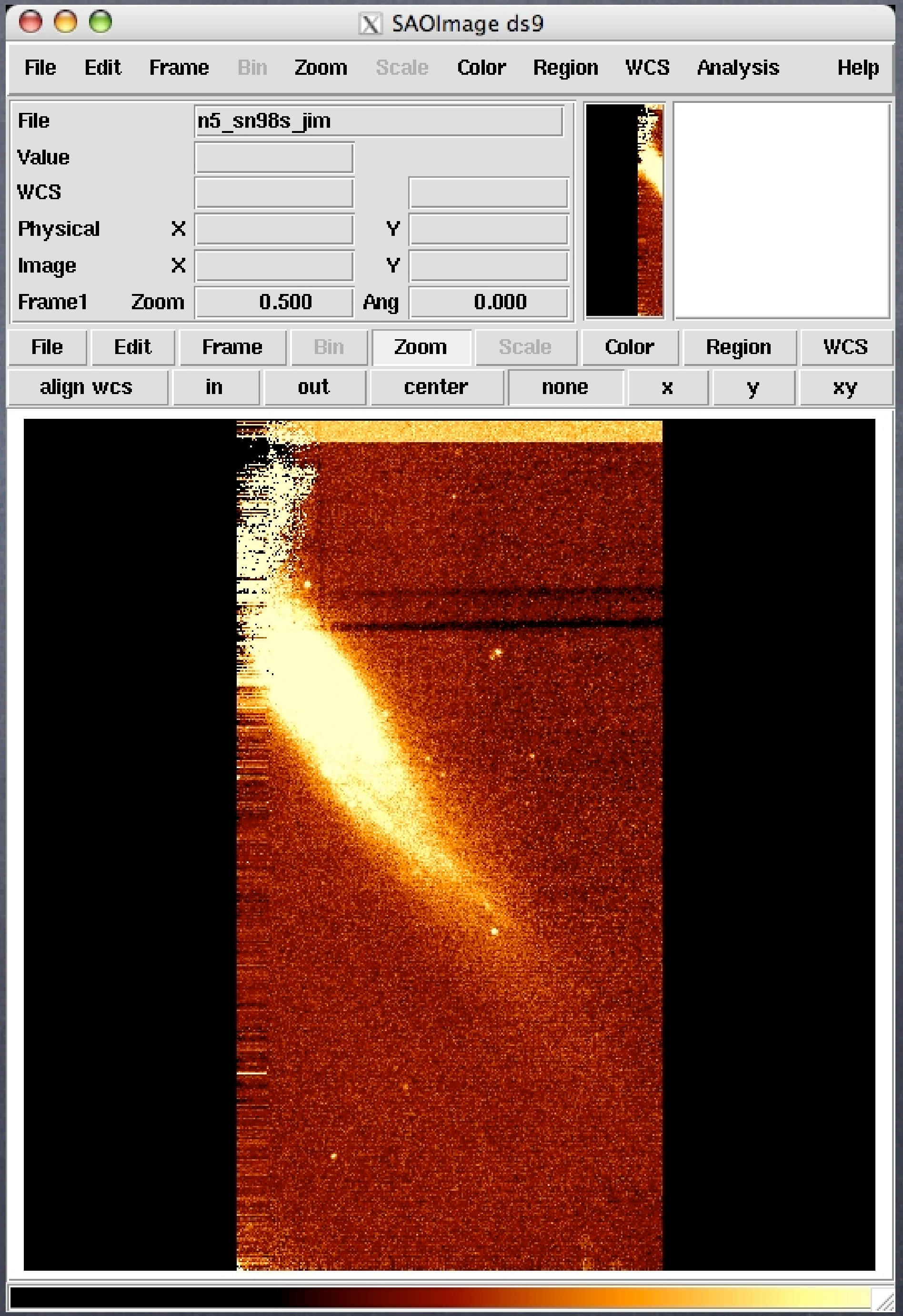
Dithering (large steps)

- For small extended sources and/or large arrays
- Large dither steps (arcmin scale)
- Simultaneous object and sky frames
- Reduces effective FOV
  - Difficult to find local field stds., esp. at high gal. latitude



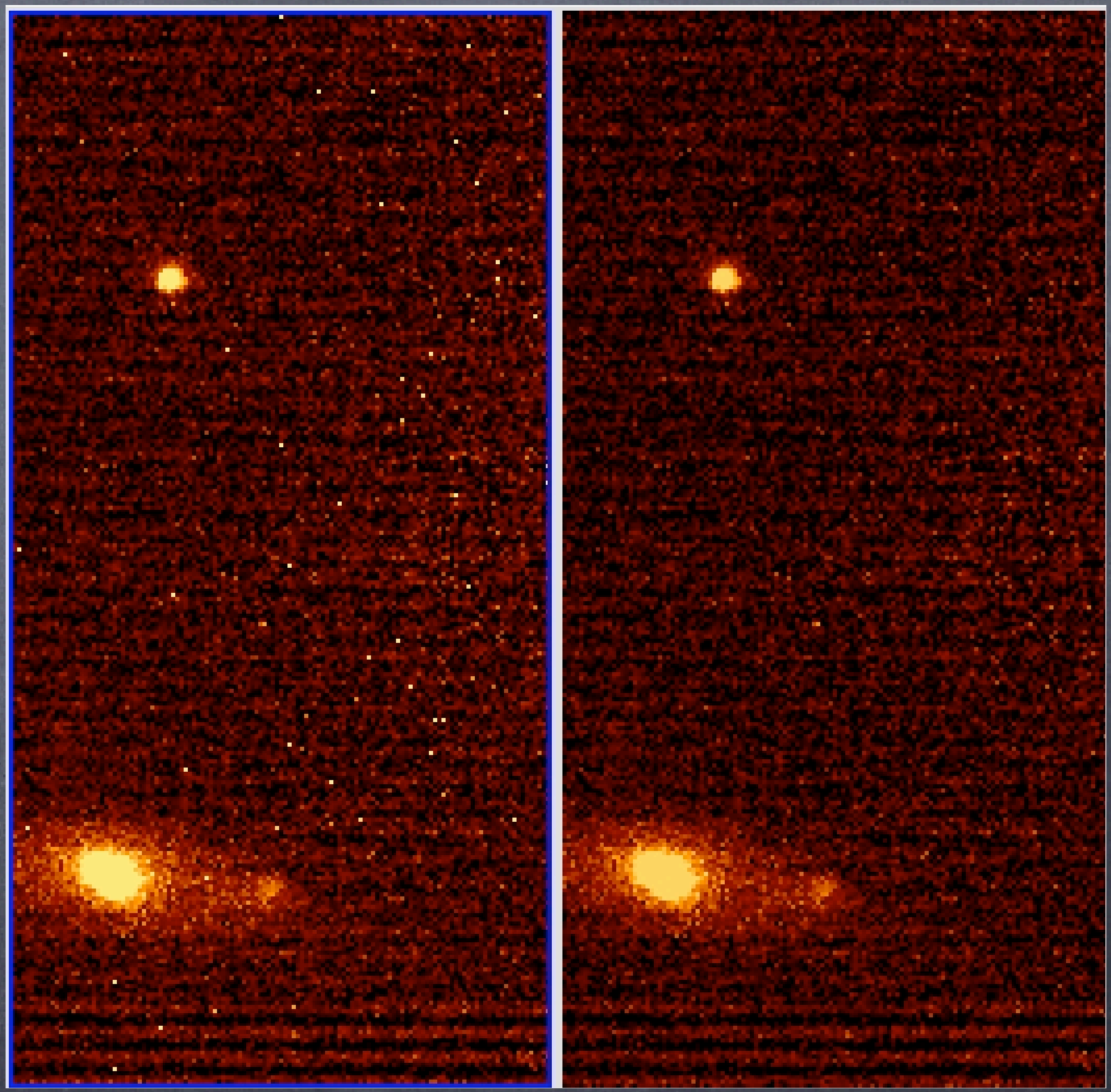
Dithering (Off-target)

- For large extended sources and/or small detectors
- Interleave object exposures with nearby uncrowded sky fields
- Dither target & sky frames (small steps)
- Retains FOV
- Large overhead.
    - BG limited -> sky needs to be as well exposed as target



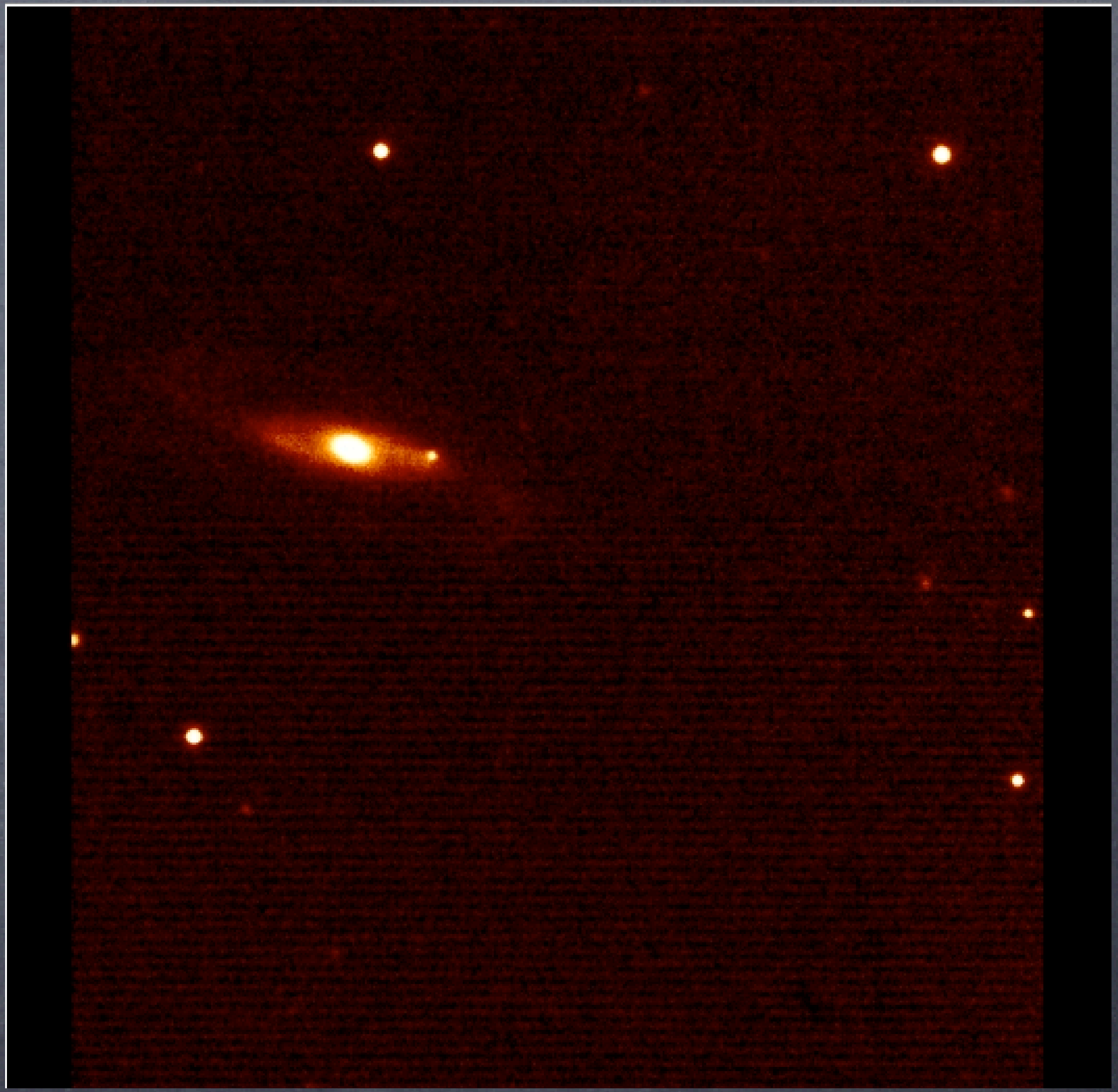
Cleaning the Pixels

- Sky-sub
- Bad-pix mask
  - Look for 'stable' bad pix (in, e.g. dark frames)
  - Mask off large dead-areas
- Cosmic-ray utilities
  - Use after sky-sub
  - Clean "both sides" (clean, invert, clean, invert)



Register & Stack

- After FF, sky-sub, cleaning/masking
- Register, shift & combine
  - Reject bad images?
  - Weighting? (esp. non-photometric)
  - Zero level matching?
- Trim to overlap region?



Registration Methods

- Blind: take offsets as given
  - Easy but not accurate, esp. if unguided
- Point 'n' click, centroid/fit matching
  - Moderate accuracy, prob. good enough for AP
  - May be a problem for PSF fitting
- Cross-correlation
  - Can be tricky & unstable, (sparse fields, structured noise!)
- "Postage Stamp" X-Corr (Use only select portions of field with emission)

IR Photometry

- Generally similar to optical, with a few caveats
- Sensitive to changes in humidity.
  - Observe stds. often.
  - Keep track of humidity
  - In principle, can be included in photometric soln.
- Stay Linear!
  - Shallow wells.
  - Check pre-subtracted images.

IR Photometry

- Beware of short exposures on shutterless cameras
- Fewer field stars, at least at high gal. lat.
  - Must keep both SN and field star on detector for rel. phot.
- Only overlap region in final stack is valid for rel. phot.
- PSF variation in unguided stacks?

IR Standard Stars

- Mauna Kea system (MKO-NIR)
  - Legget et al. 2003
- 2MASS JHKKs
  - Persson et al. 1998
- UKIRT, UKIRT FS, etc... JHK, L′ M′
  - Casali & Hawarden 1992, Hunt 1998
- SAAO
  - Carter & Meadows 1995
- ESO JHKL′M′
  - Bouchet, Manfriod & Schmider 1991
- CTIO/Caltech
  - Elias et al. 1982, 1983

Photometric Solutions

Can vary between different sites!

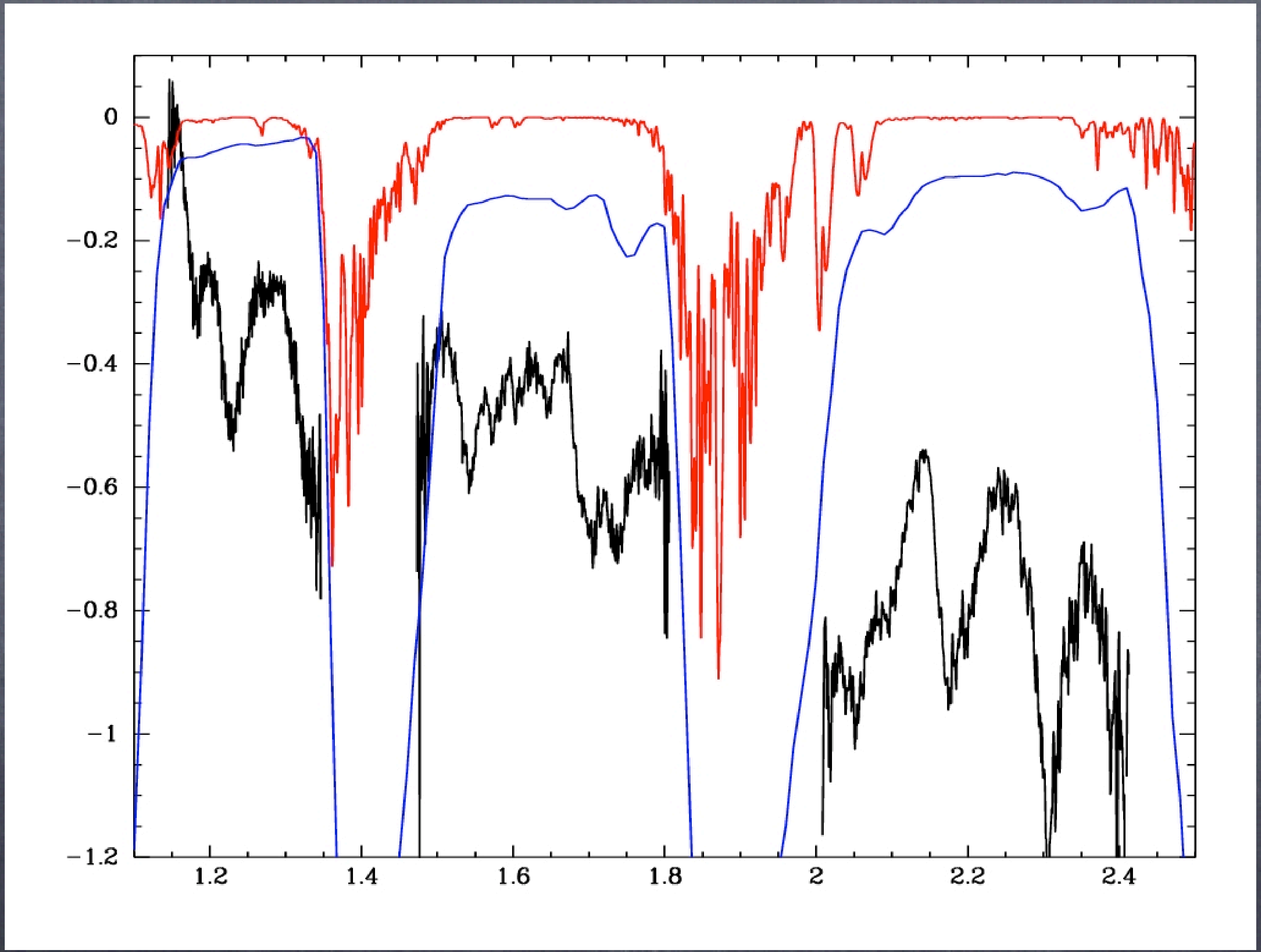
$$N_{ssub} = \int_0^\infty f_{ast}(\lambda)\phi(\lambda)\eta(\lambda)\tau(\lambda)d\lambda T\psi_{ff}$$

$$\frac{N_{reduced}}{T} \approx f_{ast}(\lambda_0)\phi(\lambda_0)\eta(\lambda_0)\tau(\lambda_0)$$

$$\frac{N_{reduced}}{T} \approx f_{ast}(\lambda_0)\chi(\lambda_0, color, airmass...)$$

$$m_{ast} \approx m_{inst} + Zpt(\lambda_0, color, airmass...)$$
$$+S(\lambda_0, color, airmass, site...)$$

