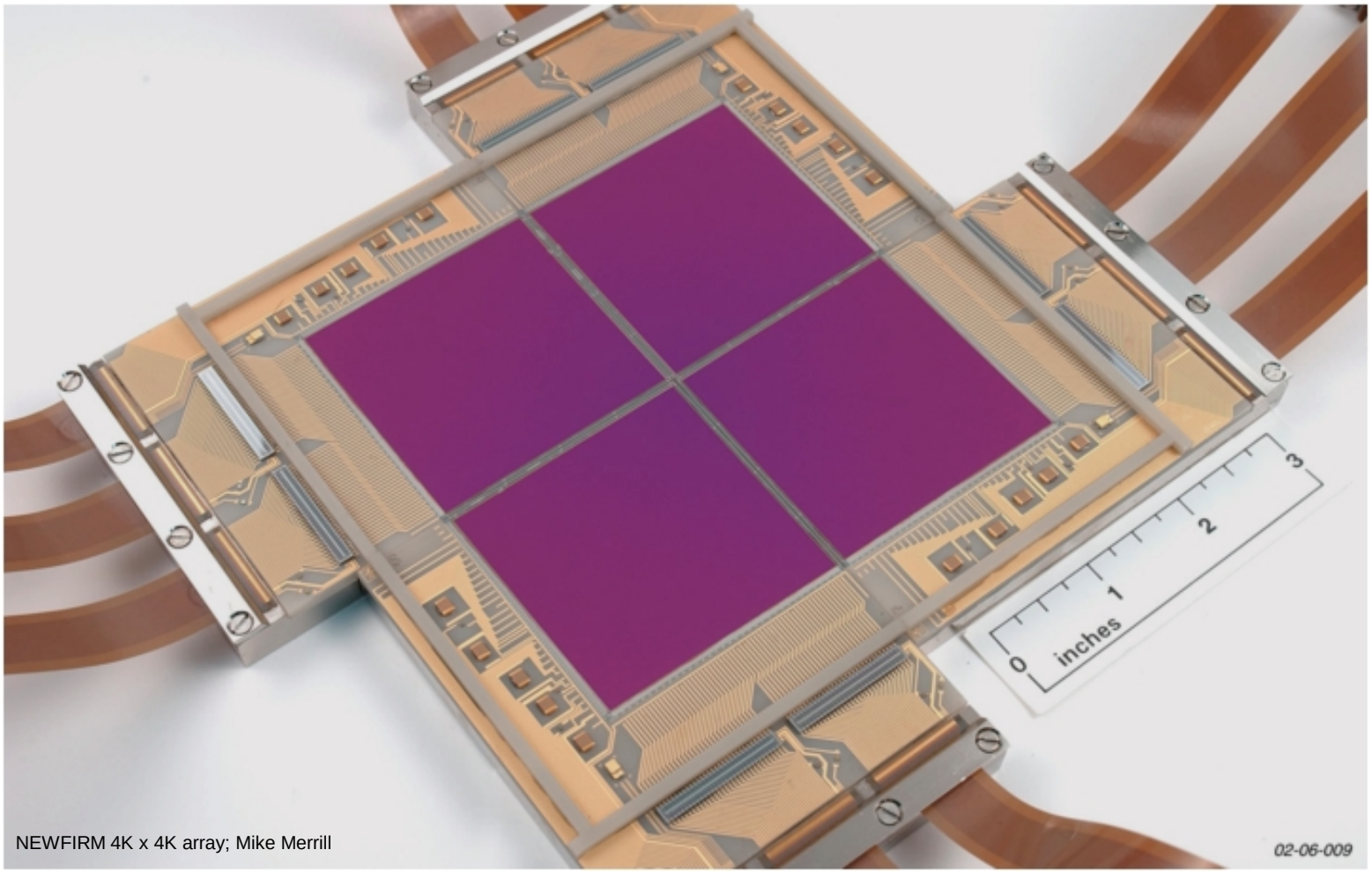
An Introduction to Infrared Detectors

Dick Joyce (NOAO)

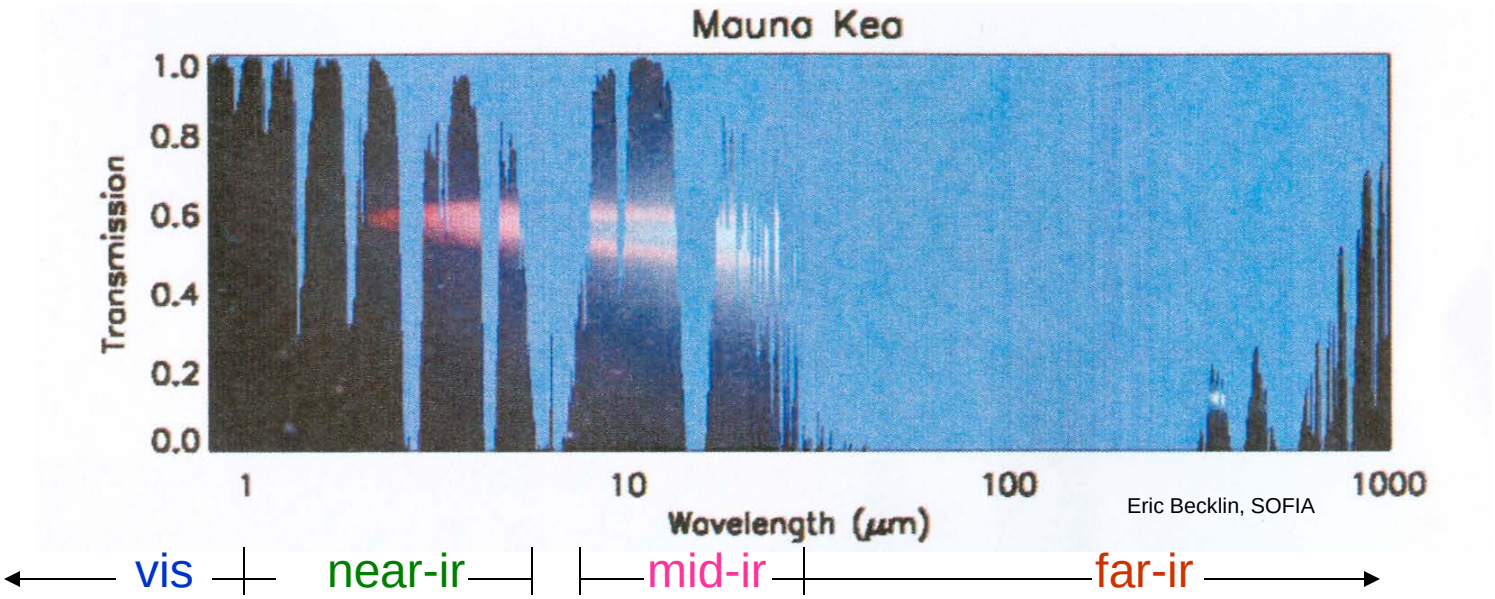


NEWFIRM 4K x 4K array; Mike Merrill

Most of you know all about CCDs…..

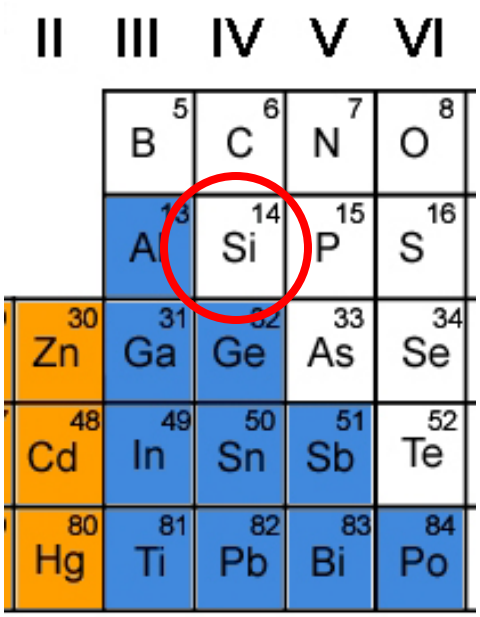
- Introduction to the infrared
- Physics of infrared detectors
- Detector architecture and operation
- Observing with infrared detectors
  - Forget what you know about CCDs….
  - Imaging and spectroscopy examples
- Observing Techniques and Data Reduction
- Additional “Features” of IR Detectors

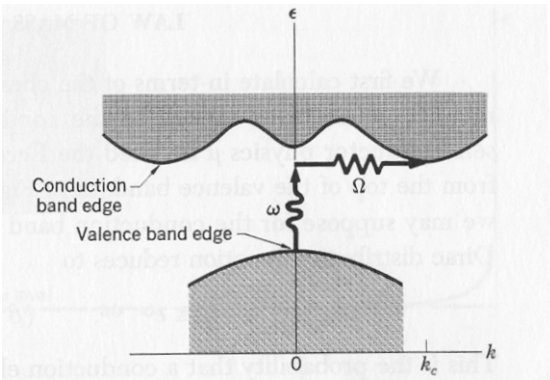
Define infrared by detectors/atmosphere



- “visible”: 0.3 – 1.0 μm; CCDs
- Near-IR: 1.0 – 5.2 μm; InSb, H_2O absorption
- Mid-IR : 8 – 25 μm; Si:As, H_2O absorption
- Far-IR: 25 – 1000 μm; airborne, space

CCD, IR Detectors: same physics

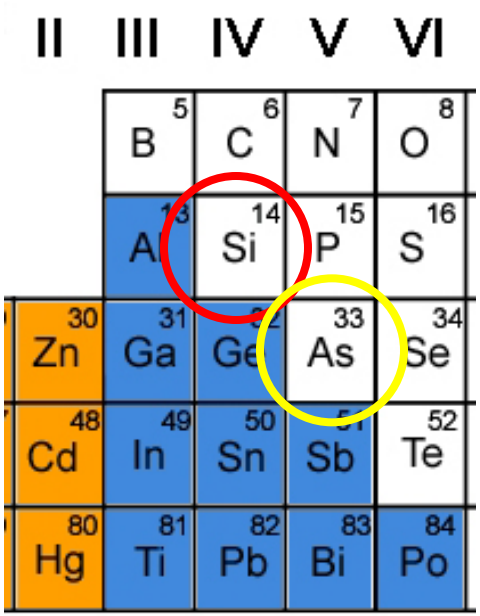




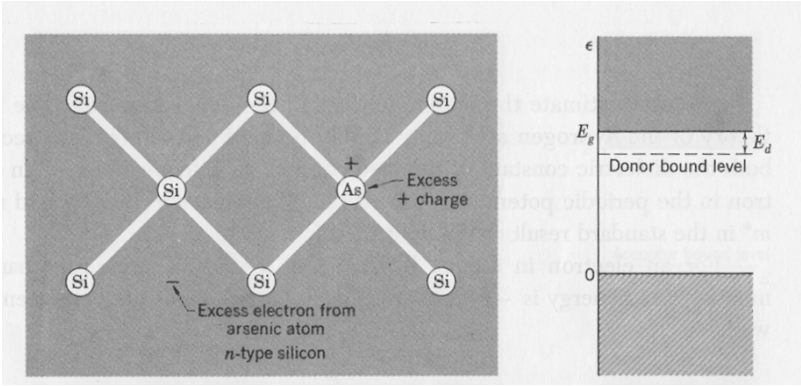
C. Kittel, *Intro. to Solid State Physics*

- Silicon is type IV element
- Electrons shared covalently in crystalline material
  - Acts as insulator
  - But electrons can be excited to conduction band with relatively small energy (1.0 eV = 1.24 μm), depending on temperature
- Internal photoelectric effect
- Collect electrons, read out

Extrinsic Photoconductor

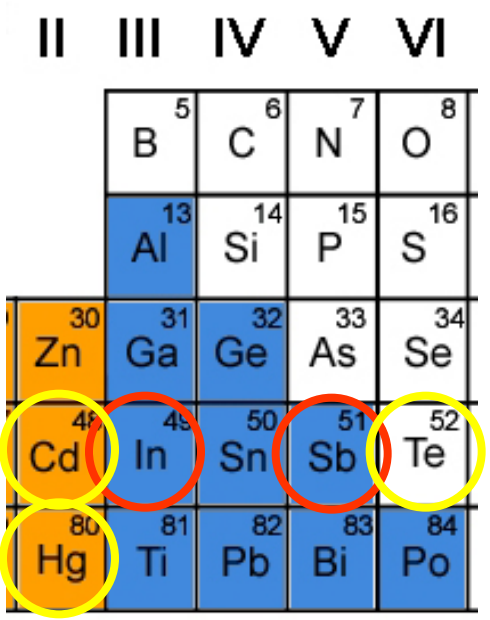


- Silicon is type IV element
- Add small amount of type V (As)
- Similar to H atom within Si crystal
  - Extra electron bound to As nucleus
  - Very small energy required for excitation (48 meV = 26 μm)
- Sensitive through mid-IR
  - Spitzer MIPS, WISE



C. Kittel, *Intro. to Solid State Physics*

Intermetallic Photoconductor



- Make Si-like compound
  - III-V (InSb, GaAs)
  - II-VI ($Hg_xCd_{1-x}Te$)
- Semiconductors like Si, but with different energy gap for photoexcitation
  - InSb 0.23 eV = 5.4 μm
  - HgCdTe 0.73 eV = 1.75 μm
    0.48 eV = 2.55 μm
    0.24 eV = 5.3 μm

(Hg/Cd ratio can change energy gap)

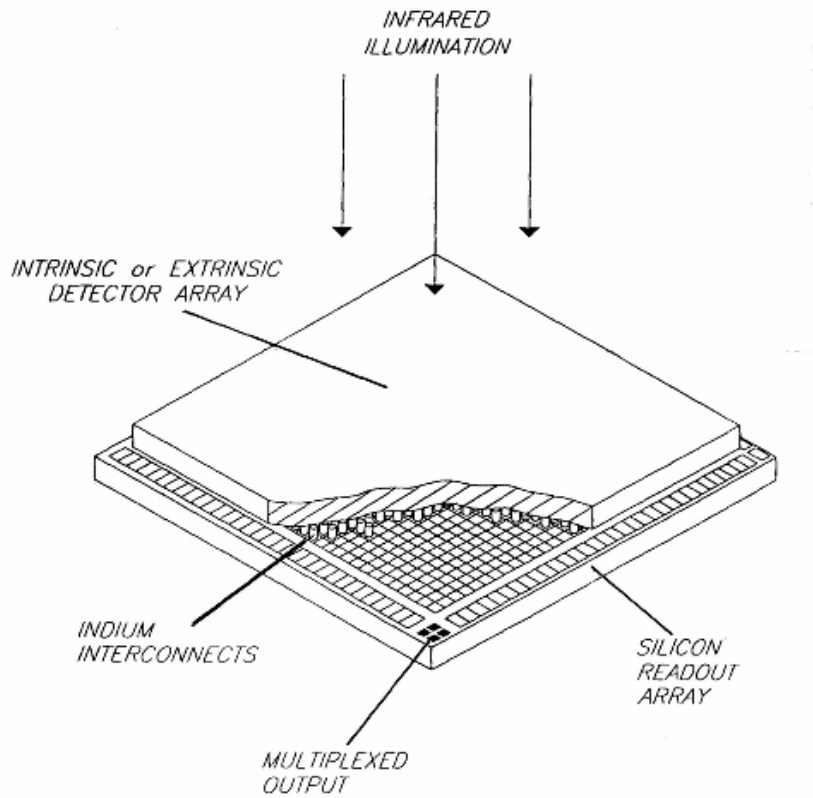
But, can excite electrons by other means……

The good, bad, and ~~ugly~~

- Good electrons, bad electrons
  - Electrons have thermal energy ~ kT, can be thermally excited into conduction band (dark current)
  - Solution is to operate detector at low temperature
    - Si CCD 0.3 – 1 μm 170 K GMOS
    - HgCdTe 0.5 – 2.5 μm 75 – 80 K NIFS, NICI, FLAMINGOS2
    - InSb 0.5 – 5.4 μm 30 K NIRI, GNIRS, PHOENIX
    - Si:As 5 – 28 μm 12 K TReCS, TEXES
- Good photons, bad photons
  - Only want photons coming through telescope
  - Eliminate thermal photons from surroundings
  - IR instrumentation, optics are in cold vacuum environment

Subject for separate presentation!

IR Detectors utilize different architecture

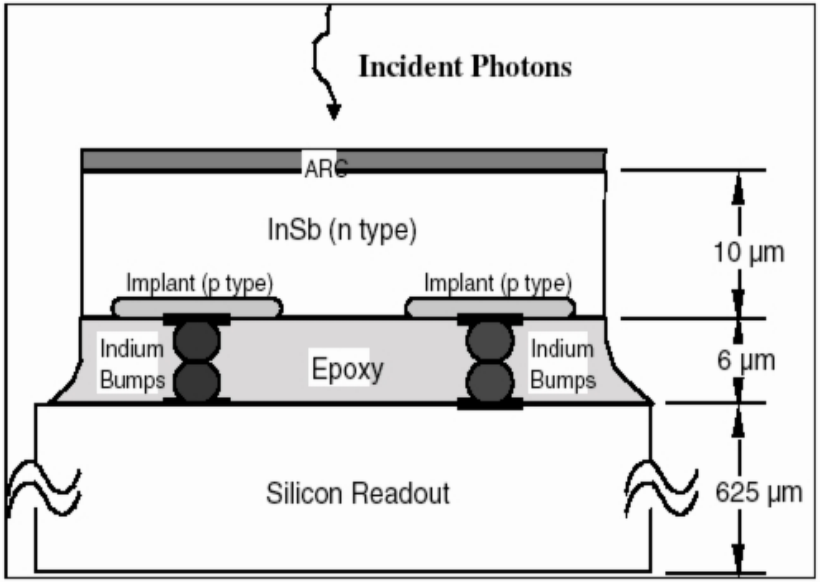


- CCDs are charge-transfer devices
  - Photoelectrons are collected, then read out by transfer from row to row
  - Attempts to make charge transfer devices from IR detector materials generally unsuccessful
- Solution is to separate photodetection and readout technologies
  - Silicon technology is very mature (1000s of man-years experience)

- Hybrid array: IR detector, Si readout makes use of best of each technology
- Detector and readout can be separately tested (improve yield)
- Same readout can be used with different IR detector materials

Hybrid array construction

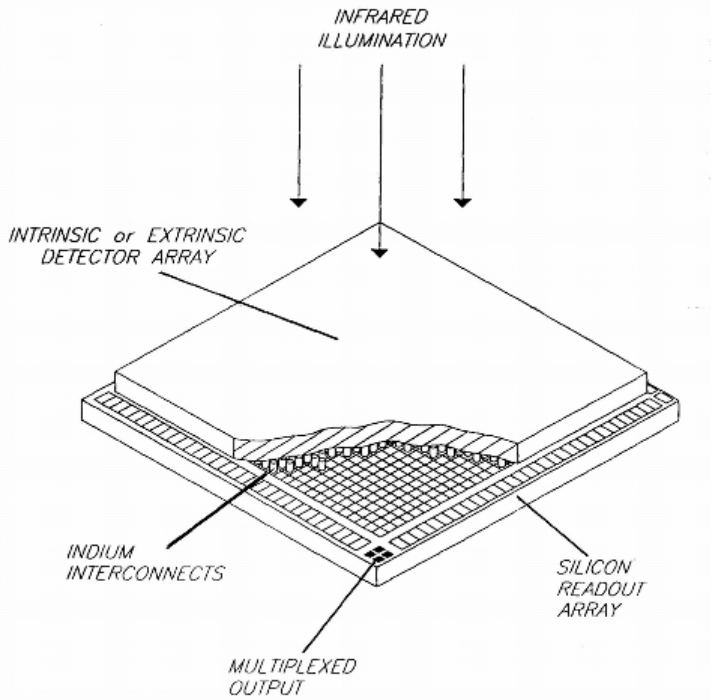
- IR detector array, Si readout separately fabricated and tested
- Indium bumps grown on each pixel of array and readout
- Two arrays are carefully aligned and pressed together – indium acts as electrical connection between detector material and readout
- Epoxy fill to support detector material
- Detector must be thinned to ~ 10 μm (backside illuminated)
  - Too thin, detector is transparent to photons
  - Too thick, photoelectrons recombine before making it to readout



- Apply antireflection coating on detector to optimize quantum efficiency (high index material)

Complex construction
Yield issues
$$!!

Hybrid architecture -- different readout

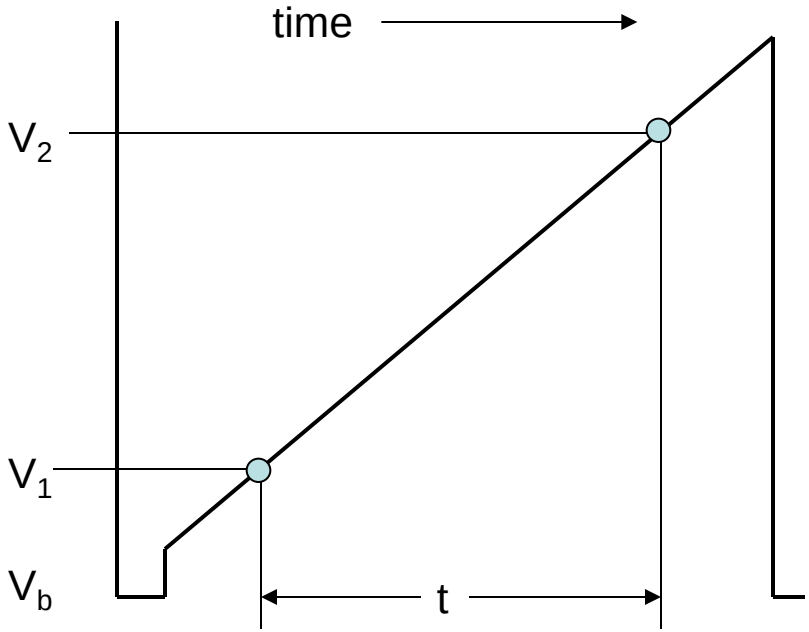


- Pixels utilize “unit cell” architecture
  - Separate readout amplifier for each pixel
- Addressed by row, column independently
  - No charge transfer, no charge transfer effects (charge trails, etc. ….)
  - Bad pixels are independent of others
- Readout is nondestructive
  - Address row/column enable, read voltage on pixel during an integration

Nondestructive readout makes it possible to read out a portion of the array or to read out the array multiple times