Interpreting Photometry

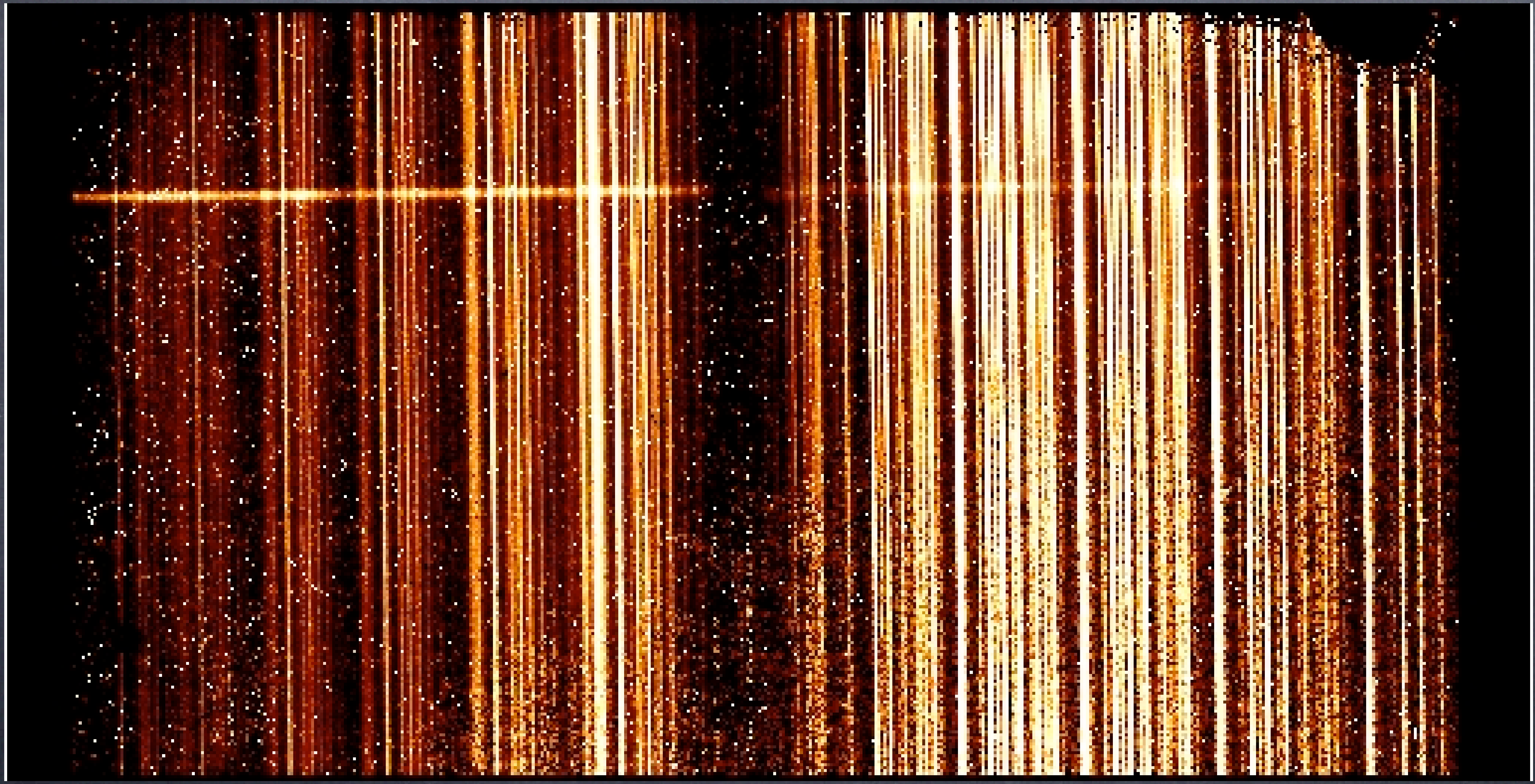


$$\frac{N_{reduced}}{T} = \int_0^\infty f_{ast}(\lambda)\phi(\lambda)\eta(\lambda)\tau(\lambda)d\lambda$$

Interpreting Photometry

- Photometry: not monochromatic flux density
  - Convolution of source, filter, transmission & inst. response functions
  - In continuum dominated objects, the convolution is relatively benign
- In SNe, the interaction between filters & features is more severe
  - Photometry dependent on redshift, spectral evolution, population variance...
  - Interpreting photometric behavior requires some knowledge of spectroscopic behavior, as well as a good understanding of filter passbands & system response, etc...

Infrared Spectroscopy



IR Spectrograph Designs

- "Imager +"
  - Primarily an imaging camera with a grism and slit installed
  - 1 Grism, M=1, L=2, K=3, H=4, J=6,7...
    - "Band at a time" (at best)
    - Hard to get broad wavelength coverage
  - e.g.: NIRI/GEMINI-N
- (Imaging) spectrograph
  - Well outfitted for spectroscopy
  - Good low-res modes ("octave at a time")
  - e.g: LIRIS/WHT, CISCO/Subaru,

IR Spectrograph Designs

- Cross-dispersed spectrographs
  - Low-order echelle mode
  - Single setup for entire detector range
  - e.g.: SpeX/IRTF, GNIRS/Gemini-S
  - Very efficient observing
  - Harder to reduce
- OH-Supression
  - Block OH line emission
  - High-res background at low spectral resolution
  - Very faint object spectroscopy

Taking IR spectral data

- Telescope/instrument features that will make life a lot easier
  - Accurate offsets, preferably while guiding
    - Aids target acquisition and nodding
  - Stable (repeatable) slit position
    - Aids target acquisition, telluric correction
  - IR guiding
    - Differential refraction, differential flexure
- Note: Sky BG is your enemy!
  - Use small slits to keep the sky out
  - Bad seeing is a big problem

Getting sky data

- For PS, nod (dither) to multiple locations along slit (typically 2: ABBAAB...)
  - Nasty cosmetic problems? Try more nod positions
  - Accurate offsets?
- For confused BG and/or diffuse objects, obtain off-target sky frames (painful)
- Integration times: typically a few minutes per exposure.
  - Want to reach BG-limited regime, but keep counts linear
  - OH-lines vary on scales of a few minutes

Telluric Correction

- TC is a must in the IR
  - Most of IR is affected by telluric absorption, in many places quite severely
- Choose ‘standards’ that will match target airmass
  - Near target, bracket observations
  - Same dec, before or after target (e.g. + or - 1hr)
  - Chose star at AM of observation just when observing standard...
    - Usually a desperation tactic. Stars at extreme dec where AM changes slowly can sometime be helpful
  - Beware short exp. with shutterless cameras

Telluric Correction

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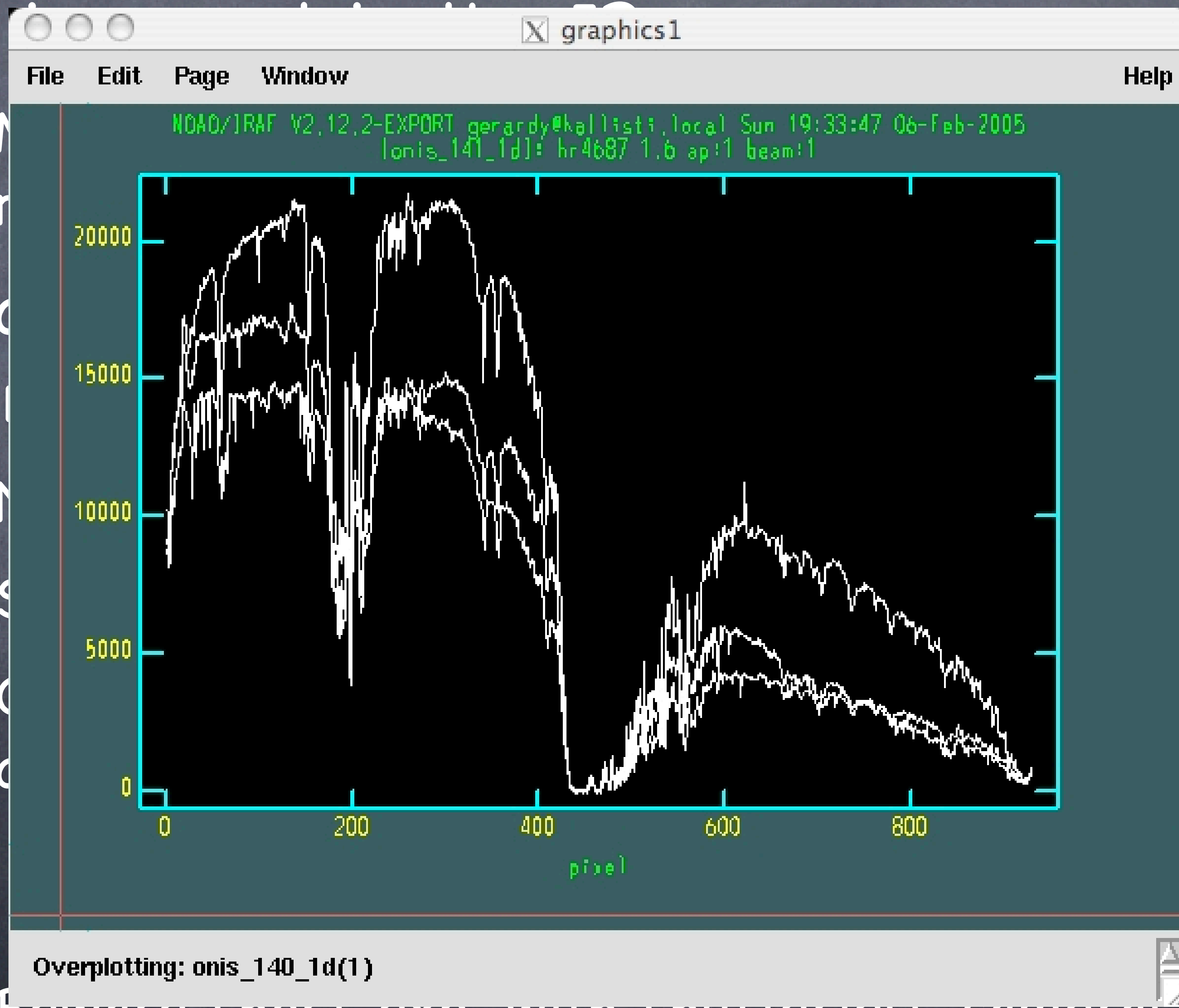
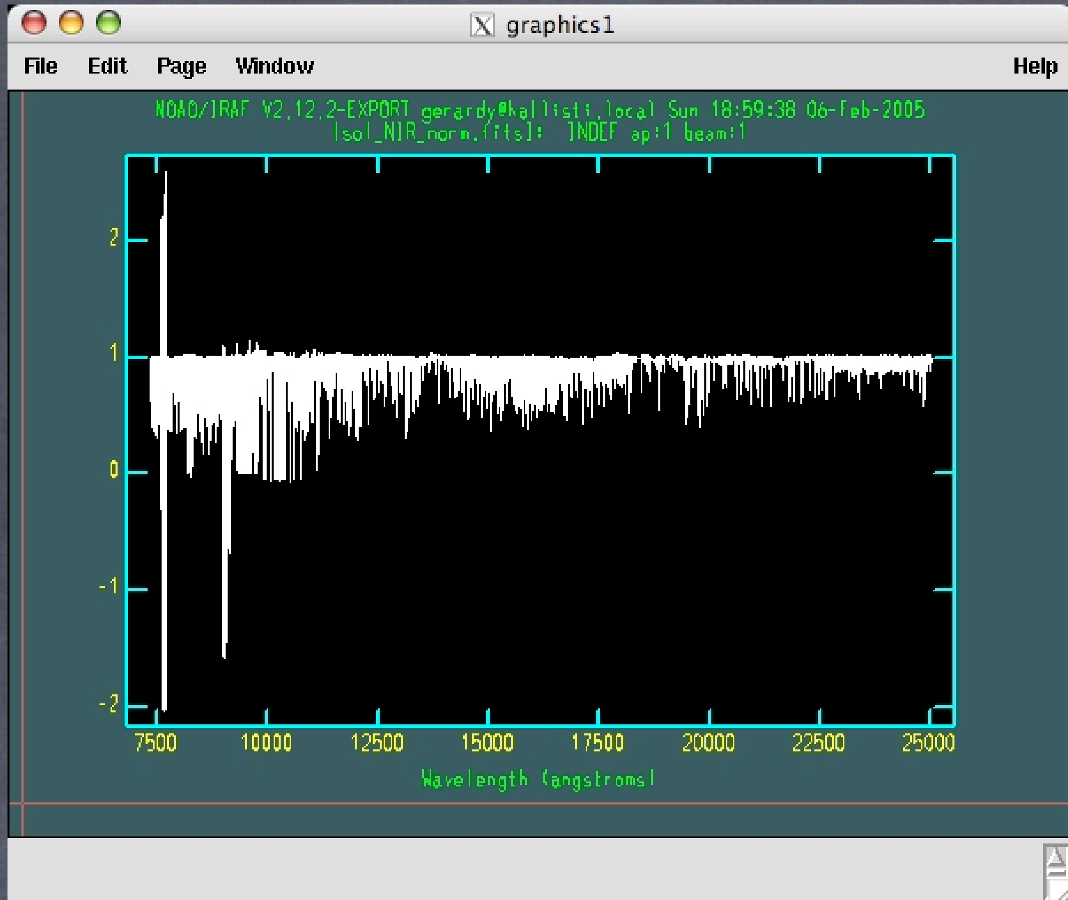
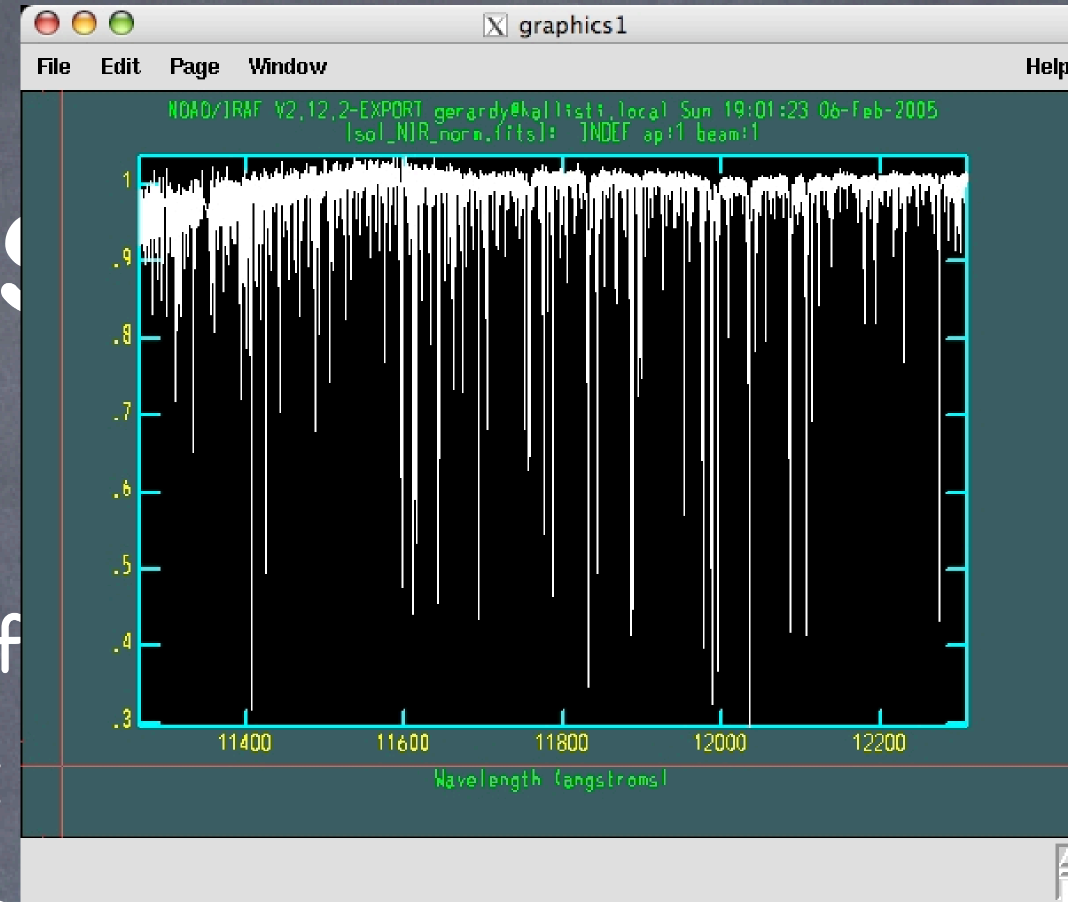
  - Beware short exp. with shutterless cameras