Nondestructive readout is versatile

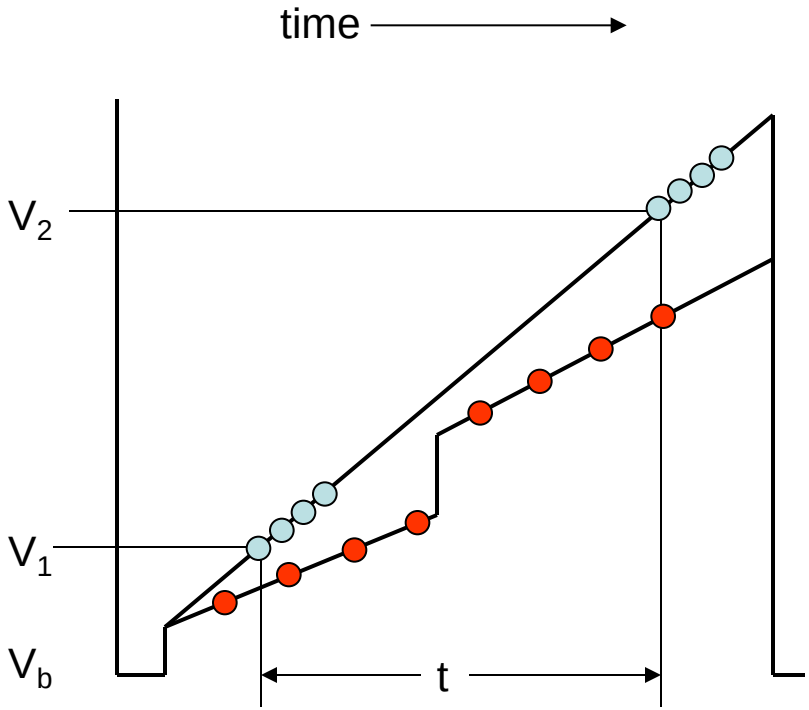
[Hypothetical voltage on a pixel as a function of time]



- Integration defined electronically (no shutter; ambient shutter gives background!)
- Initially, bias pixel to V_b
  - Creates potential well (capacitor)
  - Release, get jump (kTC jump)
  - Photoelectrons accumulate
- After bias, sample voltage V_1
- After time t, sample voltage V_2
- Subtract two readouts—difference is the final image

- Double Correlated Sampling (DCS) – removes bias
- But, minimum integration time is array readout time
  - Multiple readout amplifiers → readout time ~ seconds
- Two reads increases read noise by $\sqrt{2}$

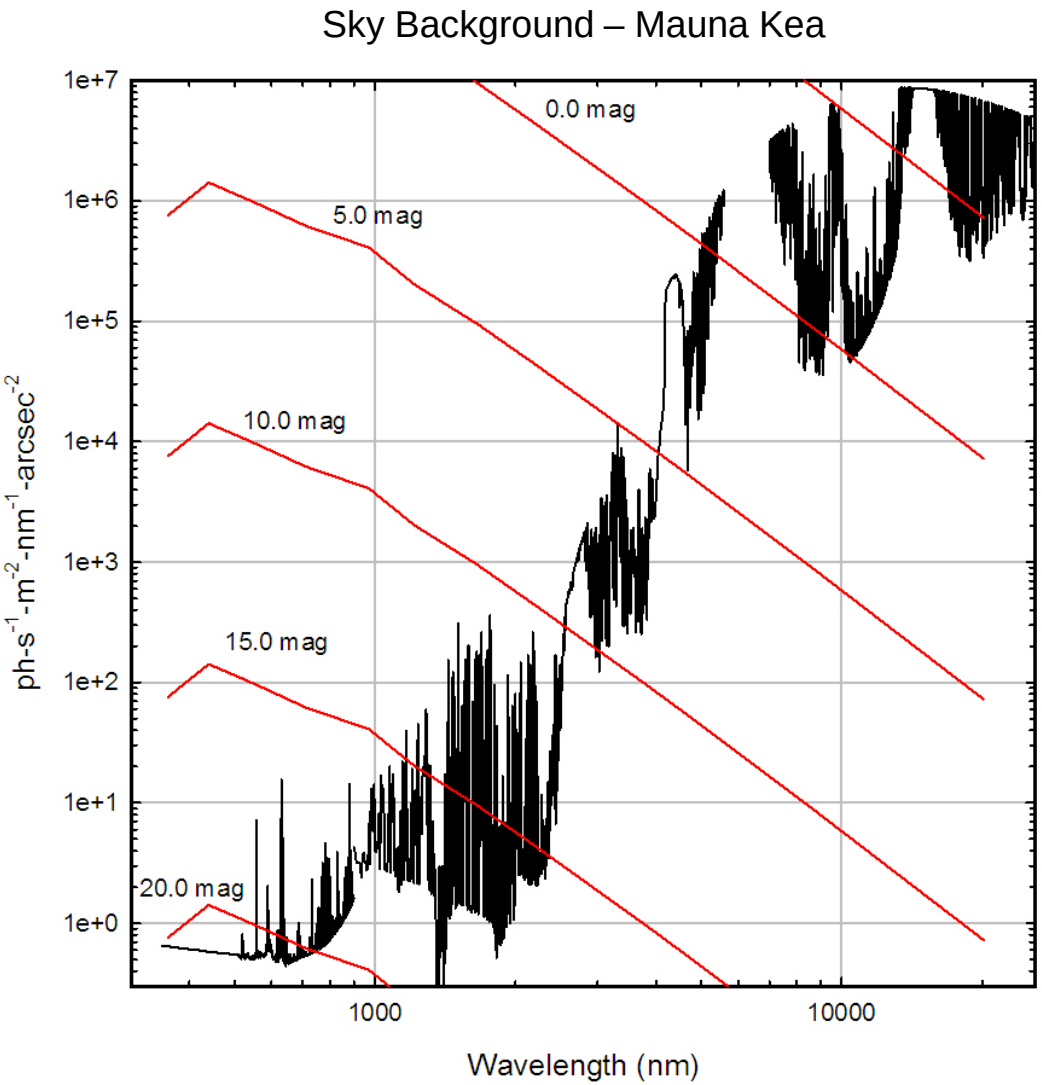
Nondestructive readout is versatile (2)



- IR arrays have higher read noise than CCD
  - 15 – 35 e vs 4-6 e
  - Higher capacitance
  - Surface channel readout
  - DCS readout
- Al Fowler (NOAO detector engineer) pioneered multiple readouts at beginning and end of readout cycle
  - “Fowler” sampling (LNRs)
  - Can reduce read noise by almost $N^{1/2}$
  - FLAMINGOS2 achieves 5 e with N=8

- Other readout mode is to sample during entire integration
  - Fit slope to samples, can achieve similar read noise reduction
  - More applicable to space instrumentation in removing discontinuities due to particle events

The good, bad, and ~~ugly~~ (continued)



- More bad photons come through the telescope
- Sky is very bright in IR, compared to visible
  - Moonlight not an issue > 1 μm
  - OH emission lines 0.8 – 2.3 μm
  - Thermal emission from telescope and atmosphere
- Even in K band, one wants to detect sources at 10^{-3} of sky (13 mag-arcsec^{-2})
- In mid-IR, sky is brighter than 0 mag-arcsec^{-2}

Counting up the Electrons…

Take an image; we actually measure voltages on the detector node.

$$V_{total} = V_{bias} + g*N_{dark} + g*\eta*N_{sky} + g*\eta*N_{source}$$

V_{bias} is the bias signal

N_{dark} is dark current electrons (detector, residual instrumental)

N_{sky} is the sky/telescope background signal electrons

N_{source} is the source signal electrons

g is the effective gain of a pixel (charge → volts → ADUs)

η is the quantum efficiency of a pixel (photons → electrons)

We want to get N_{source}

Counting up the Electrons…

$$V_{total} = V_{bias} + g*N_{dark} + g*\eta*N_{sky} + g*\eta*N_{source}$$

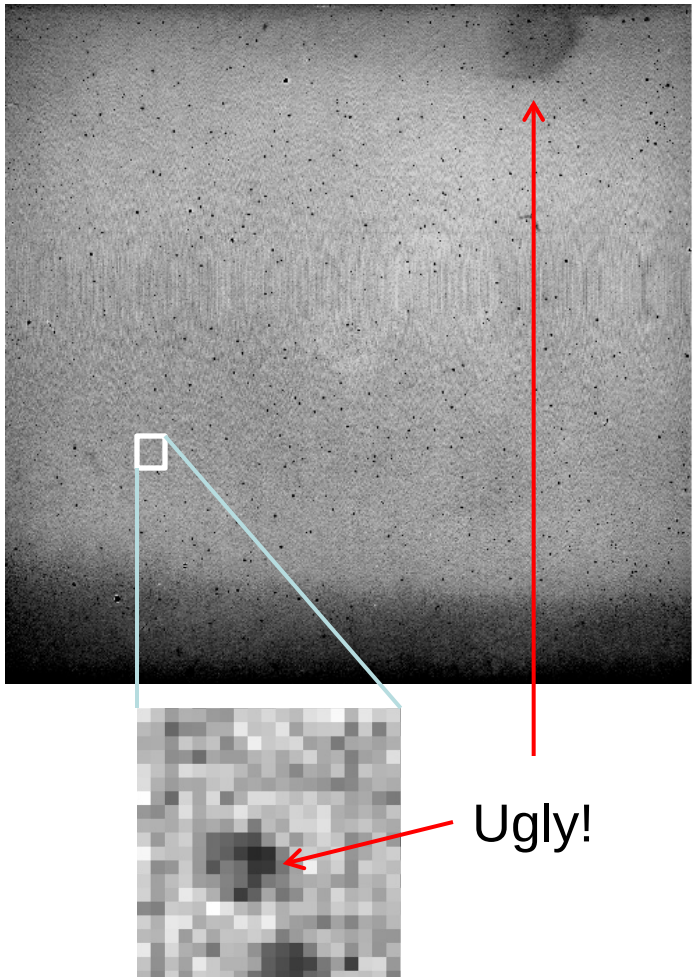
- V_{bias} is removed by double correlated sampling
- Take (multiple) dark images at same integration time as science observations, average, and subtract
- Divide by $g*\eta$
- Subtract constant N_{sky}

That's all there is to it!

All we need is to figure out $g*\eta$

Flatfielding

- Each pixel is independent, so g*η varies pixel-by-pixel
- “The only uniform CCD is a dead CCD” – Craig Mackay

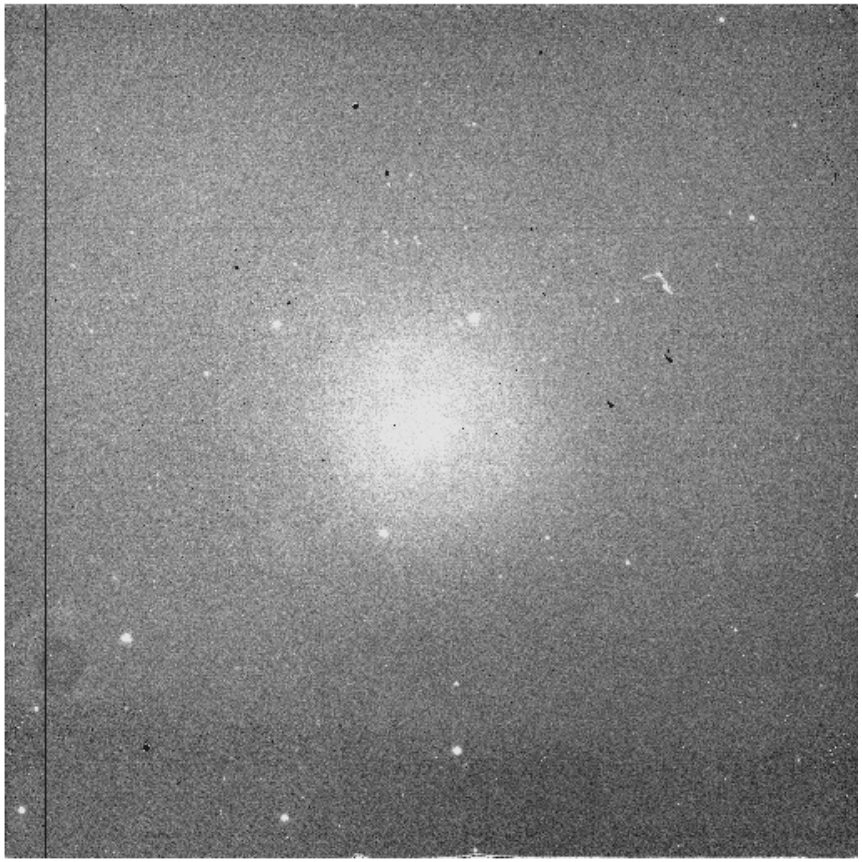


Generate a “flatfield” image

- Observe a uniformly illuminated target (dome screen, calibration screen)
  - Multiple images to improve statistics
  - Equal number with illumination off
  - Subtract (take out dark current, background)
  - Normalize to 1.0
- Can also use sky (more on that later)
  - Generate sky frame from multiple observations
  - Observe dark frames at same integration time
  - Subtract to remove dark current
  - Normalize to 1.0
- Wavelength dependent! Must do for each filter.

So let's give it a try……

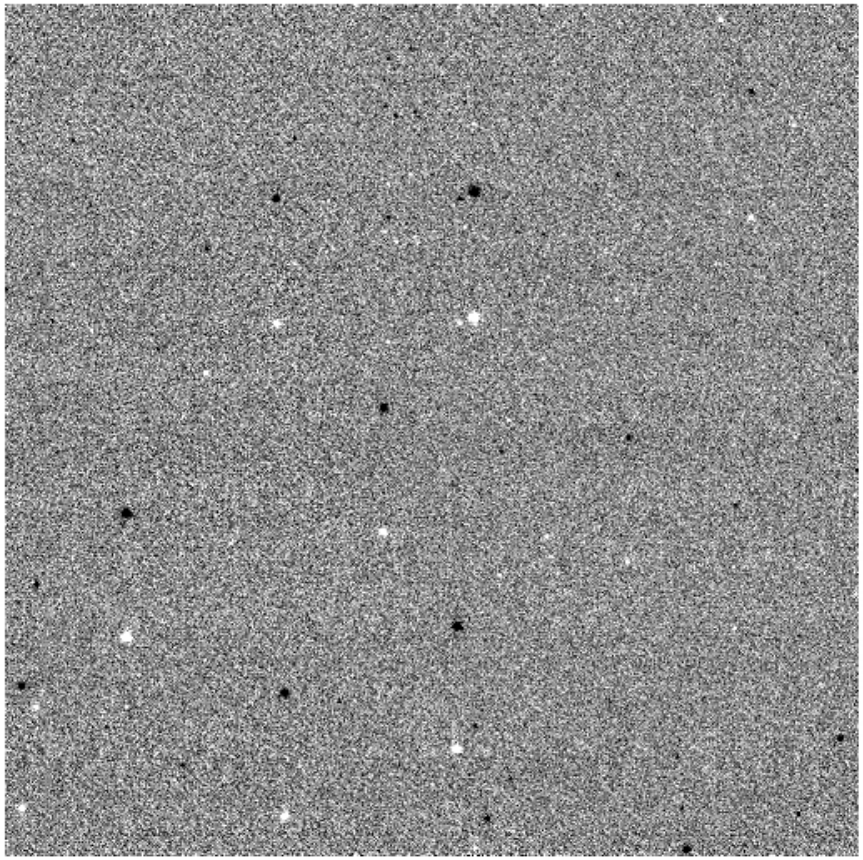
- Obtain science images
- Obtain calibration images
  - Dark frames at same integration time
  - Flatfield images of uniform target
- Subtract dark frame from science images
- Divide dark-subtracted images by flatfield
- → Image of science field with uniform sky level
- Subtract (constant) sky level from image
- But, here is what we get…..
  - Still pretty ugly!



Small flatfield errors on sky still larger than faint science targets

Since the sky is the problem…

- Subtract out the sky (or as much as possible) *before* the flatfield correction
- Obtain two images of field, move telescope between
- Subtract two images
  - Eliminate almost all sky signal
  - Subtracts out dark current, maverick pixels
- Divide by flatfield image
- Result has almost no sky structure

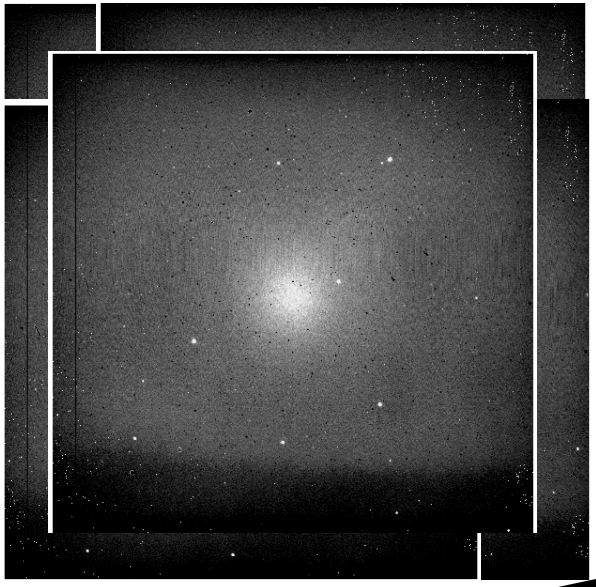


Subtracting sky minimizes effects of flatfield errors
(but noise increased by 1.4)

Typical sequence for IR imaging

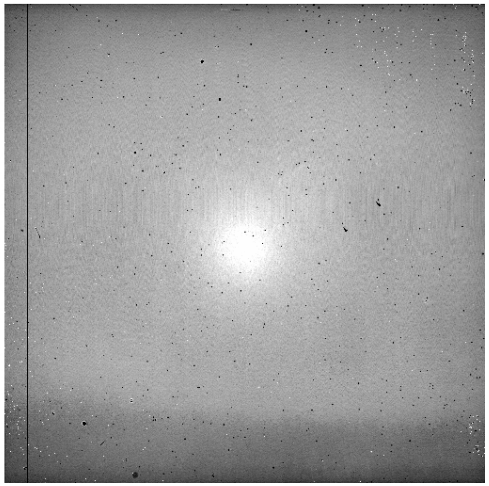
- Multiple observations of science field with small telescope motions in between (dithering)
  - Sky background limits integration time, so multiple images necessary anyway
  - Moving sources on detector samples sky on all pixels
  - Moving sources on detector avoids effects of bad/noisy pixels
- Combine observations using median filtering algorithm
  - Effectively removes stars from result→ sky image
  - Averaging reduces noise in sky image
- Subtract sky frame from each science frame → sky subtracted images
- Divide sky subtracted images by flatfield image
  - Dome flat using [lights on] – [lights off] to subtract background
  - Sky flat using [sky image] – [dark image] using same integration time
  - Twilight flats – need to be quick, since twilight is short at IR wavelengths
- Shift and combine flatfielded images
  - Use reference star common to all images to determine relative shifts
  - Rejection algorithm, bad pixel mask, or median can be used to eliminate bad pixels from final image

Here’s what it looks like….