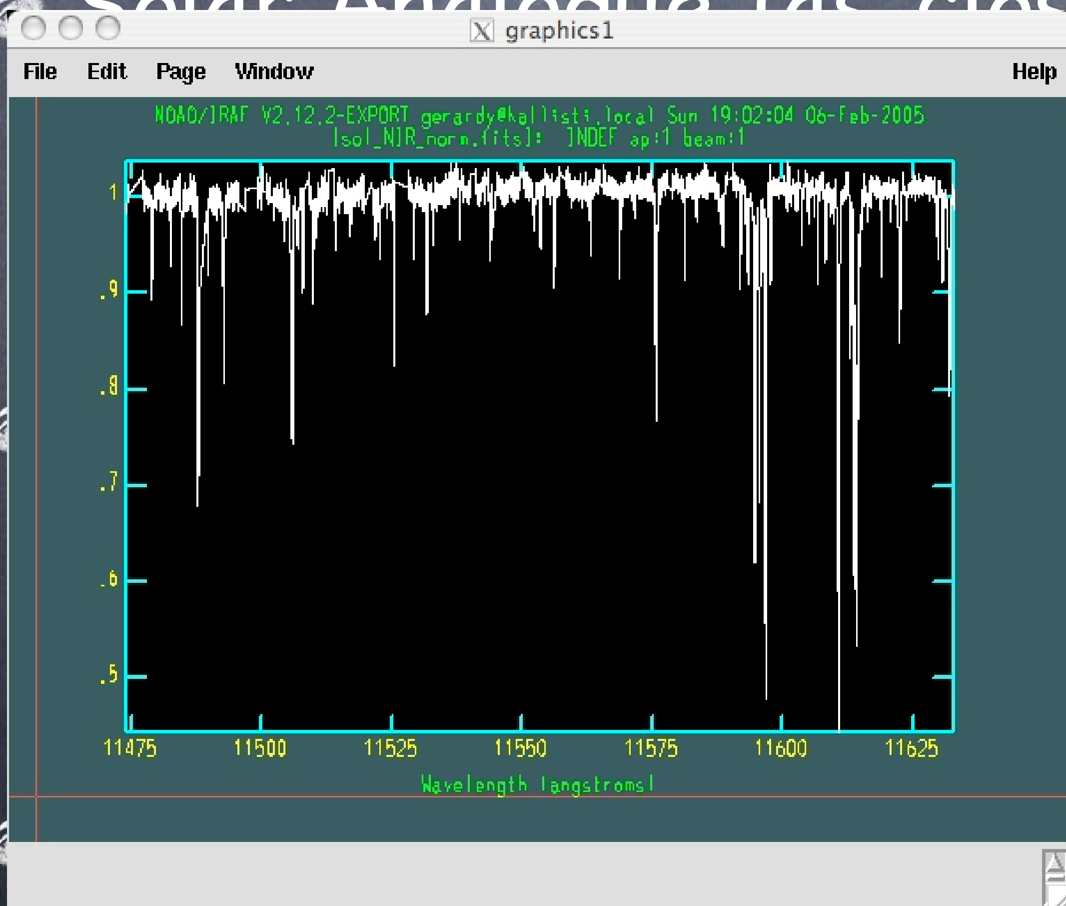
What stars to use?

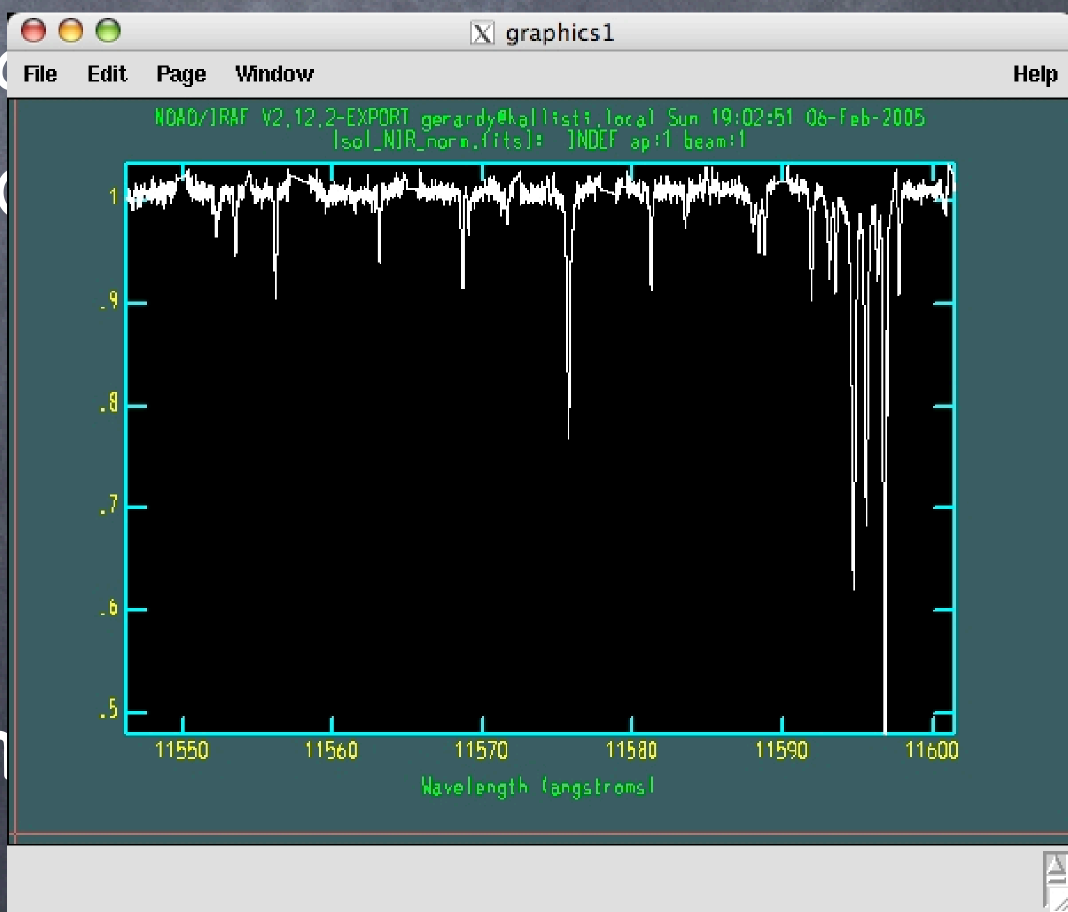
- Choose stars with well known spectral types
  - Need to remove stellar features from spectrum
  - Often using std for flux calibration
- Solar Analogue (as close to G2V as possible)
  - Use solar spectrum to remove stellar features
  - Lots of subtle features in G-star spectra....
- A stars
  - Simple spectrum
  - Strong H features
- F-stars: split the difference





- Solar Analogue (as close to G2V as possible)





What stars to use?

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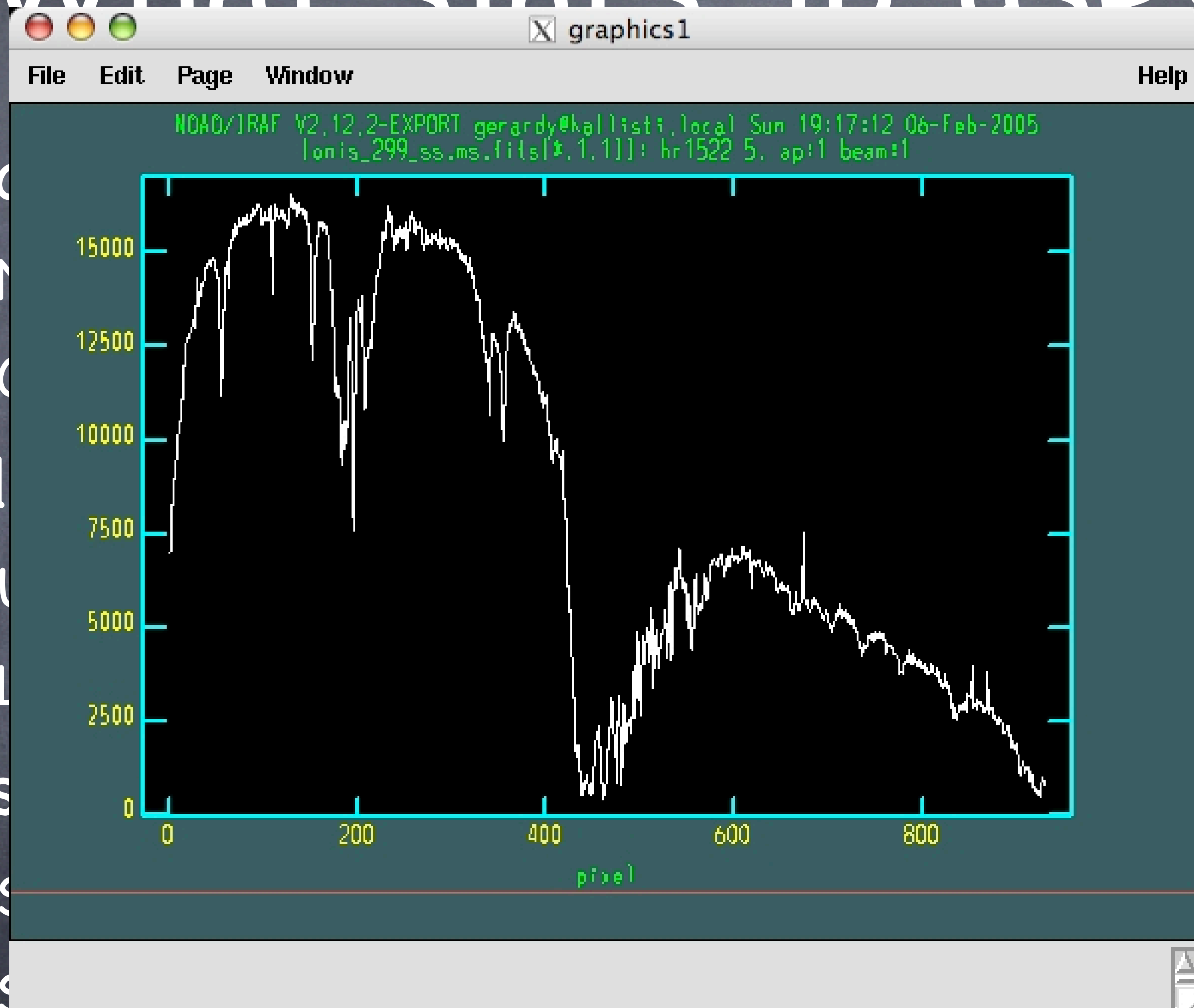

- F-stars: split the difference

What stars to use?

- Hanson method: use both G stars and A stars
  - Use Solar Analogue method to remove telluric features from the A-star.
  - Fit the stellar features in the corrected A-star spectrum, and remove them from the uncorrected A-star spectrum
  - Use result to remove telluric features from the target
  - Limits uncertainties in G-star spectrum to A-star stellar features
  - Need 2 stds!
  - See Hanson et al. 1996 ApJS 107 281;
    1998 AJ 116 1915

Where to find them?

- Bright Star Catalog
- General Catalogue of MK Spectral Types
- Hipparcos Catalog
- SAO Catalog
- Lists and searchable databases at UKIRT, IRTF, Gemini, Subaru websites (probably others as well)

Other Calibration Data

- Flats: As with optical, usually use on-instrument/telescope flat-lamp
- Bias/Darks: Often not needed. (Exceptions: flats with no "off", high dark current, obs with no sky frames...)
- Wave cal: Arc lamps (e.g.: Ne, Ar, Xe) or OH-lines
  - OH not sufficient for K-band. Also beware aliasing & confusion with low-res
- Spectrophotometic Stds: There aren't any
  - Use telluric stars and stellar atm. model
- Photometry: The best way to flux!

Processing spectral data

- Mostly similar to optical reductions
- No overscan
  - use bias, dark, or ‘off’ frames for flats
  - removed with sky-subtraction for data
- Check for thermal signature in flats
- “Response” flats with low order fit
  - Avoids amplifying noise at the ends of the spectrum, while removing high frequency filter features
- FF data by setup

Proce data

- Mostly
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  - use bi s
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- Check f ts
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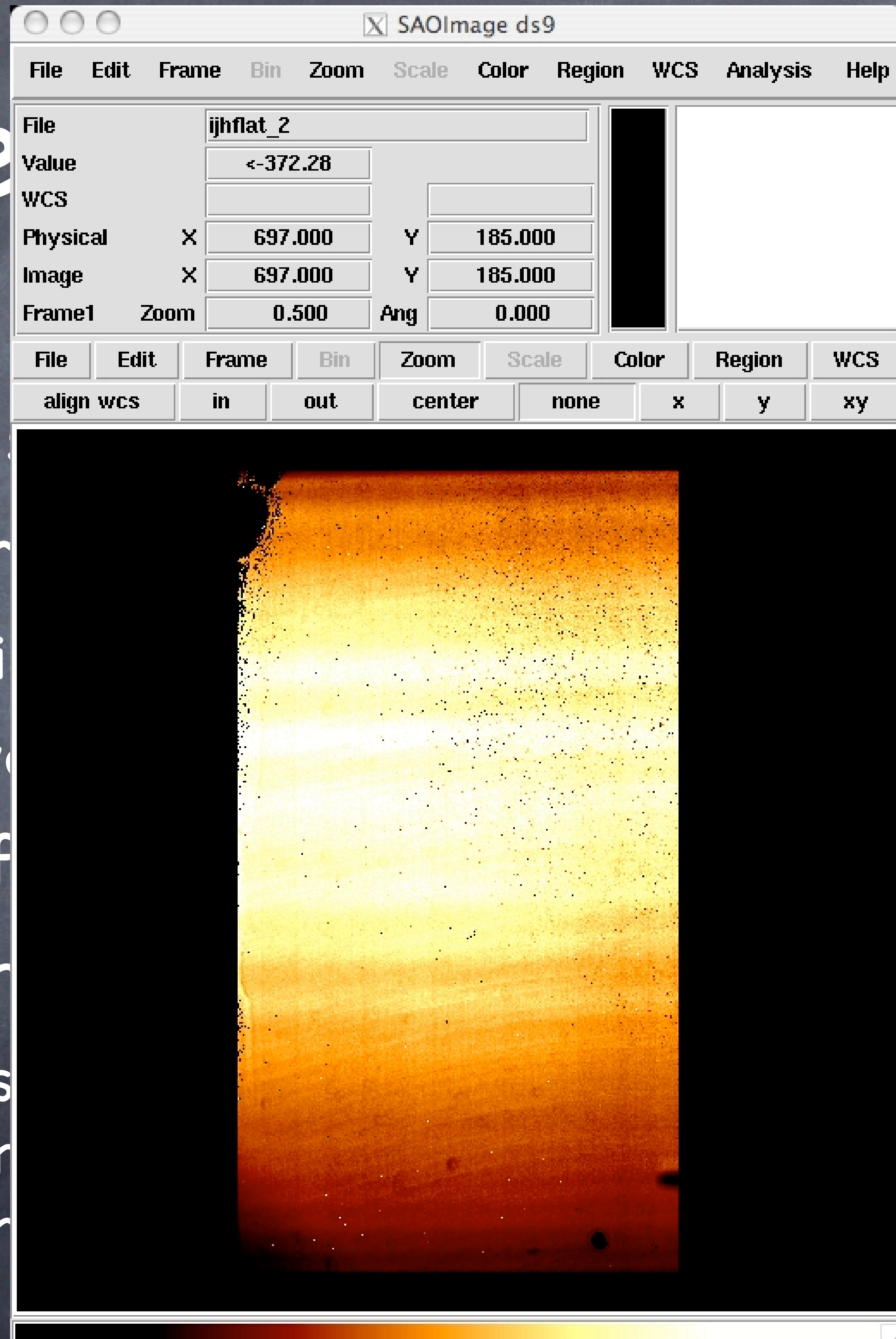
  - Avoids the spectr cy filter featur
- FF data by csrap