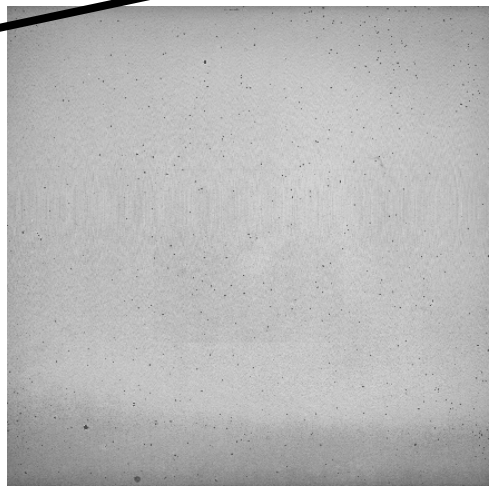


Median

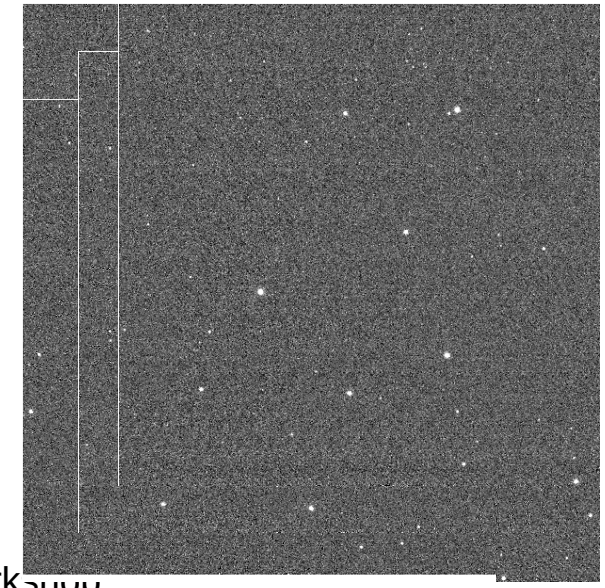
Sky frame



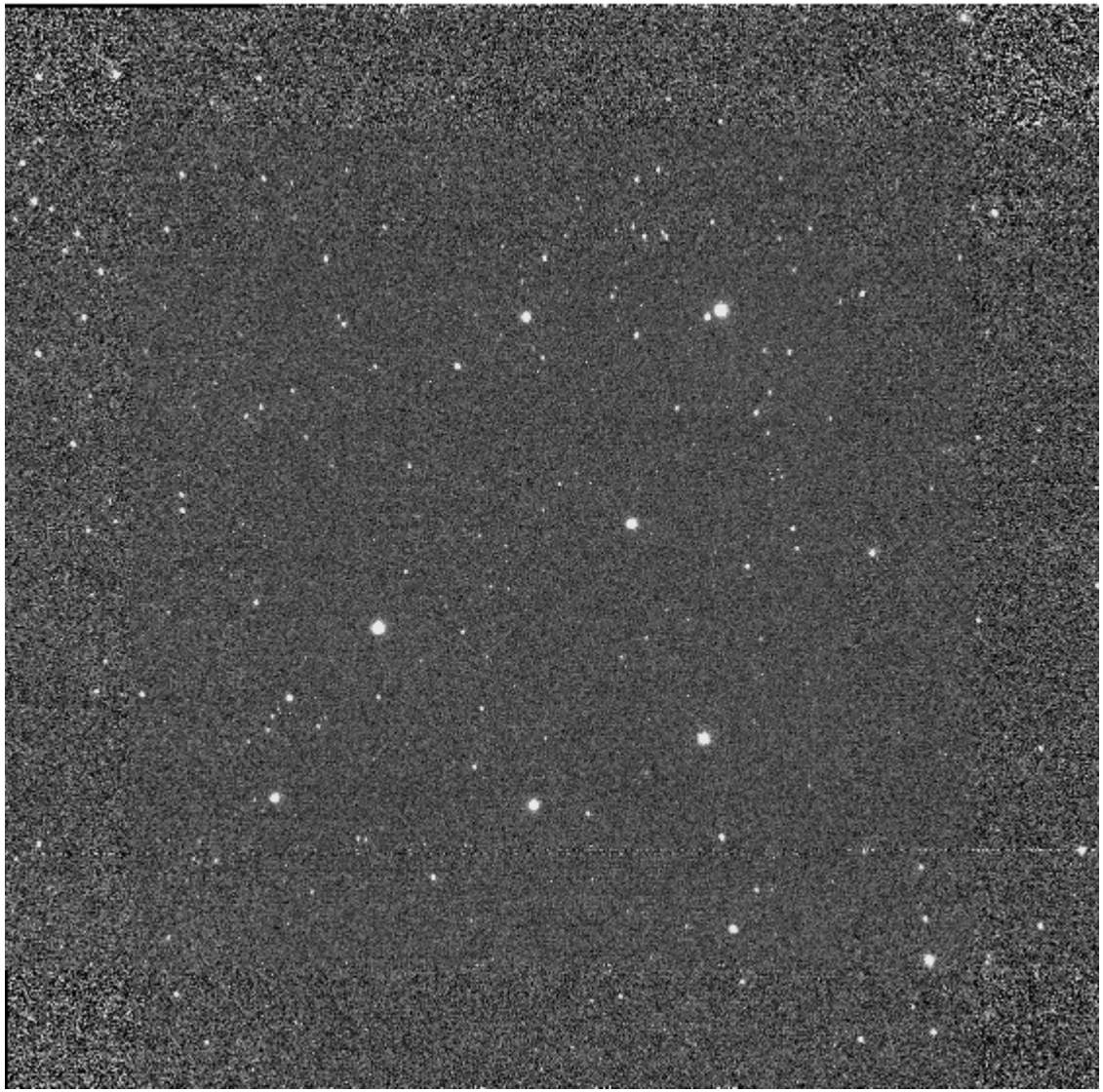
Subtract sky,
divide each by



Flatfield



Shift and combine images



- NGC 7790, Ks filter
- 3 x 3 grid
- 50 arcsec dither offset

Bad pixels eliminated
From combined image

Higher noise in corners than in center (fewer combined images)

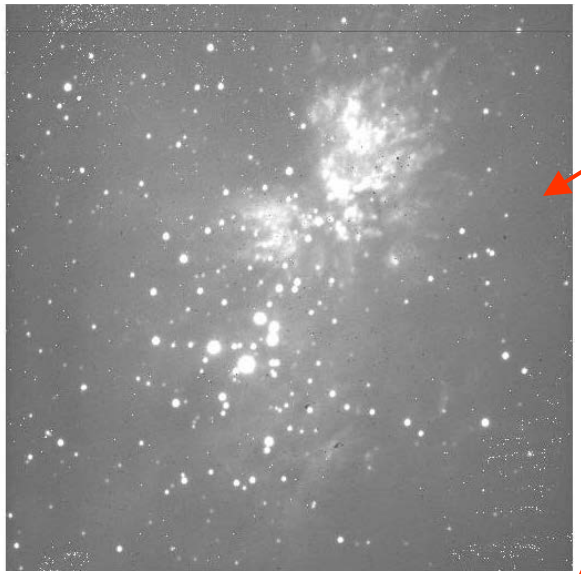
This works fine in sparse fields, but what about crowded fields, extended targets?

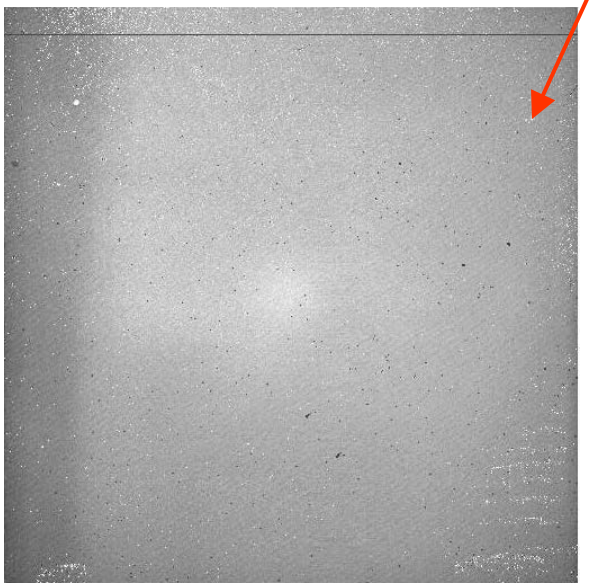
- In addition to dithered observations of science field (still necessary for sampling good pixels), it is necessary to obtain dithered observations of a nearby sparse field to generate a sky image.
- Requires additional observing overhead, but this is the only way to obtain proper sky subtraction

"And if you try to cheat, and don't take the proper number of sky frames, then you get what you deserve"

--Marcia Rieke

An example: M42



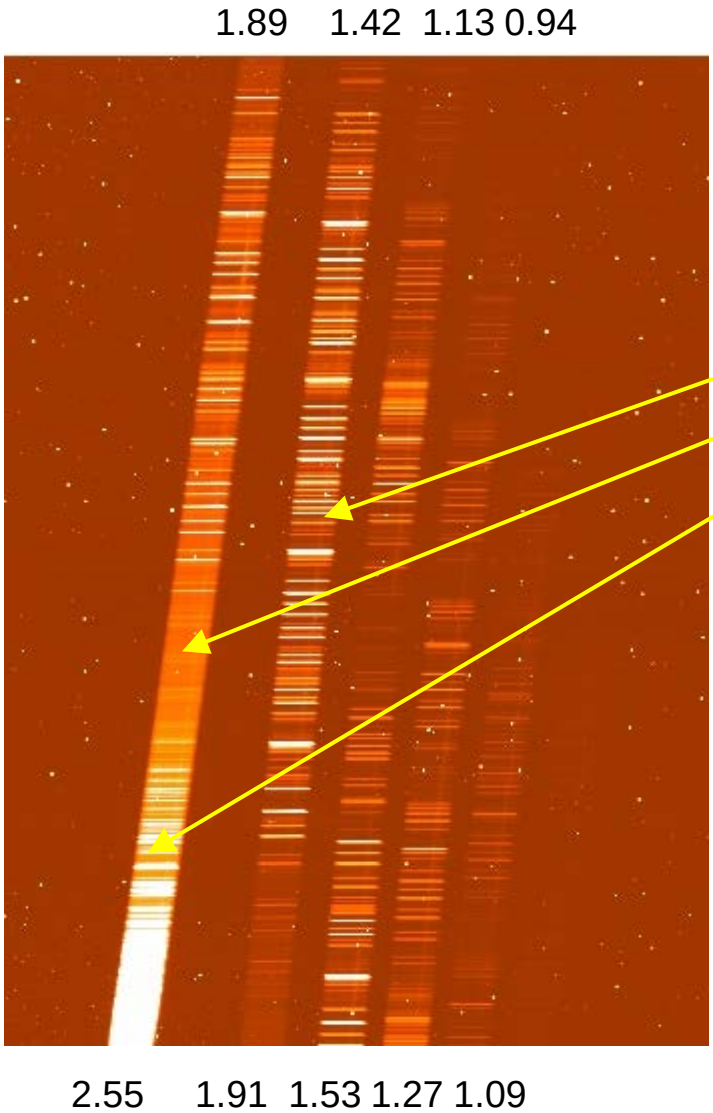


Raw image in narrowband H_2 filter

Off-source sky frame

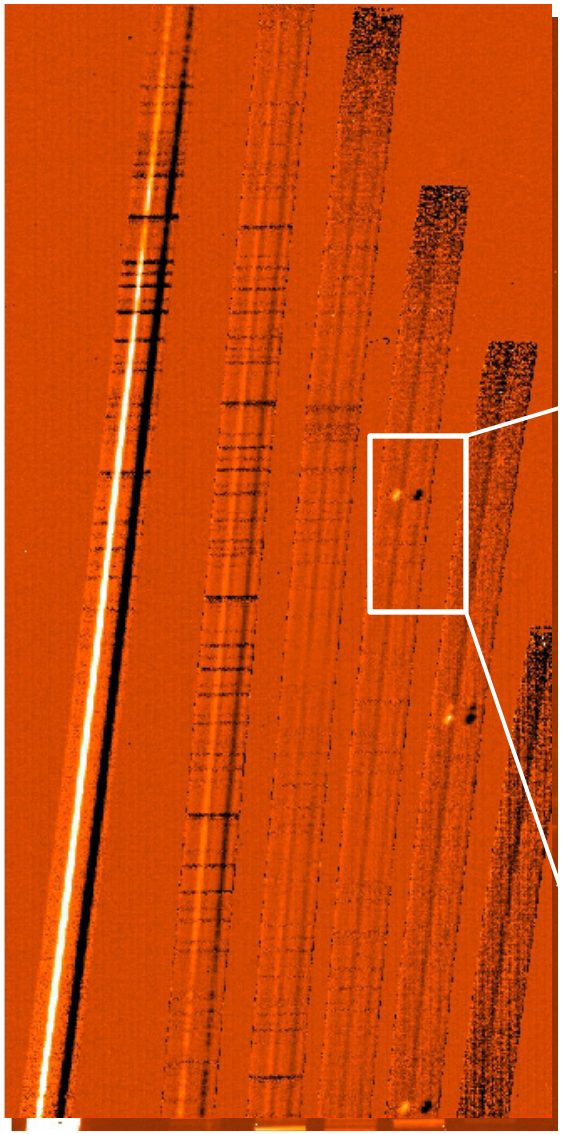
Sky-subtracted, flatfielded image

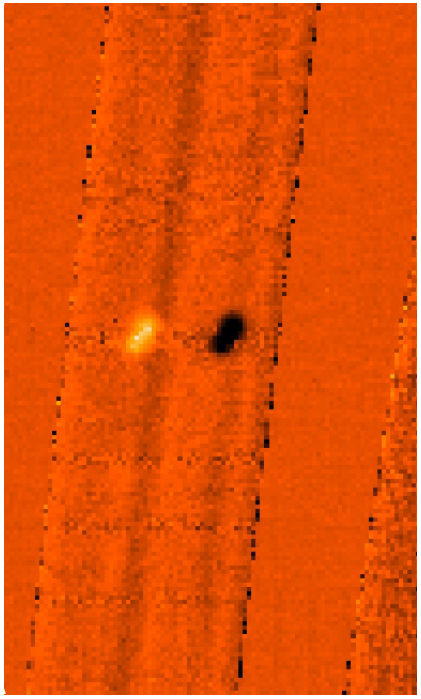
Spectroscopy uses similar strategy



- Example: GNIRS spectrum
  - R ~ 2000, cross-dispersed
  - 0.7 – 2.5 μm in six orders
- Strong, wavelength-dependent sky
  - OH emission lines 0.8 – 2.3 μm
  - Thermal continuum 2.0 + μm
  - Atmospheric absorption > 2.3 μm shows up as emission in thermal
- Need to subtract out sky

Subtract sky by dithering along slit





- Initial 600s exposure
- Move target 4 arcsec along slit, expose
- Subtract
- Eliminates most of sky lines
  - OH emission time variable
  - Remove residual sky using software
  - Additional noise in OH lines