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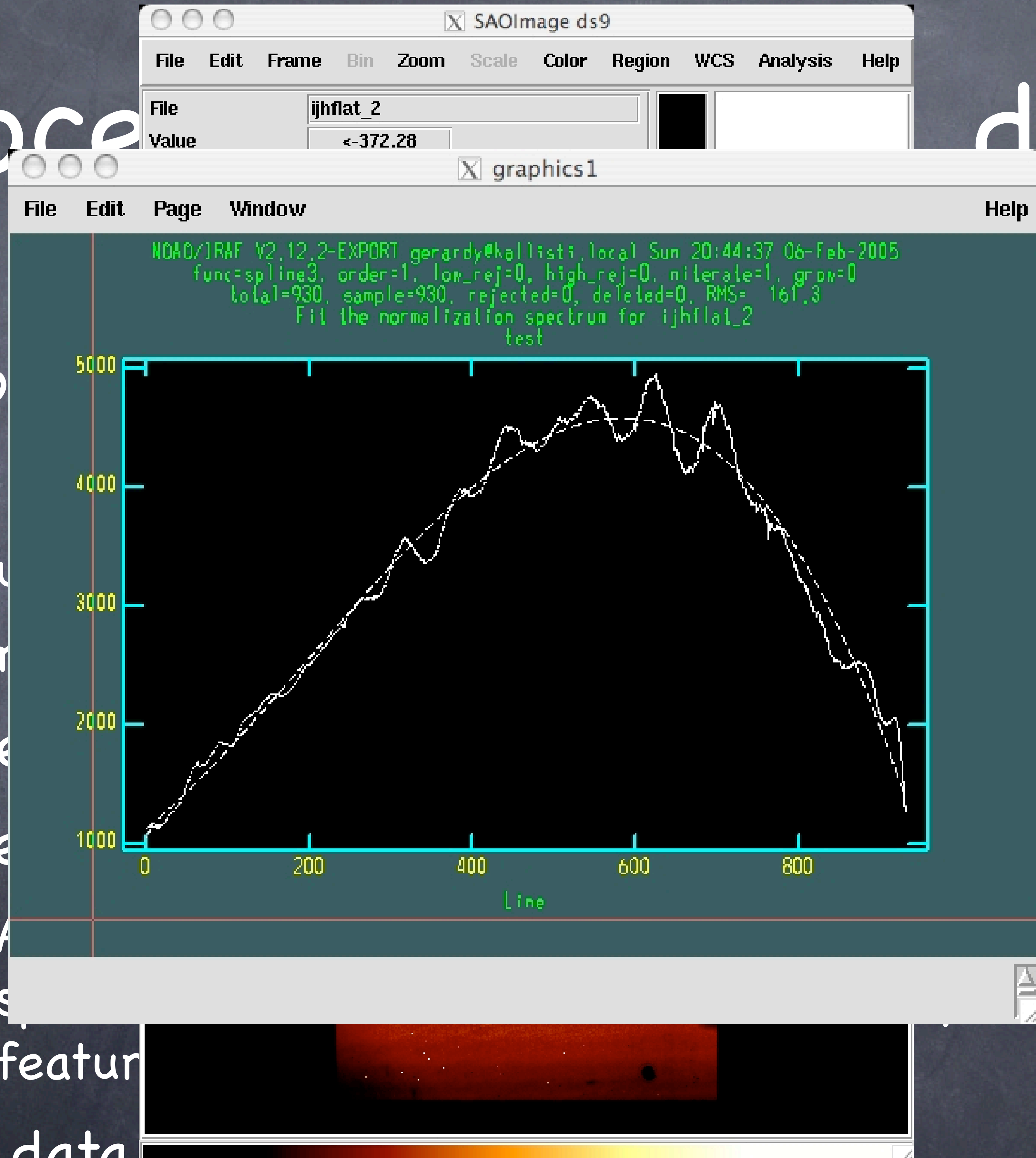

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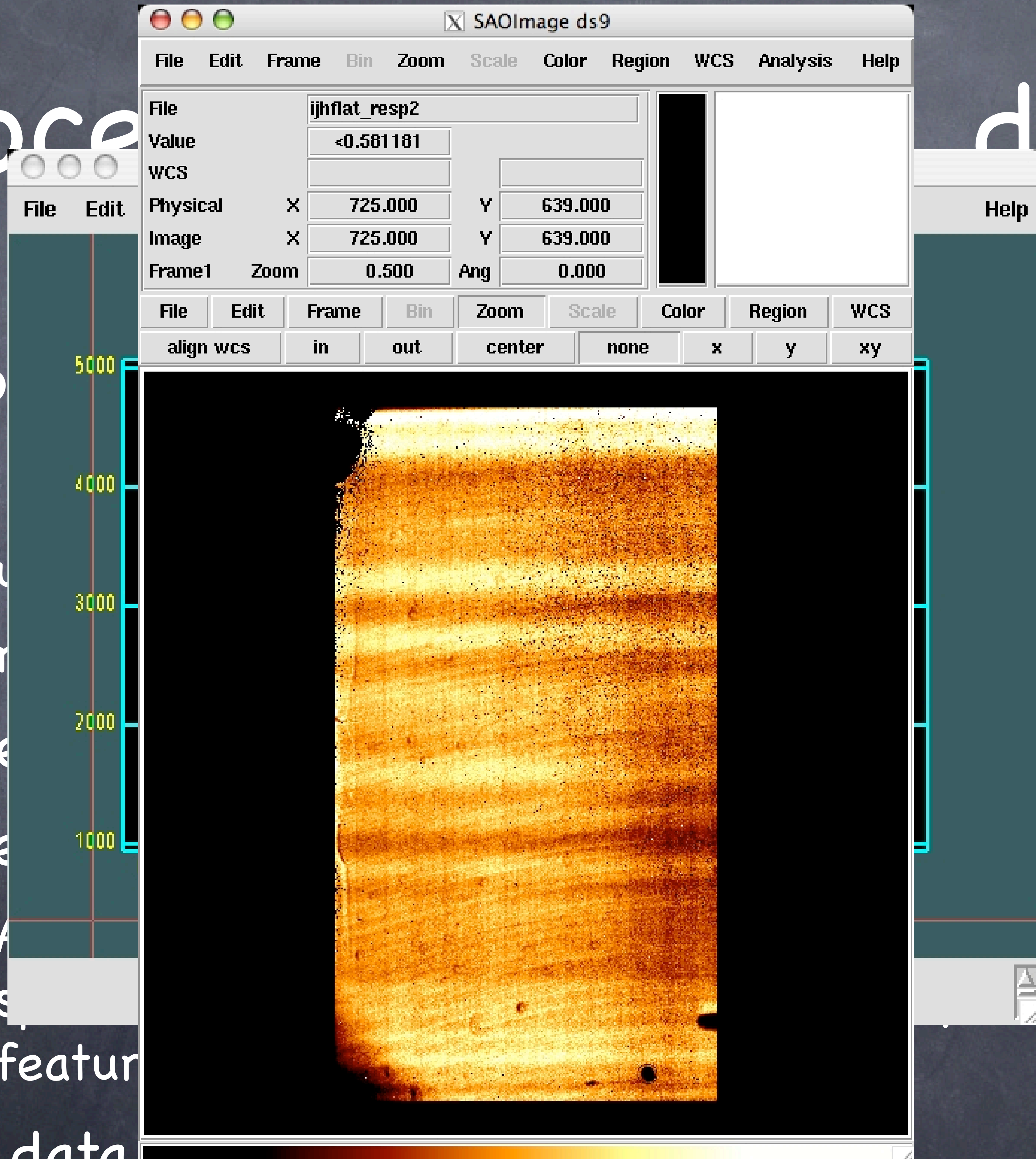
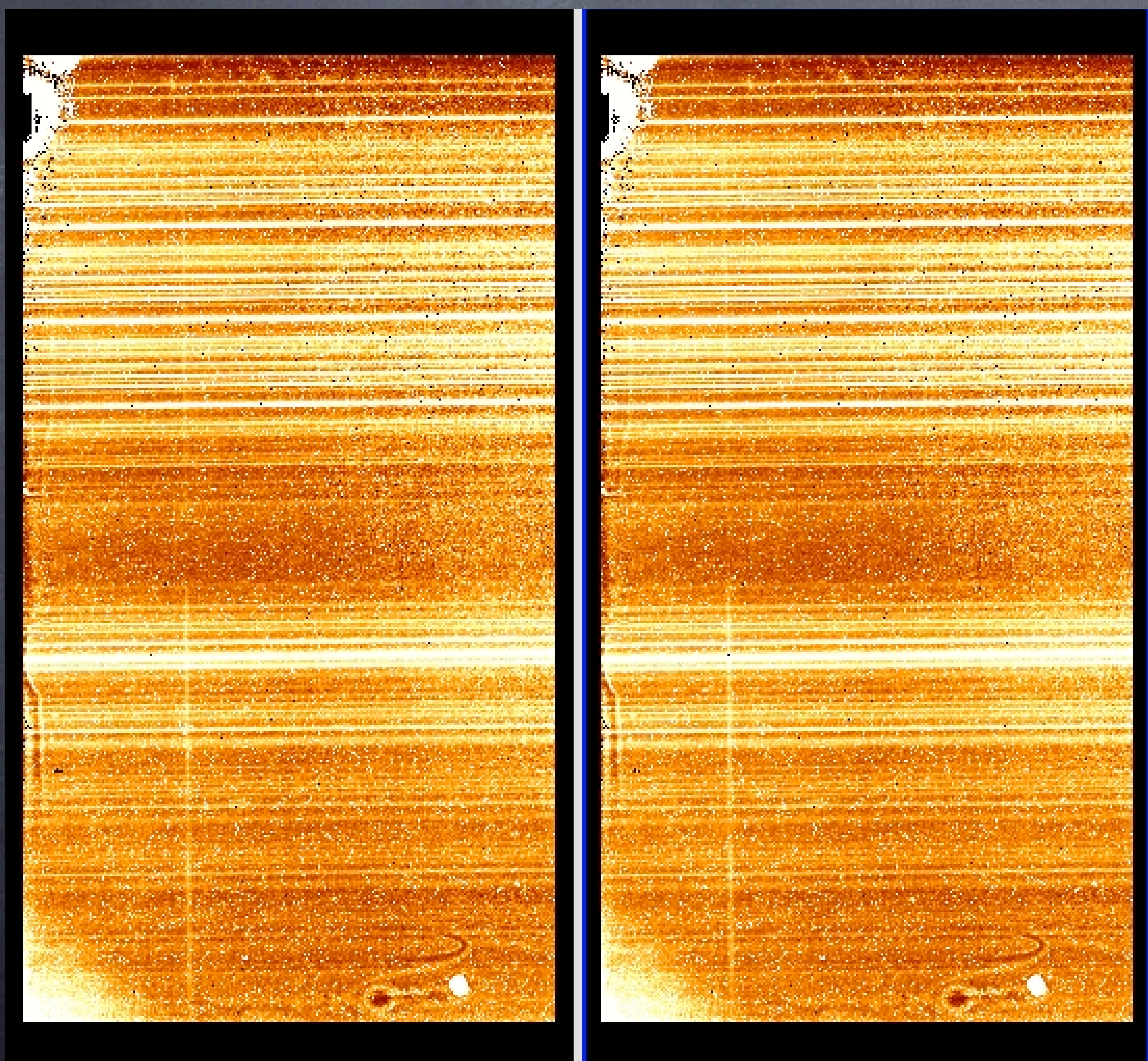
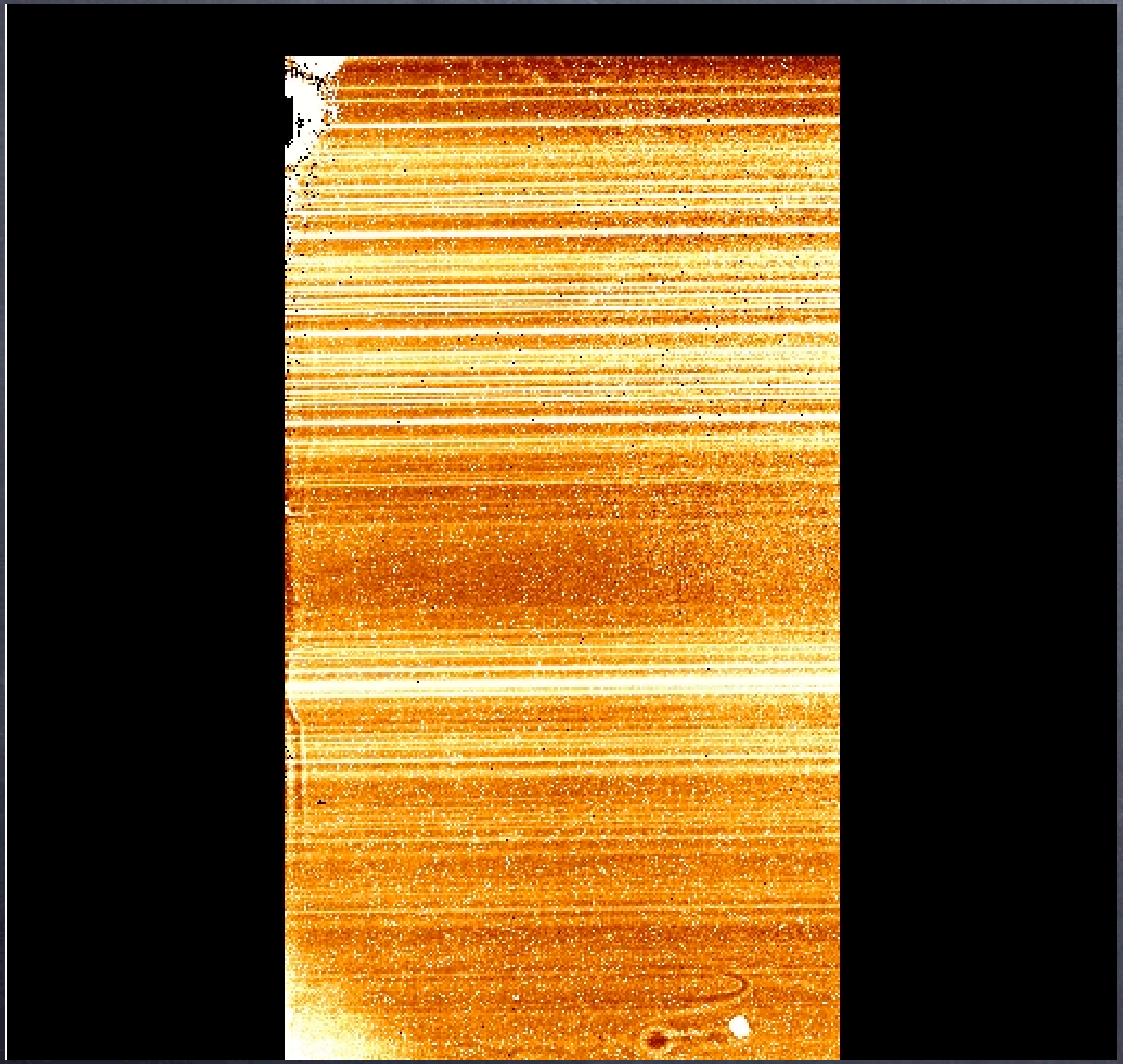


Sky Subtraction



- For 2-point nod pattern, subtract pairs
- Else combine other nods (perhaps with high-pixel rejection) and subtract.

Sky Subtraction



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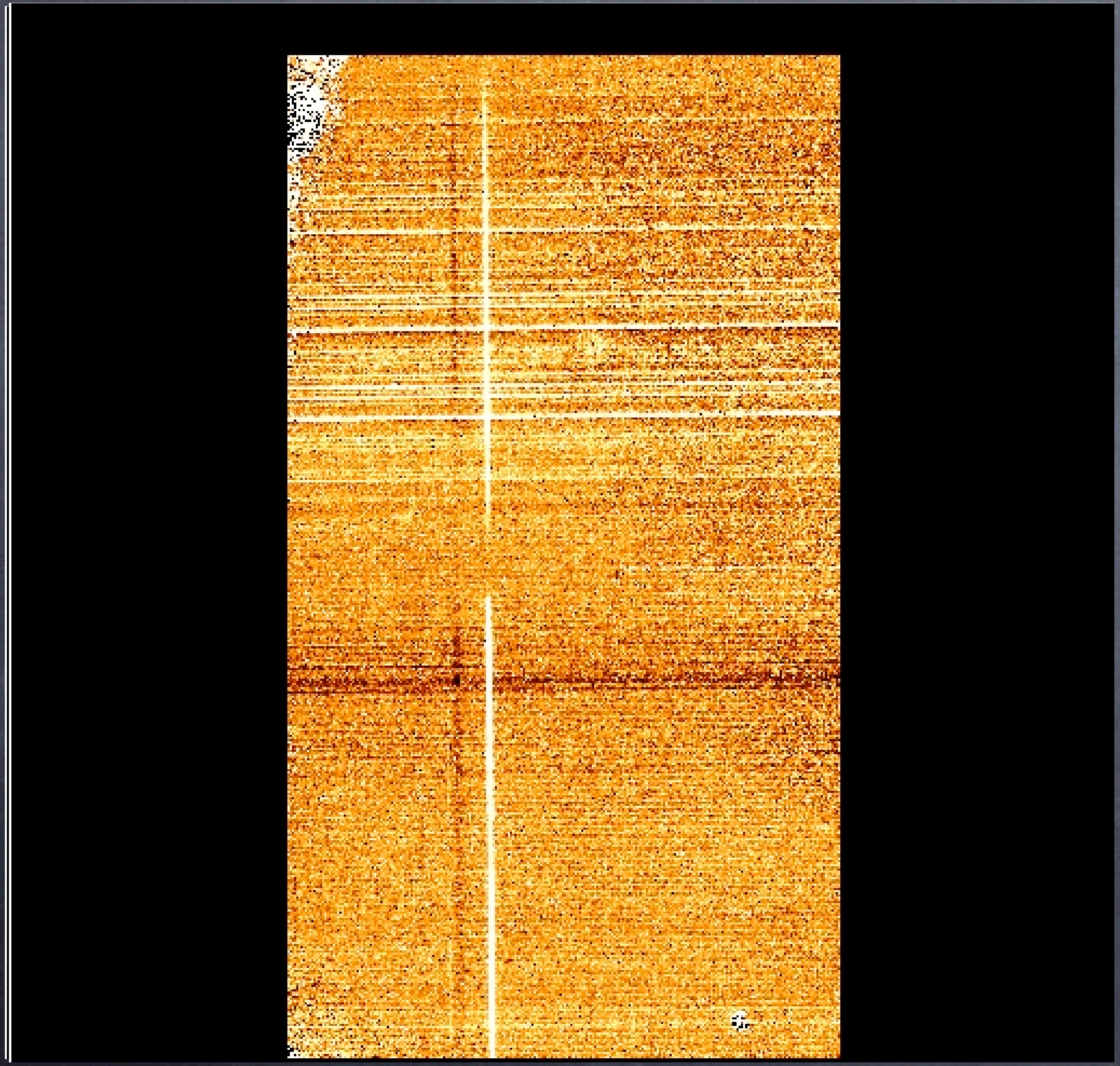
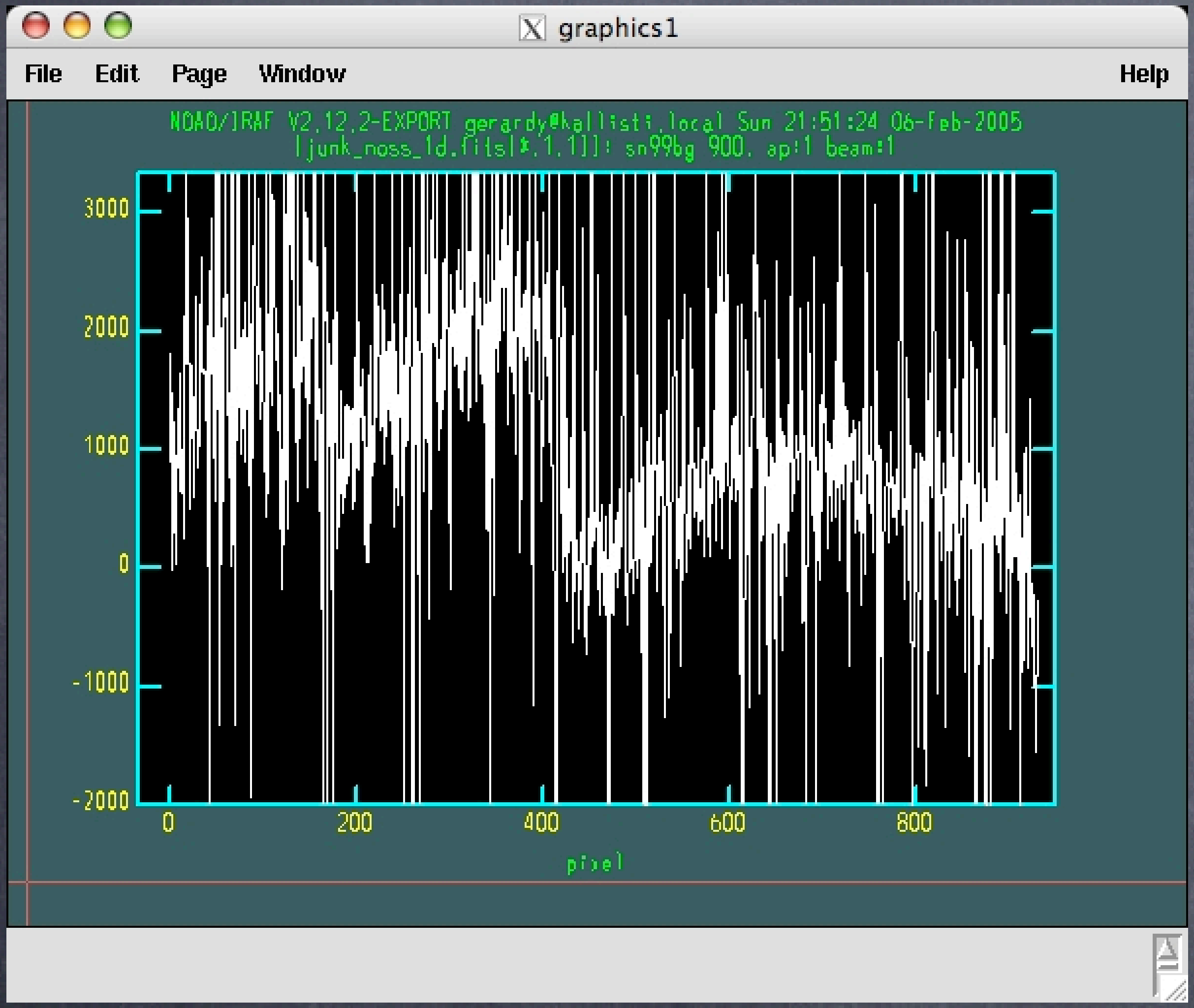
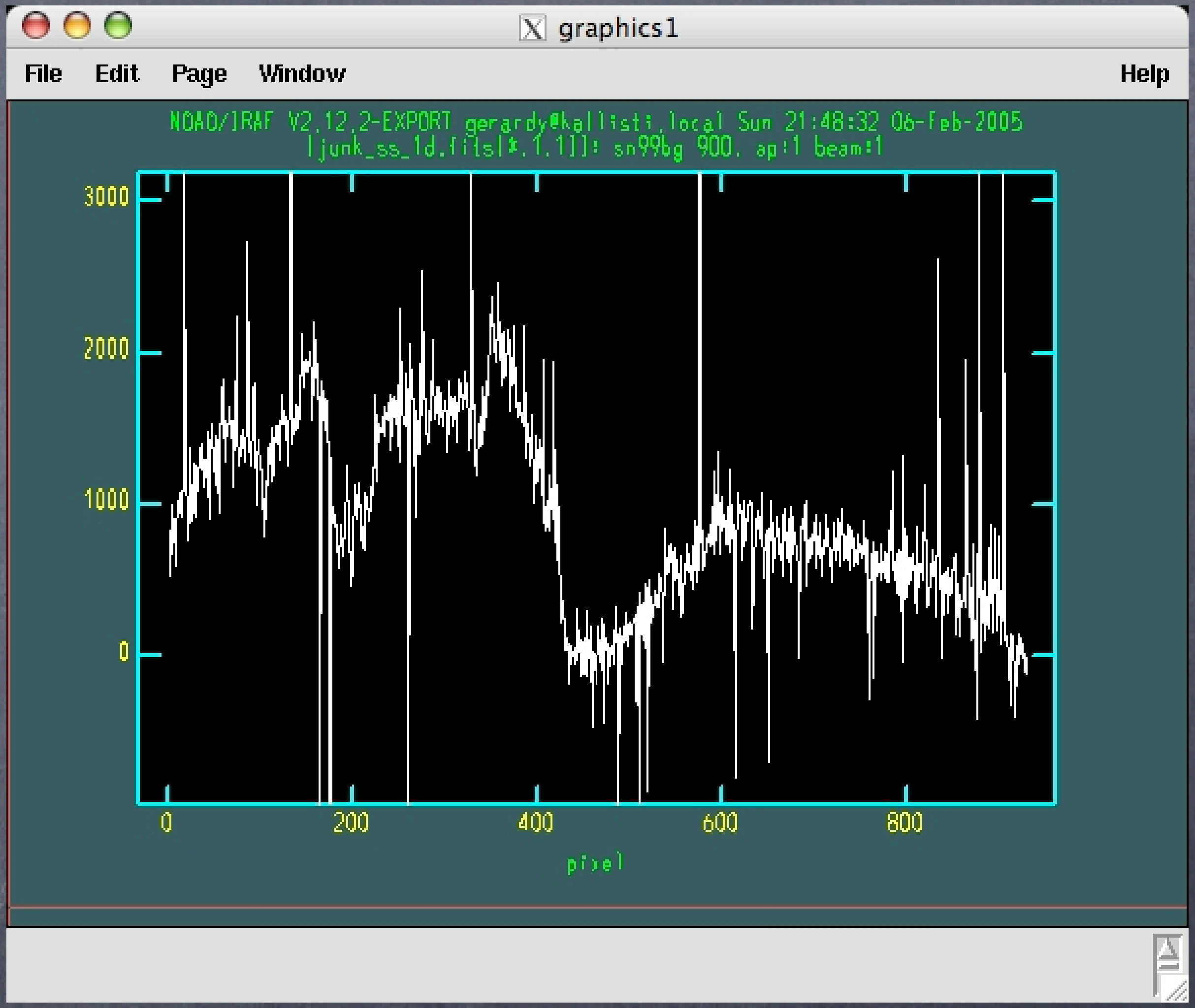


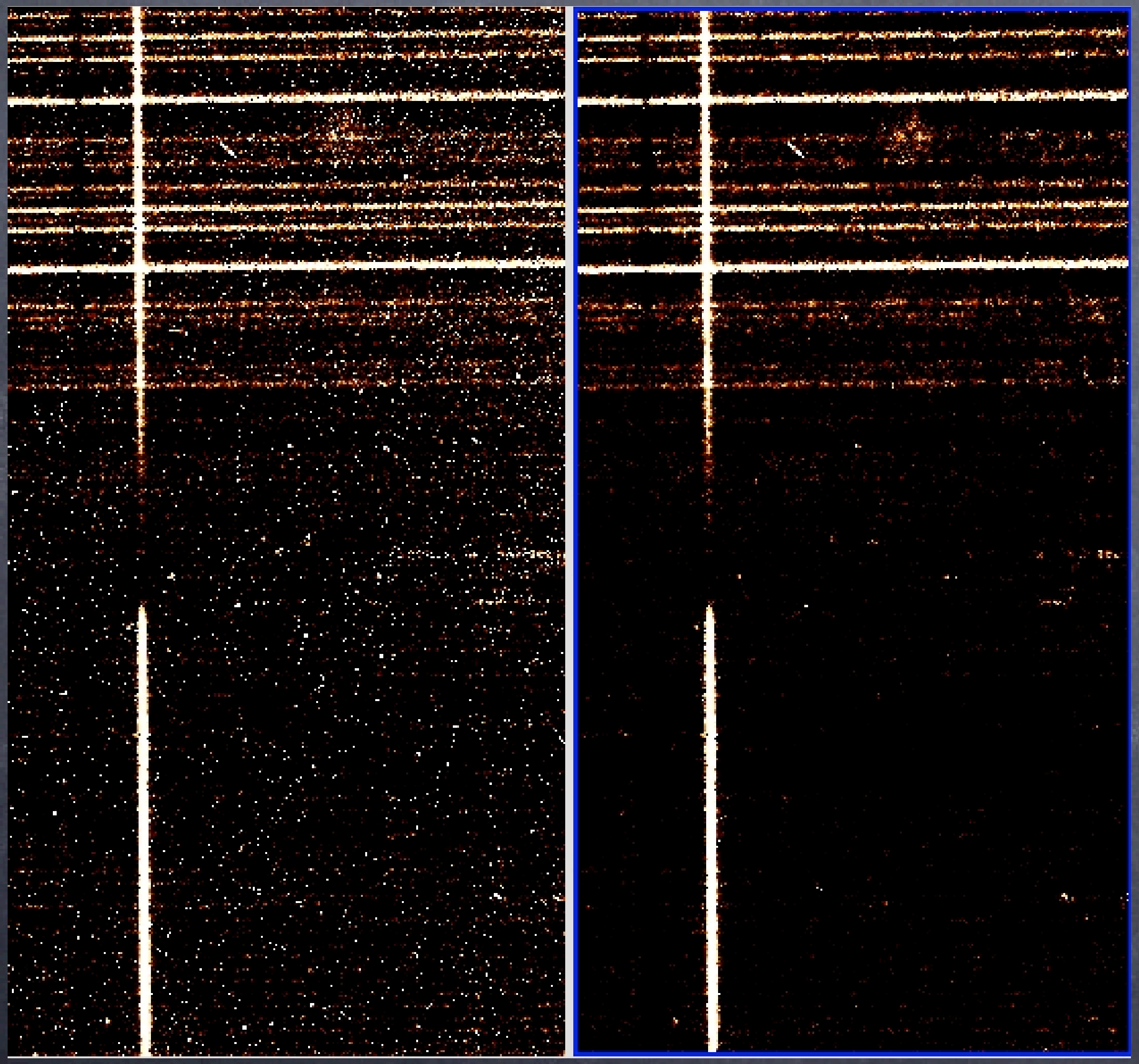
- For 2-point nod pattern, subtract pairs
- Else combine other nods (perhaps with high-pixel rejection) and subtract.

Sky-sub helps!



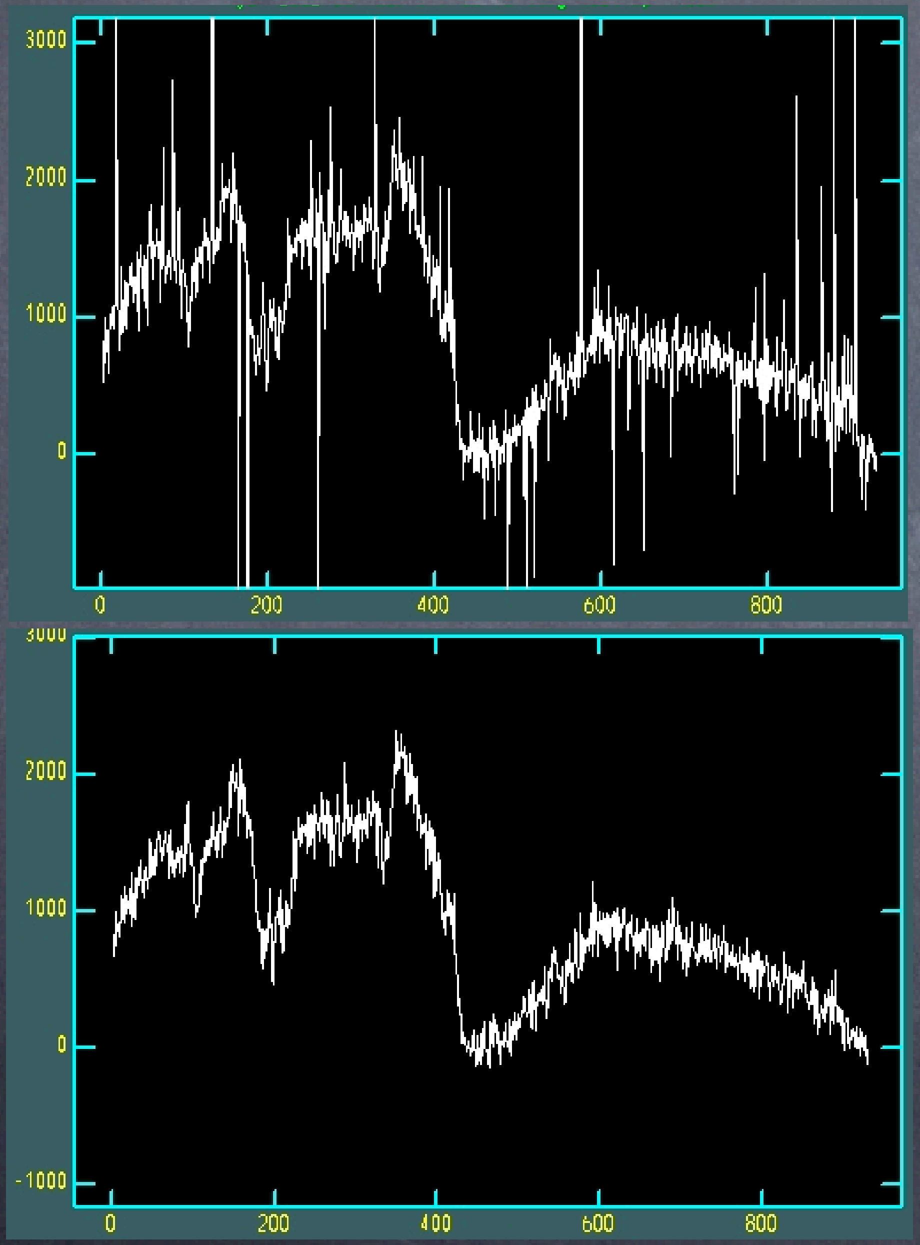


Clean bad pix



- Again, cosmic-ray tools work fairly well
- "Clean both sides" (clean, invert, clean, invert)
- Clean before binning!

Clean bad pix



- Again, cosmic-ray tools work fairly well
- "Clean both sides" (clean, invert, clean, invert)
- Clean before binning!

Pre- or Post-combine?

- If nod positions are stable, stack as 2D nods
  - Extract stacked nod positions & wave-cal data
- Else, extract single exposures
  - Wave-cal & combine individual exposures
- Weight combinations by counts or S/N?
- Extract & wave-cal as with optical data
  - Do second background subtraction, interpolating or fitting sky in apertures adjacent to target.
  - OH-lines can provide a measure for wave-cal stability and effective spectral resolution

After extraction & wavecal...

- (Divide by smoothed stellar spectrum?)
- Create instrumental response spectrum
- Create telluric absorption corrections for each obs.