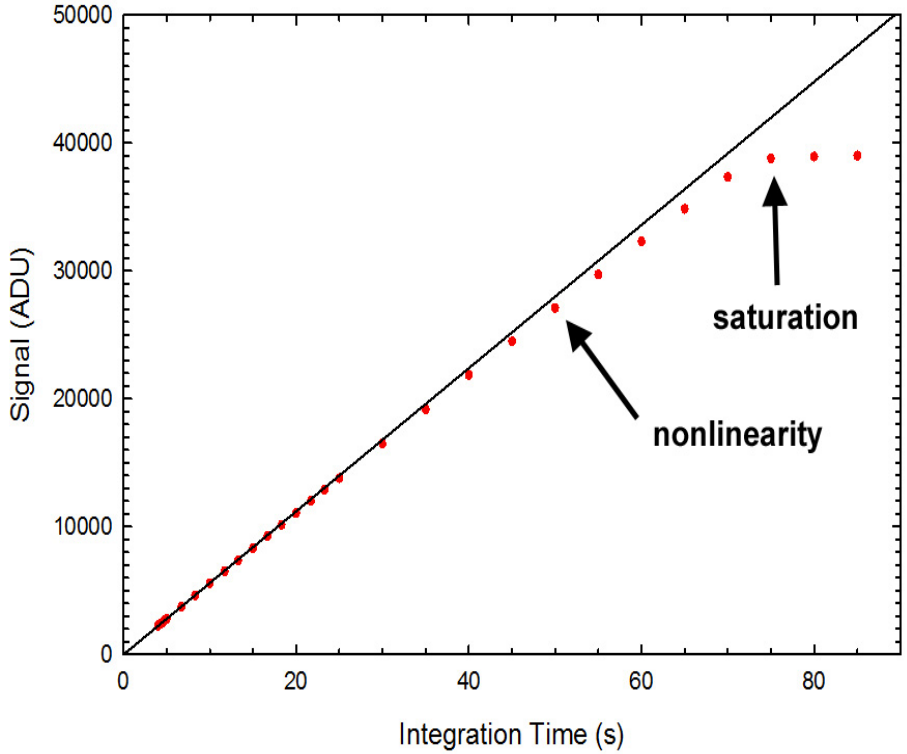
Rachel will explain how!

Additional “Features” to Consider

- Issues pretty much common to all IR arrays:
  - Nonlinear response
  - Bad pixels
  - Geometric field distortion
  - Pupil Ghosts
  - Fringing
  - Image Persistence
  - “Phobos” or “tachyon” events
- Some of these can often treated silently as part of any scripted data reduction process.
- Some are unavoidable, but can be alleviated by observing strategy.

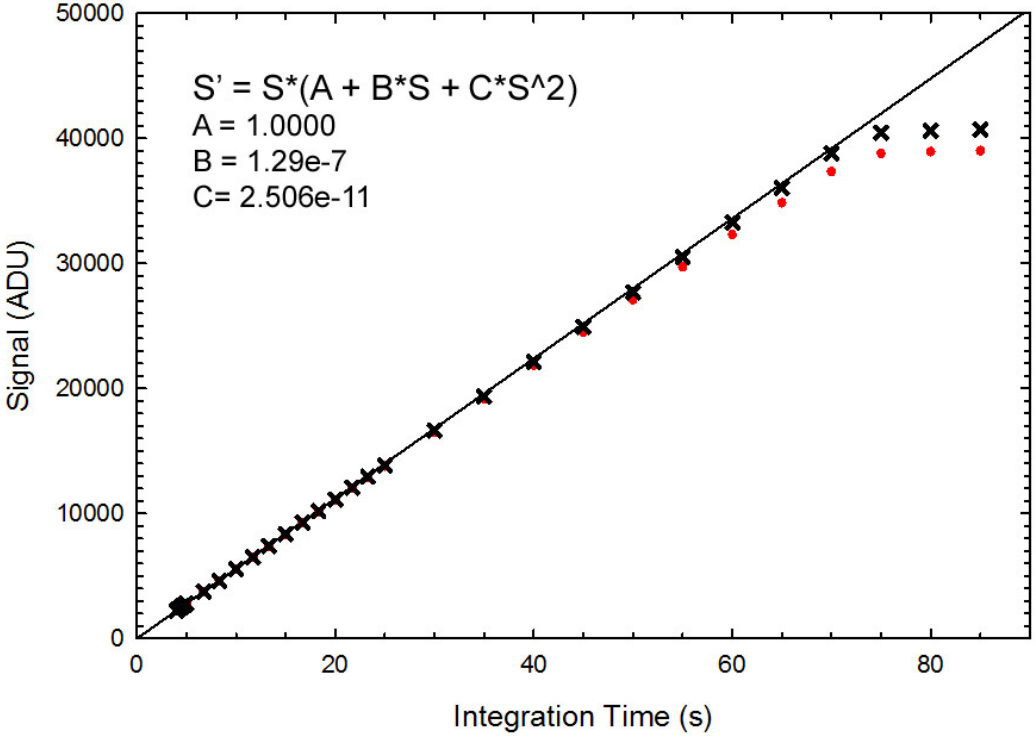
Detector Nonlinearity

- Biasing a detector pixel creates a potential well, essentially a capacitor, on which charge is collected
- As potential well fills up, capacitance increases, so measured voltage/charge relation on unit-cell readout changes [V= q/C(V)]
- More charge required for ΔV → sublinear response



Nonlinearity typically ~ 1% at 50% full well, ~3% at 85% full well, but will depend on the array and bias voltage

Detector Nonlinearity (2)

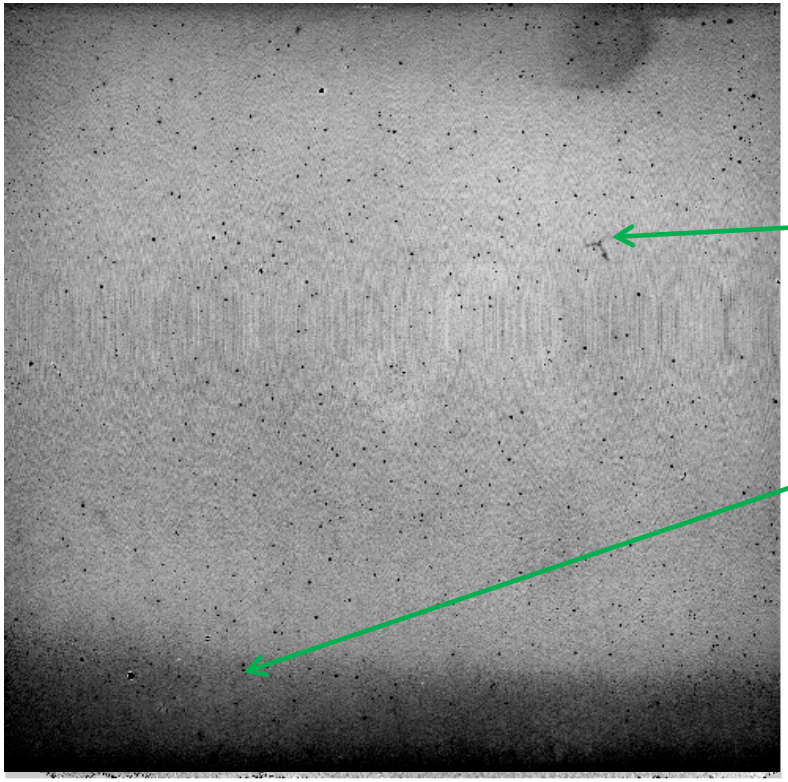


- Nonlinearity can be fit fairly well by quadratic function
- Generally can correct linearity to better than 1% to 85% of full well
- Must correct raw data!

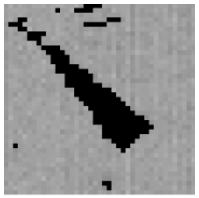
If possible, strategy is to avoid linearity issues by staying below 50% full well while observing

Array Defects

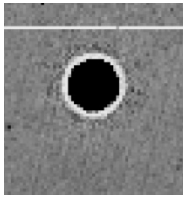
- In addition to sensitivity variations (cf. flatfielding), arrays are generally far from pristine.
- Hybridizing, thinning, A/R coating, thermal stress……



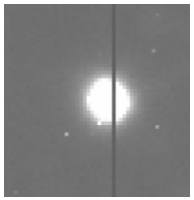
Cracks!
No contact (during hybridizing)



Arrowhead (dig)