Can be 1 step

- Calibrate data (to relative spectrophotometry)
- Match & join overlapping spectral setups
- Use photometry (if available) to set final flux levels

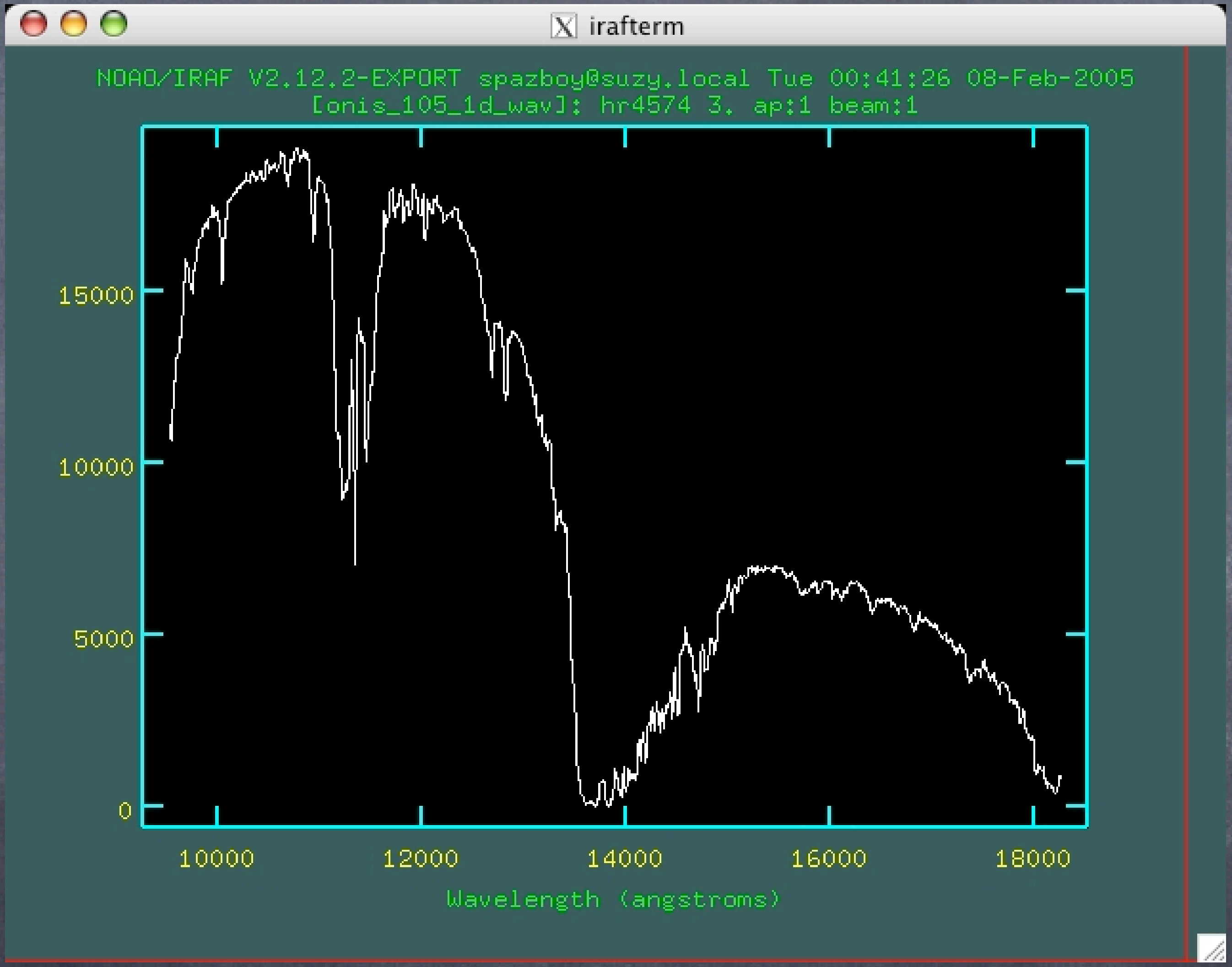
Multiplicative corrections

$$\alpha_{correction}(\lambda) = \frac{f_{meas}(\lambda)}{f_{``ideal''}(\lambda)}$$

$$spec_{``fixed''}(\lambda) = \frac{spec_{meas}(\lambda)}{\alpha_{correction}(\lambda)}$$

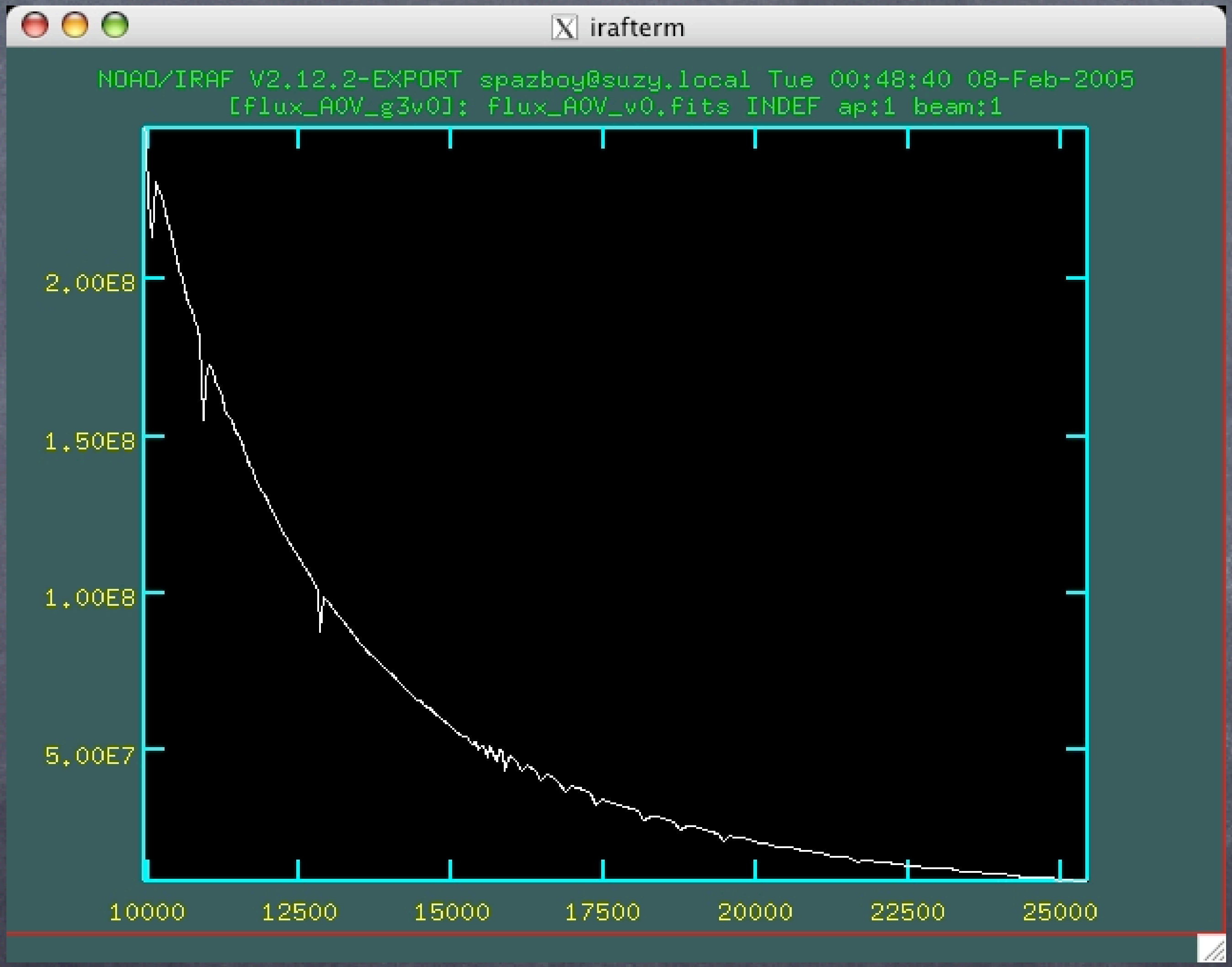
Telluric correction, instrumental response, etc...

Building an instrumental response spectrum



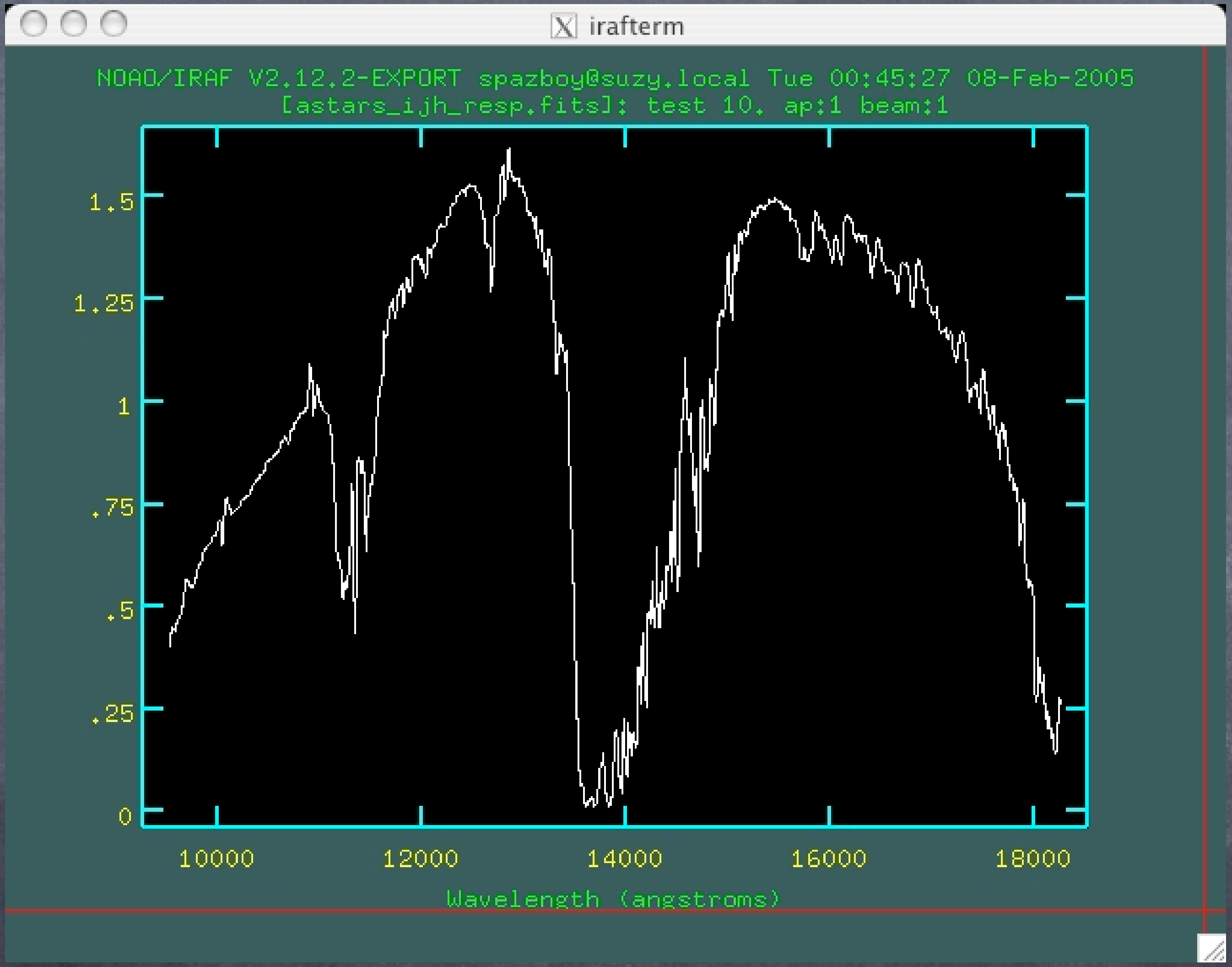
Start with spectrum of telluric star

Building an instrumental response spectrum



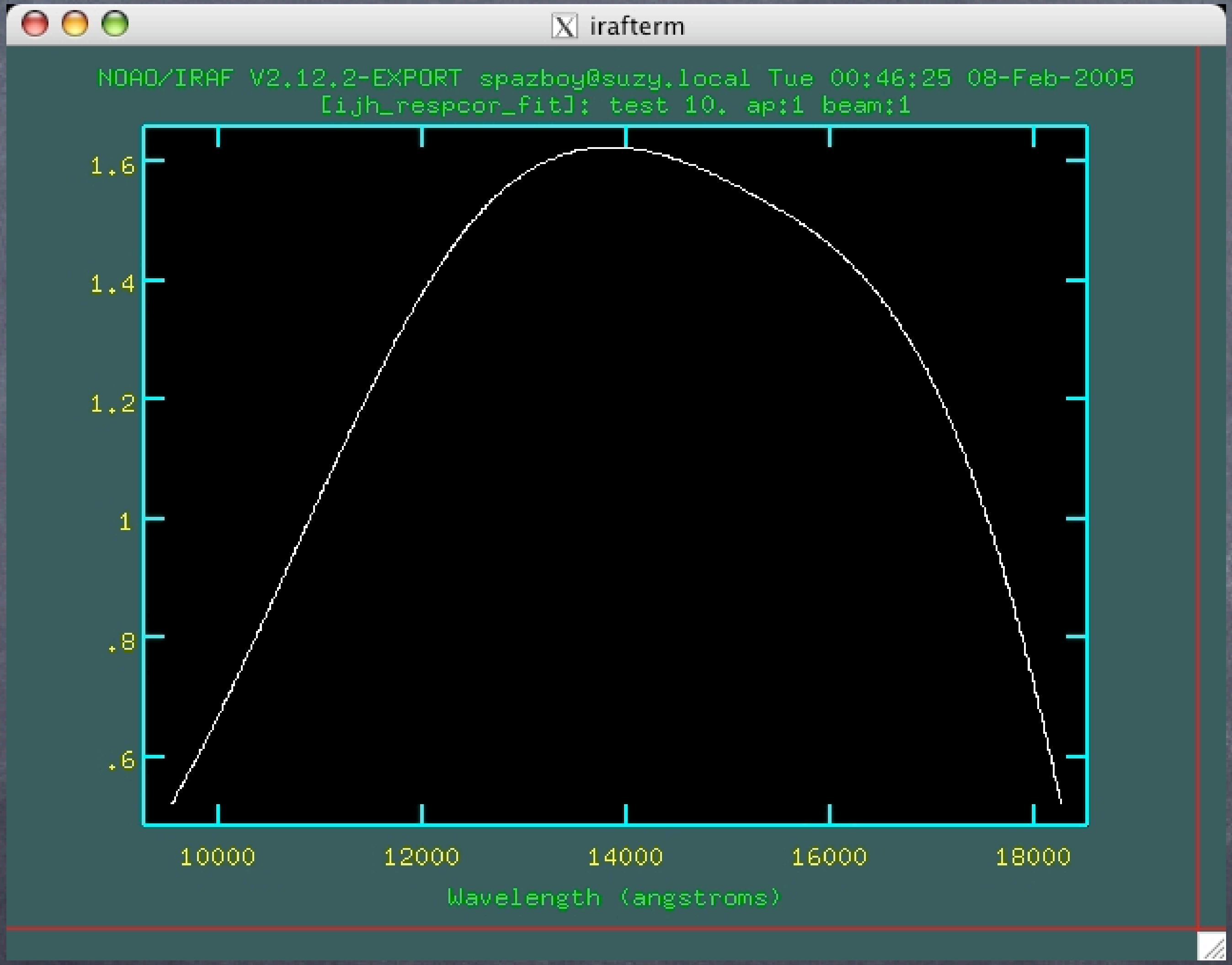
Divide by spectral model

Building an instrumental response spectrum



Combine with ratios of other TS/model pairs

Building an instrumental response spectrum



Fit continuum of averaged ratios

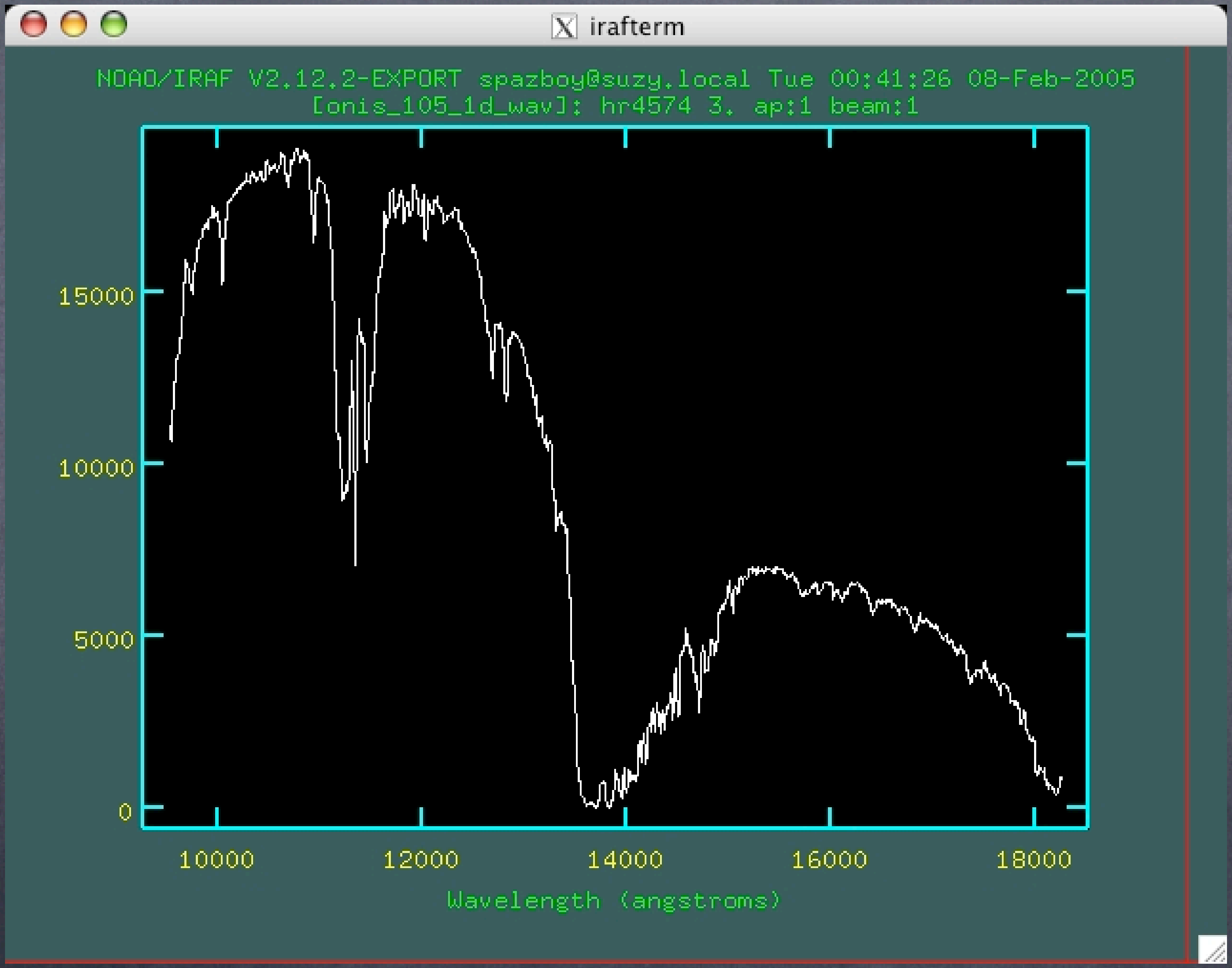
Using a smoothed stellar spectrum

- Can help to remove any sharp or "high frequency" features in instrumental response function without resorting to high-order fitting function
- "Clip out" telluric and stellar features and "smooth" spectrum.
- Divide into all data, stds, etc.
  - "idealised" is flat spectrum...

Using telluric stds

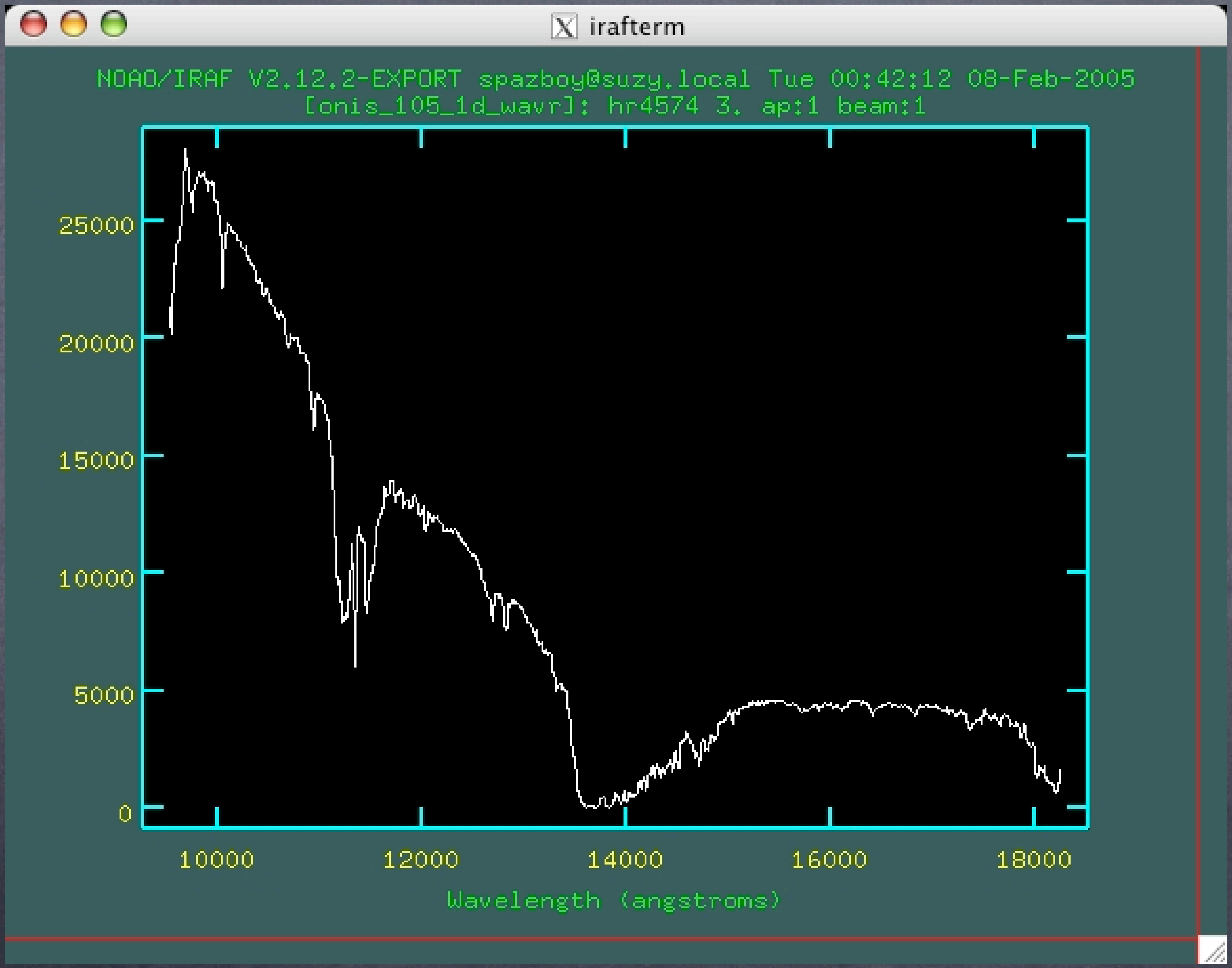
- Divide telluric standards by model atm. spectra to remove stellar features and set instrumental response correction
  - e.g.: Kurucz models
  - Solar analogue: use solar spectrum to remove stellar features, then use line-removed model to fix continuum
  - Average response from several TS to create global response?
  - Tweak telluric correction?