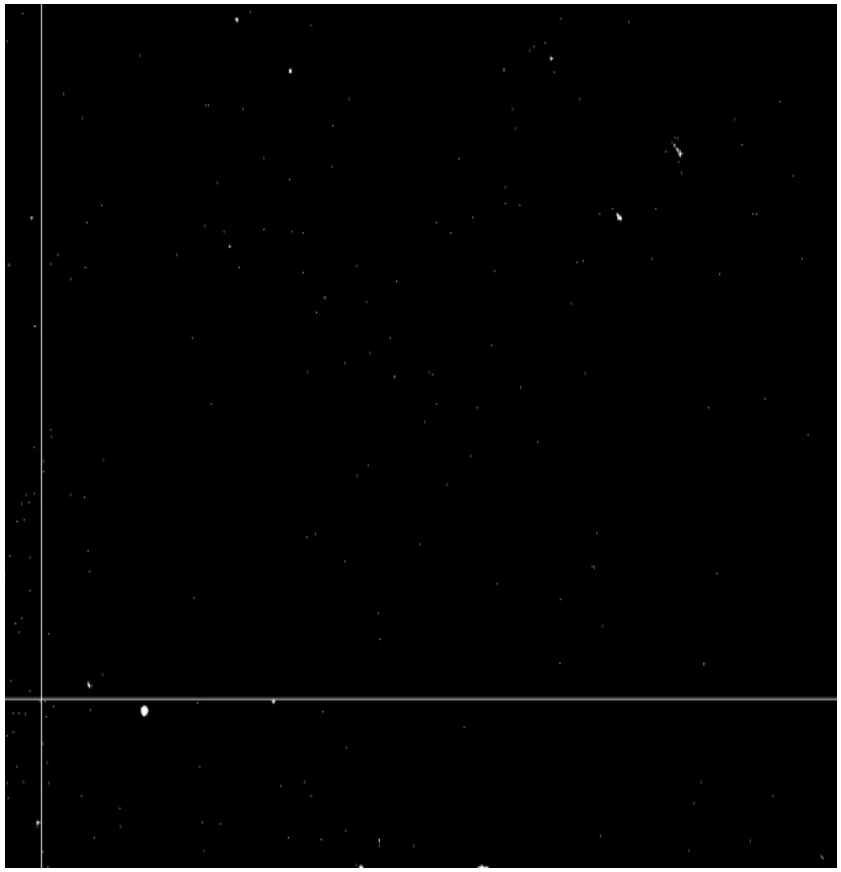


Dead Row
Photoemitting Defect



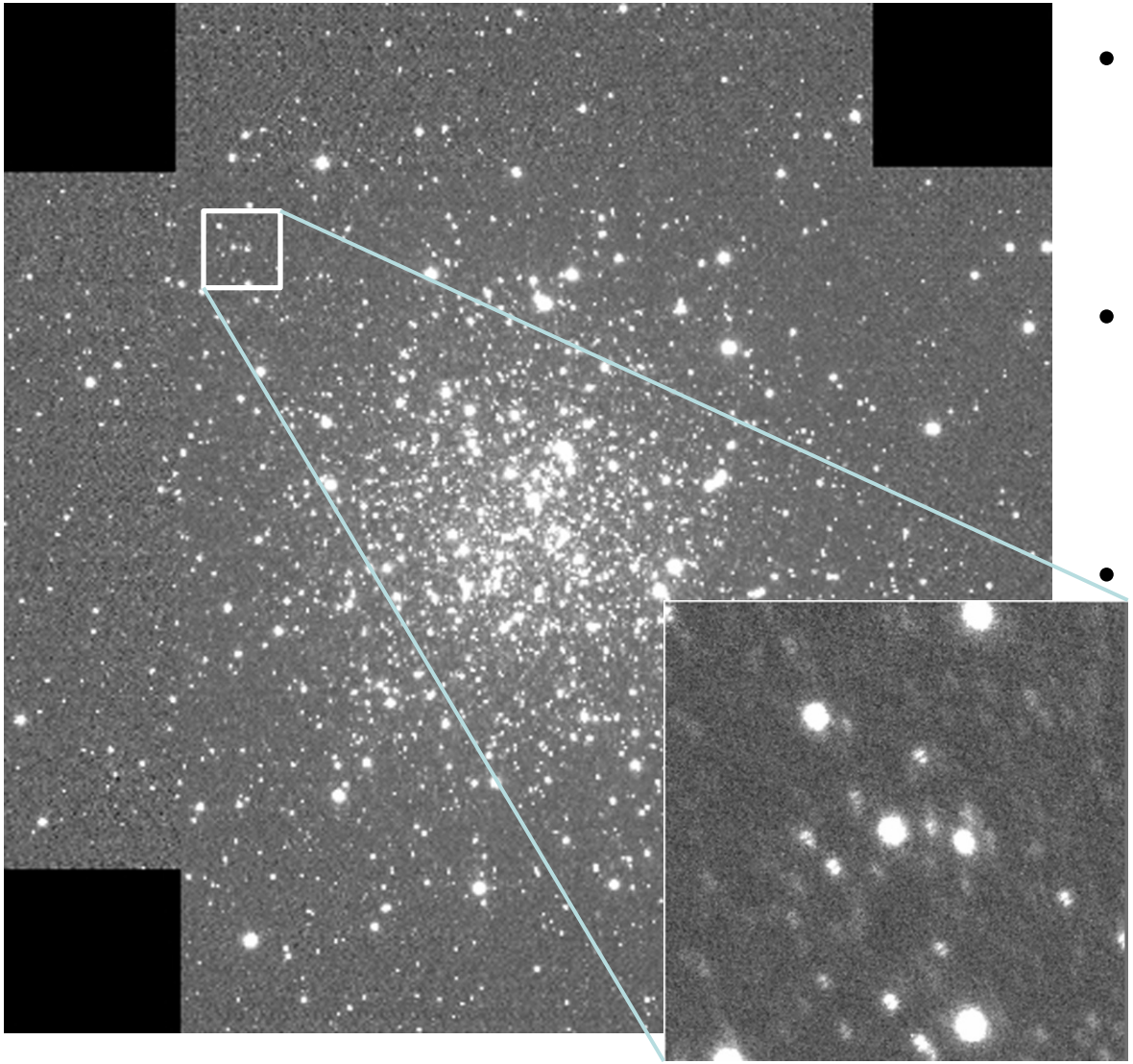
Dead Column
through star
Help!

Bad Pixels Masked Out



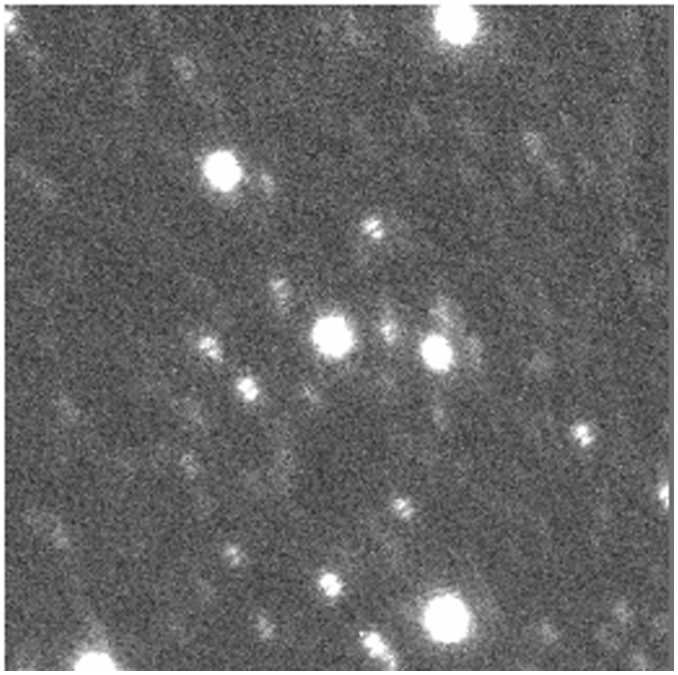
- Generate “bad pixel mask”
- Ratio flats at different integration times, reject those which differ from expected value
- Good pixels = 0, bad = 1
- ‘fixpix’ task will replace masked pixels with average of surrounding
- Can also use other rejection techniques when combining images (avsigclip, minmax)

Field Distortion

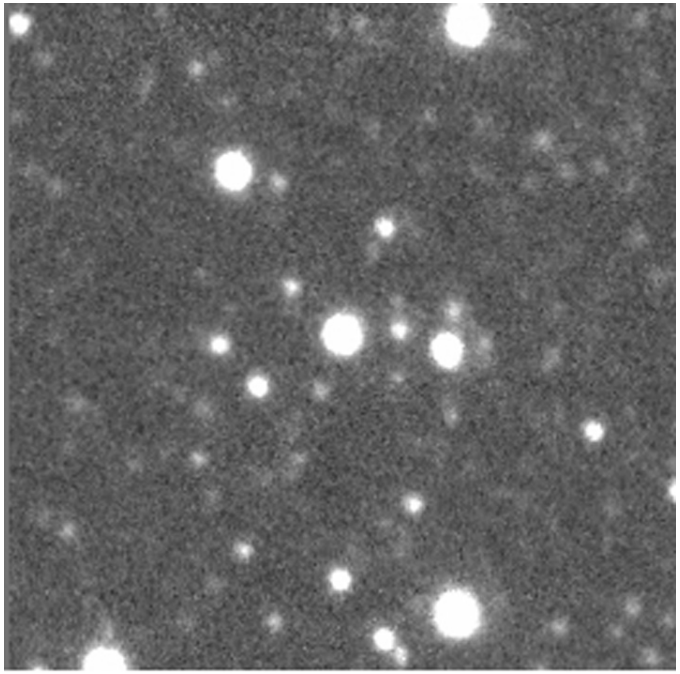


- Telescope focal surfaces are generally not flat, whereas detectors are
- Field reduction and flattening optics generally result in some field distortion
- This leads to poor registration of images when generating maps or combining many dithered images

Field Distortion



- Tasks such as IRAF ‘geomap’ can be used to map distortion from astrometric field
- ZEMAX analysis of optical system can be used as input to ‘geomap’.
- Task ‘geotran’ will correct distortion

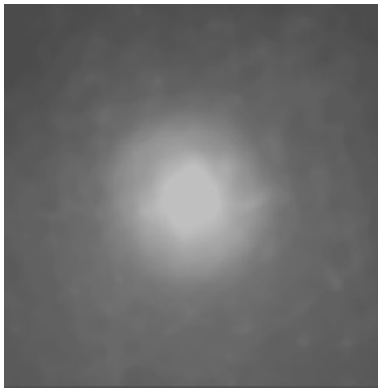


Pupil Ghosting

- Internal reflections within on-axis refractive optics can result in a ghost image from the sky background (pupil ghost)
- May be image of the exit pupil (donut) or central peak
- The pupil ghost will subtract out with sky subtraction, but will appear in the flatfield
- IRAF task ‘rmpupil’ fits a template of the ghost to the observed feature and subtracts it

Pupil Ghost Removal

Template



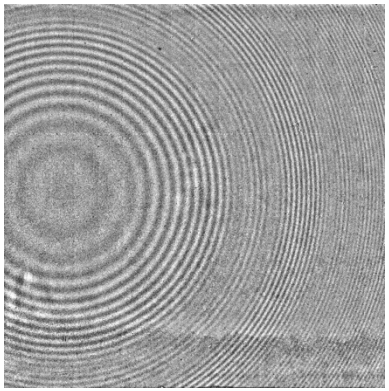
'rmpupil'

Fringing

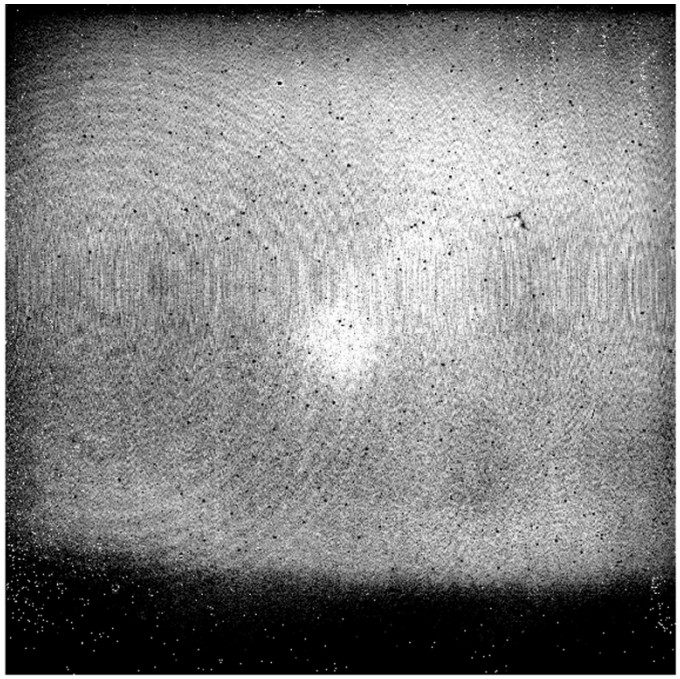
- In both CCDs and IR arrays, the detector becomes transparent near its long wavelength response limit
- Sky emission lines can produce Fabry-Perot like interference fringes in the image
- Interference fringes can also be produced between parallel surfaces within the instrument optics.
- As with pupil ghosting, solution is to create a template which can be fit to the fringe pattern for subtraction (IRAF task ‘rmfringe’)

OH H-band Fringe Removal

Template



‘rmfringe’
+ ‘rmpupil’



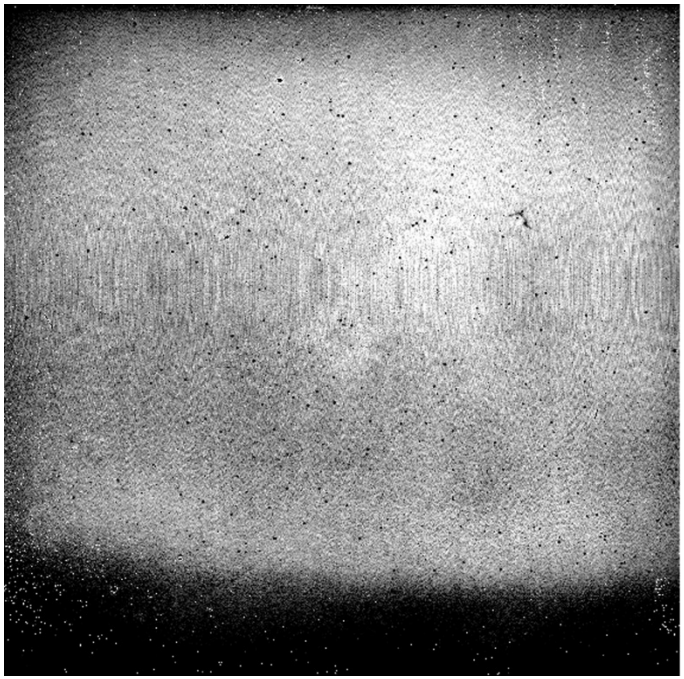


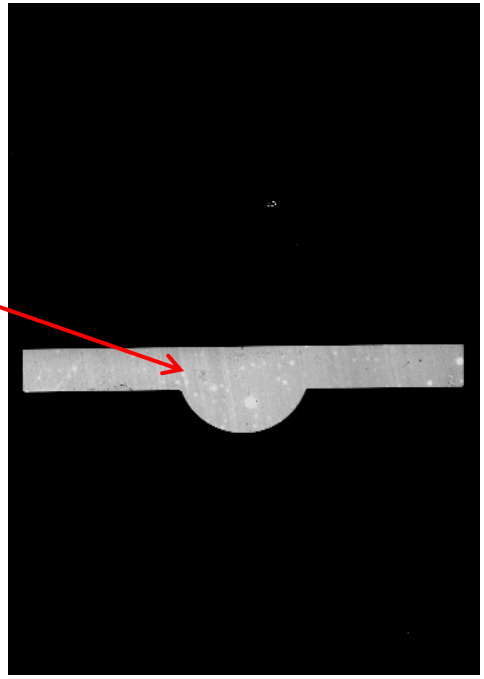
Image Persistence

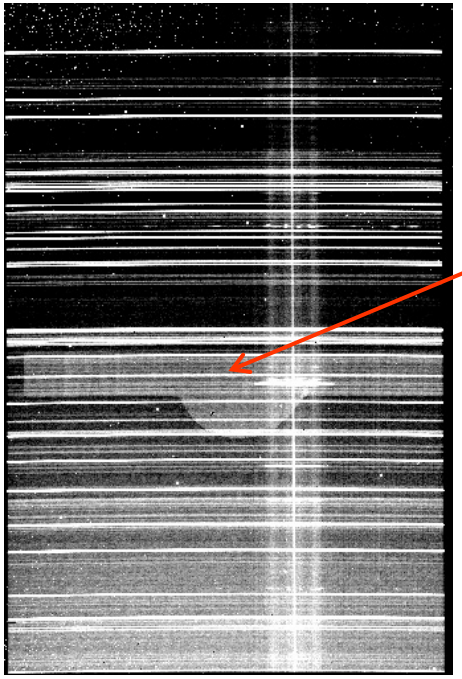
- Long-exposures under low background following an exposure at a high flux level can show an “afterimage” of the previous exposure.
  - Afterimage can persist for multiple images, with long decay time
- Physical cause seems to be ‘traps’ generated by high flux levels, which decay slowly, creating elevated dark current.
  - Generally, but not always, a feature of older detector arrays, particularly InSb
  - Effect appears to be significantly reduced in recent generation HgCdTe arrays
  - Anecdotal evidence that persistence is less evident when detector is maintained in high vacuum for long periods (mythology?)

Image Persistence (2)

- Effect can be annoying and make data reduction difficult
- Example: GNIRS spectrum following acquisition of target shows afterimage of acquisition field.

Acquisition field



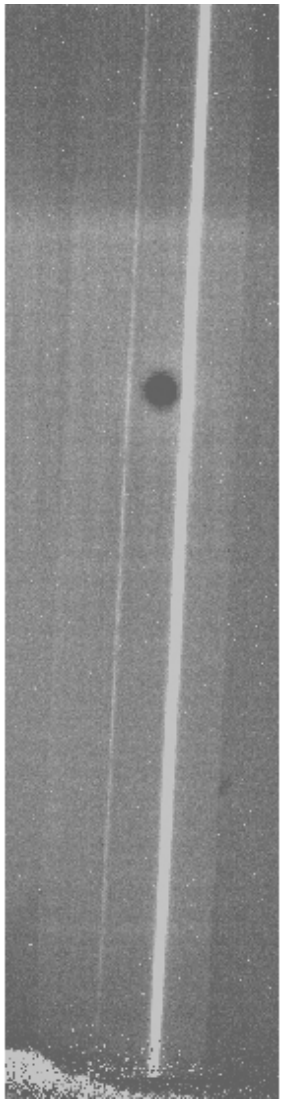


Afterimage of acquisition field in spectral image

Image Persistence (3)

- Much mythology associated with minimizing this effect
  - Frequent readout during ‘idle’ time between exposures
  - Taking short ‘junk frames’ between acquisition and science images
  - These seem to be of limited utility
- Best approach is to minimize or avoid the effect through observing strategy
  - In instruments which use the same array for acquisition and science images, utilize narrowband filters for acquisition and keep signal levels well below full well
  - For spectroscopy, use different dither offsets from the nominal target position for bright telluric standard and faint science exposures to avoid persistence from the telluric spectra.

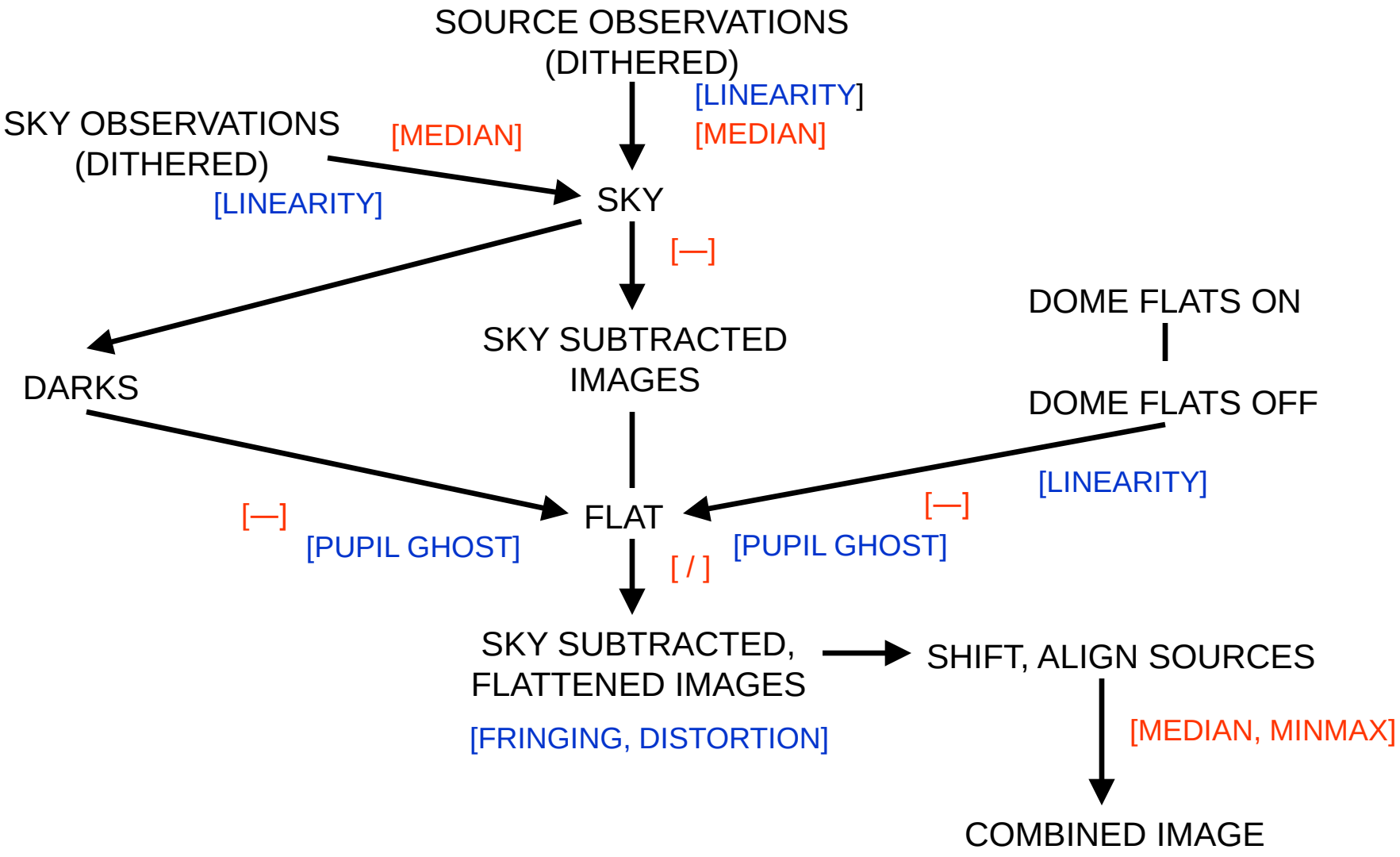
‘Phobos’ Events



- ‘Phobos’ or ‘tachyon’ events are crater-like features which can appear almost anywhere on the array
- Generally appear as a ‘hole’ with negative signal often with a surrounding annulus of positive signal
- May be result from internal stresses within the detector causing an electrical discharge
  - Anecdotal evidence that they occur more often shortly after the array has been cooled from ambient
  - But they are also seen after the instrument has been cold for a long time
- Not much can be done except to hope that they don’t occur on an important part of the detector

Summary

- Infrared arrays utilize same physics as CCDs
- Architecture is different from CCDs
  - Hybrid construction: separate detector and readout
  - Unit cell: row/column addressing – no charge transfer
  - Nondestructive readout – double; multiple correlated sampling
- Low temperature operation
  - Minimize detector dark current (bad electrons)
  - Minimize thermal radiation from instrument (bad photons)
- More bad photons – sky is limiting factor in infrared
  - Imaging: sky >> astronomical signals
  - Spectroscopy: sky bright, emission lines
  - Strategy: dithering to eliminate sky contribution
- Nonlinearity, bad pixel removal, field distortion
  - May be included in pipeline reduction programs
- Pupil ghosts and fringing
  - May require more interactive removal
- Persistence and Phobos/tachyon events
  - Former can be alleviated by observing strategy, latter by good luck.


SOURCE OBSERVATIONS
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[MEDIAN]
SKY OBSERVATIONS
(DITHERED)
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SKY
[—]
DOME FLATS ON
SKY SUBTRACTED
IMAGES
DARKS
DOME FLATS OFF
[LINEARITY]
[—]
FLAT
[—]
[PUPIL GHOST]
[PUPIL GHOST]
[/]
SKY SUBTRACTED,
FLATTENED IMAGES
SHIFT, ALIGN SOURCES
[FRINGING, DISTORTION]
[MEDIAN, MINMAX]
COMBINED IMAGE

Mid-infrared strategy

- Sky background at 10 μm is 10^3 – 10^4 greater than in K band
  - Detector wells saturate in very short time (< 50 ms)
  - Very small temporal variations in sky >> astronomical source intensities
- Read array out very *rapidly* (20 ms), coadd images
- Sample sky at high rate (~ 3 Hz) by *chopping* secondary mirror (15 arcsec)
  - Synchronize with detector readout, build up "target" and "sky" images
  - But tilting of secondary mirror introduces its own *offset* signal
- Remove offset by *nodding* telescope (30 s) by amplitude of chop motion
  - Relative phase of target changed by 180° with respect to chop cycle
  - Relative phase of offset signal unchanged
  - Subtraction adds signal from target, subtracts offset
- http://www.gemini.edu/sciops/instruments/t-recs/imaging