Final Stages Example



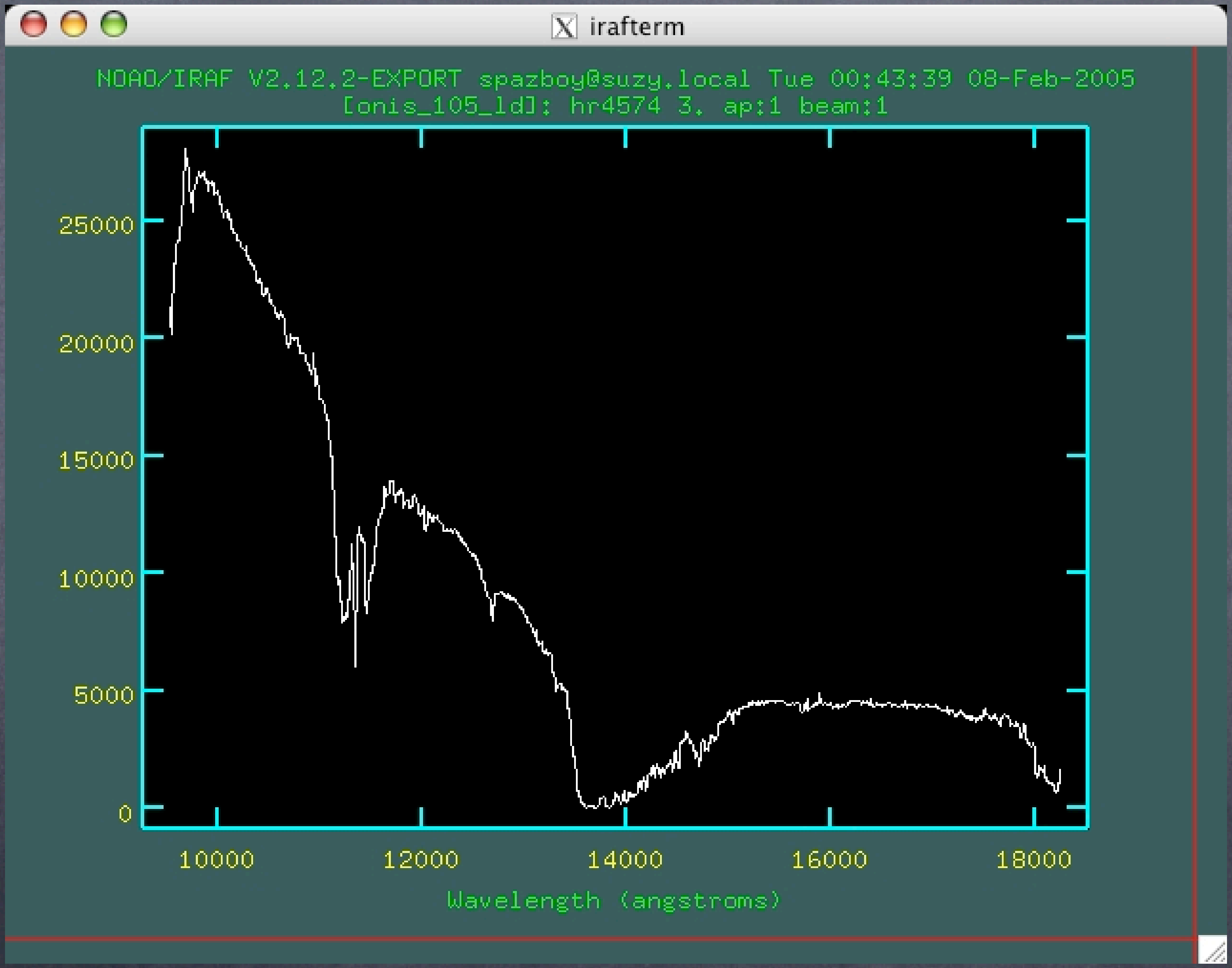
Extracted A-star

Final Stages Example



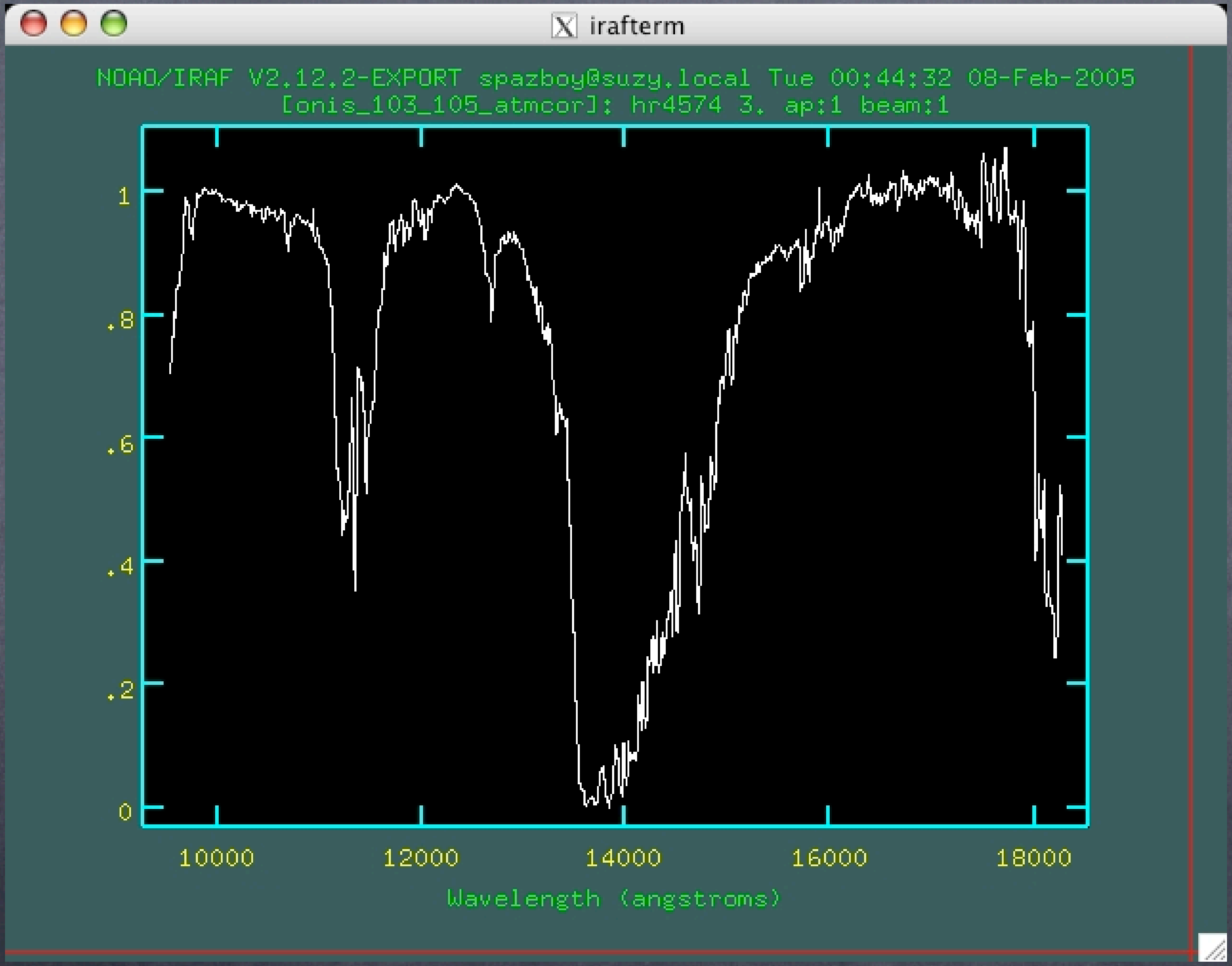
Divide by inst. resp. correction

Final Stages Example



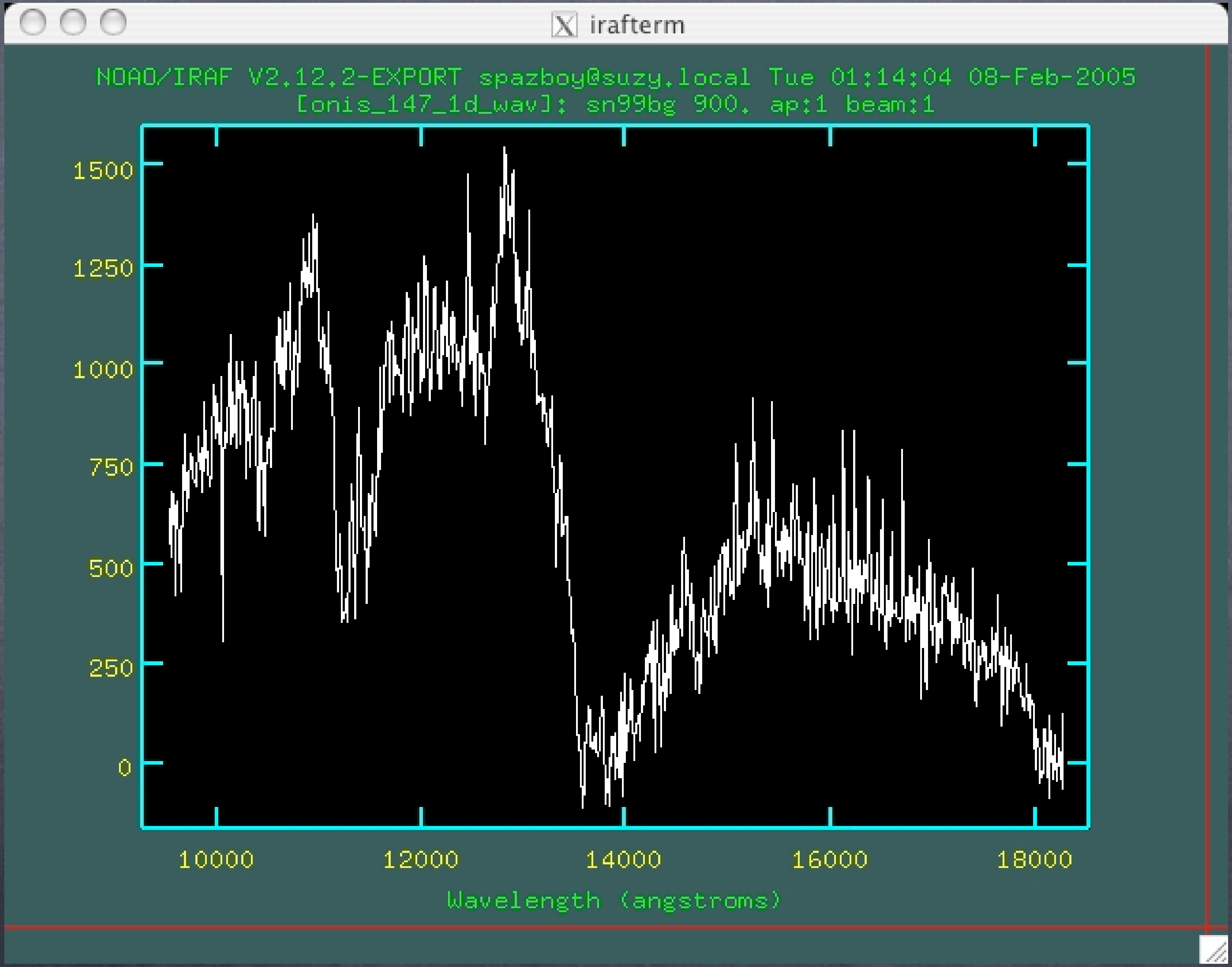
Divide out stellar features from model

Final Stages Example



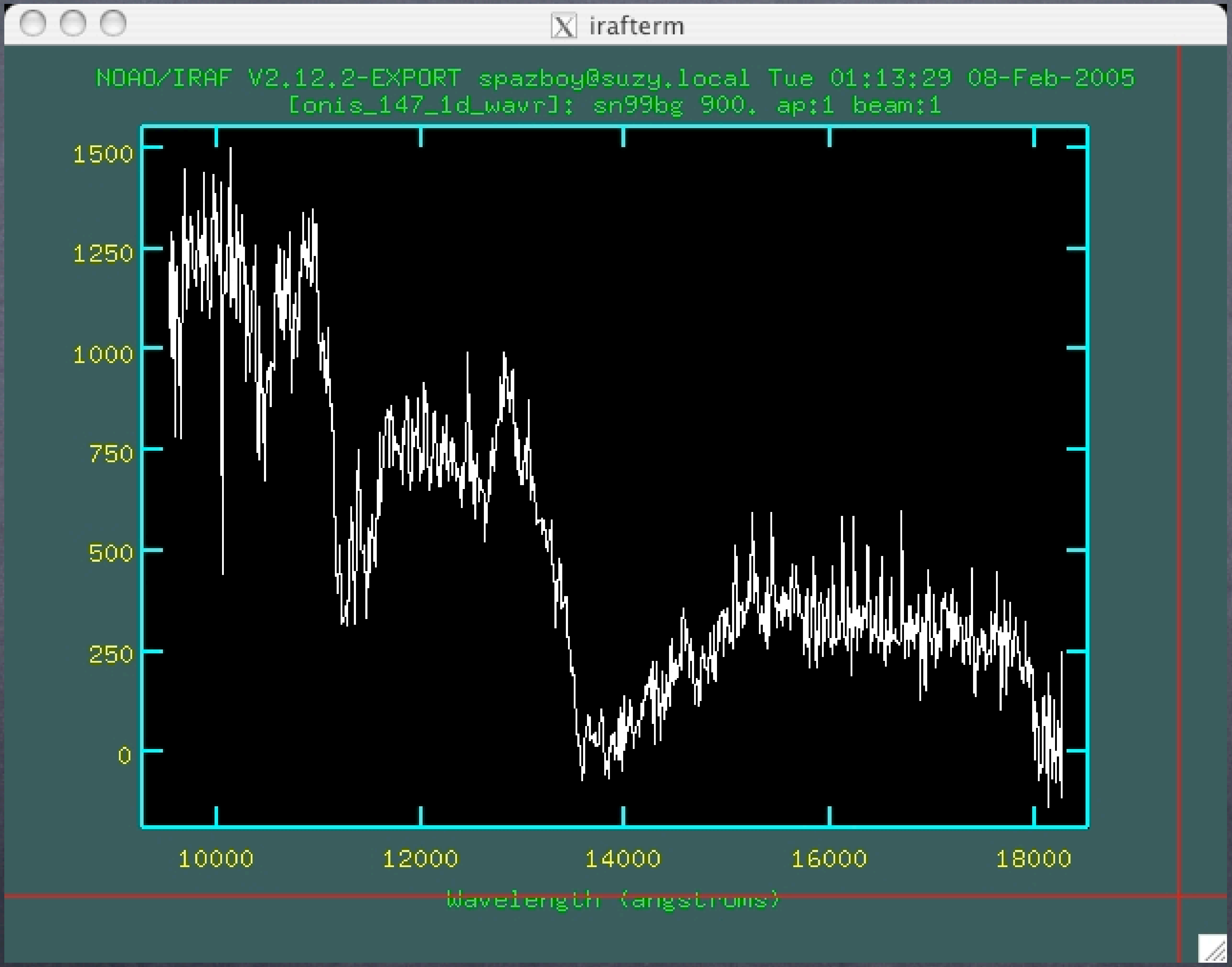
Continuum divide to make atmcor

Final Stages Example



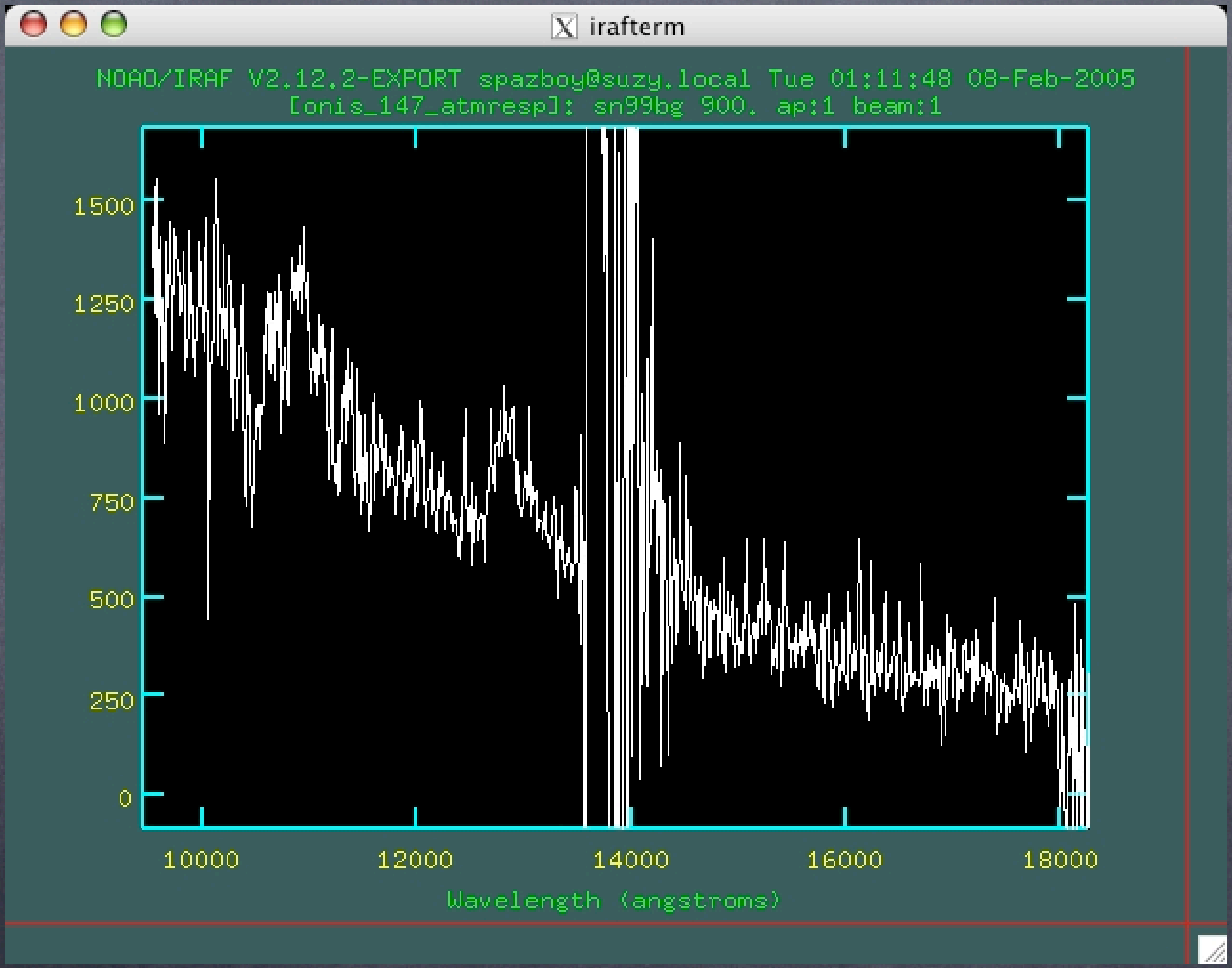
SN: single exp. extracted spectrum

Final Stages Example



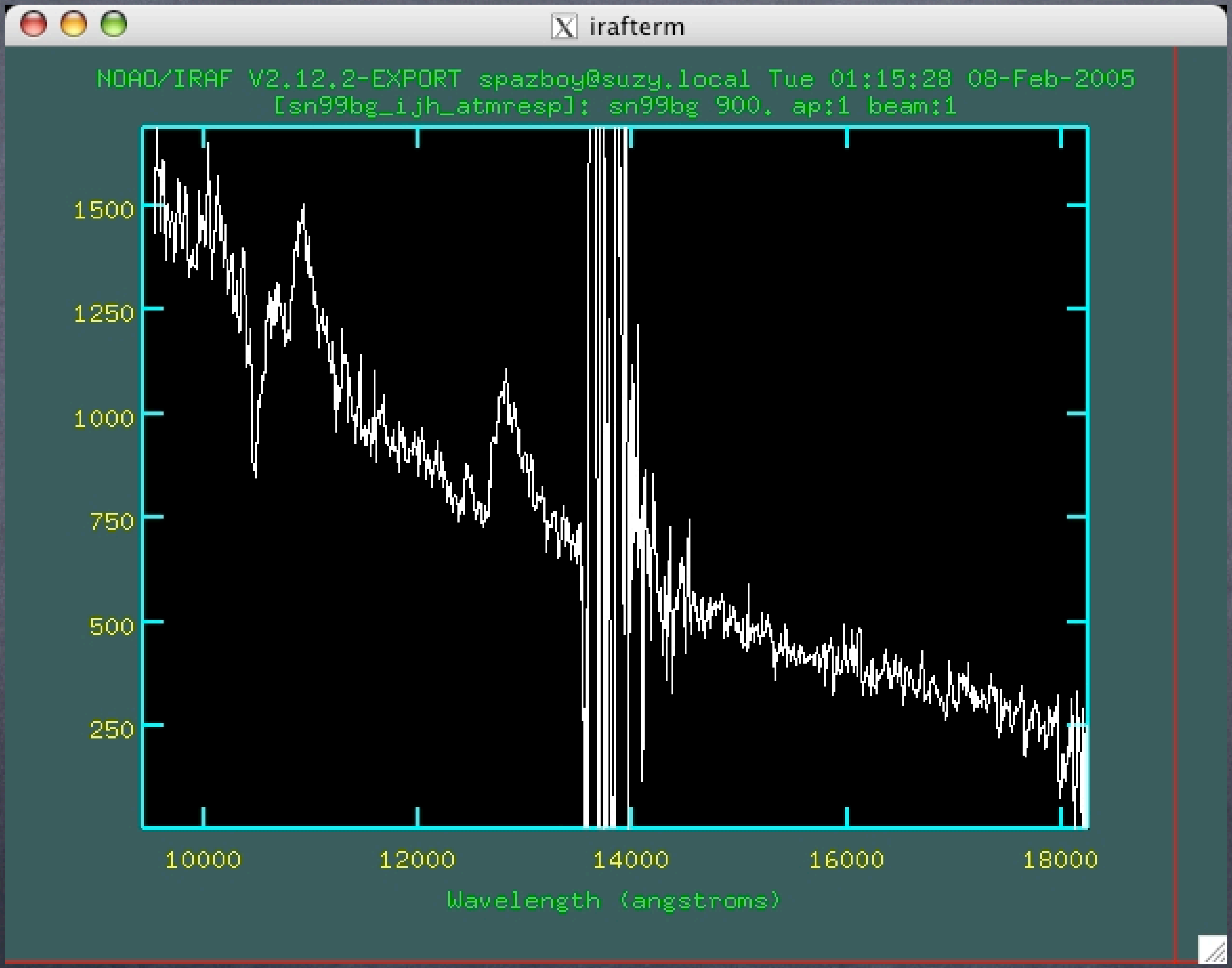
Divide out response

Final Stages Example



Divide by atmcor

Final Stages Example



Combine with other exposures

Merging orders/setups

- If data exist in multiple overlapping setups (or orders for x-disp).
  - Divide 1 overlapping spectrum by the other
    - Where ratio is flat, measure ratio
    - Where ratio diverges, trim
  - Multiply one spectrum by appropriate constant
  - Combine trimmed, normalized spectra
  - Check for artifacts, esp. at the edges of overlap

Fluxing IR Spectra

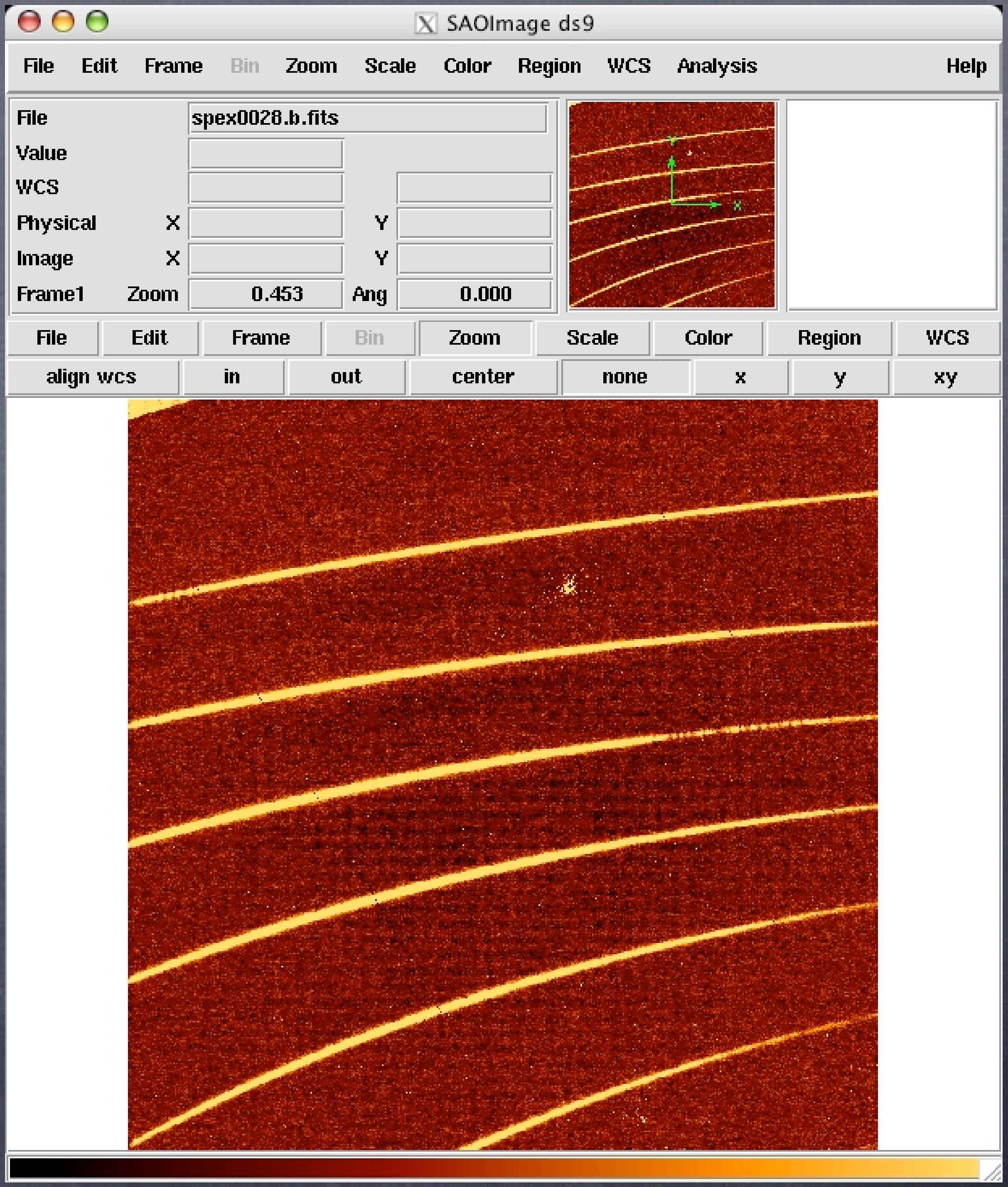
- No spectrophotometric standards
- Fluxing off the slit:
  - Use optical mag & type of telluric stds
  - Observe optical spec-phot stds & match at blue end of IR
  - Observe NIR phot stds.
  - Slit losses!   (Small slits keep out the sky!)

Fluxing IR Spectra

- Better: Flux with NIR photometry!
  - Use your imaging spectrograph!
  - $$\frac{N_{reduced}}{T} = \int_0^\infty f_{ast}(\lambda)\phi(\lambda)\eta(\lambda)\tau(\lambda)d\lambda$$
    $$= \alpha\int_0^\infty N_{ast}(\lambda)\phi(\lambda)\eta(\lambda)\tau(\lambda)d\lambda$$
  - Cross check with instrumental response, etc

Exotica: Cross dispersion

- Disperse weakly perp. to main dispersion axis
  - Orders don't overlap on chip... get them all at the same time!
- Curved spectra!
  - Tracing apertures is trickier
  - Telluric stds. can make good aperture guides... try to hit the same nod positions



Exotica: OH suppression

- The idea:
  - Disperse spectrum to high resolution, mask out OH emission, and converge beam back to low dispersion
  - Low-res spectrograph with the background of a high-res spectrograph
- The effect:
  - Can reduce the BG in J and H by 99% or more!
  - Long Exposures: BG limited in 2000s
  - Push a mag or two deeper below sky

Exotica: OH suppression

- Some issues:
  - O_2 and thermal not blocked
  - OH mask makes dropouts in spectrum.
    - Largely removed with telluric correction
    - Beware of interaction between unresolved lines and OH mask
    - Wave-cals can interact with mask.
  - Long Exposures... keep an eye on the tellurics

Final Thoughts

- Airmass Kills, Seeing Kills, Humidity Kills, Sky Brightness Kills…
- Using TS from other nights doesn't work well
- S/N highly wavelength dependent
- NS lines CAN make correlated noise features
- Coadds are your friend, (esp. imaging)
- ~~Grayscale~~ -> Orangescale
- Use wacky units
- Log plots are your friend