Error Recognition in Interferometric Imaging

A Lecture Presented at the 8th Synthesis Imaging Summer School

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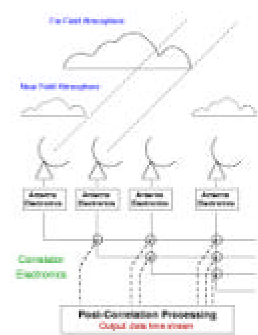
Goals

- Locate the causes of possible errors and defects
- Relate visibility errors to image defects
- Learn methods of diagnosing common problems
- Find solutions for correction of errors
- Figure out who to blame when you can't fix it!

Where Are Errors Introduced?

- far field (atmosphere, ionosphere, beyond)
- near field (atmosphere, ionosphere)
- antenna frontend (optics, receiver)
- antenna backend (amplifiers, digitizers, etc.)
- baseline (correlator)
- post-correlation (computer, software, user)

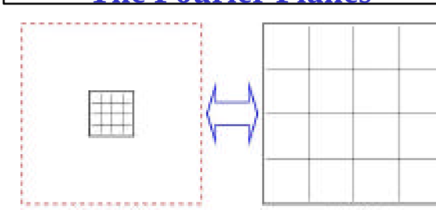
Interferometer Signal Block Diagram



Topography of the *uv* Plane

- the sky has spherical geometry
  - spherical harmonics form complete basis
  - multipole expansion in *l*,*m*
  - at small angles this is Fourier transform in *u*,*v*
- *uv* plane = "momentum space"
  - points in *uv* plane = plane waves on sky
- effects in one domain mirror the other
  - " uncertainty principle": localized ⇔ broadened
  - truncation ⇔ convolution

The Fourier Planes

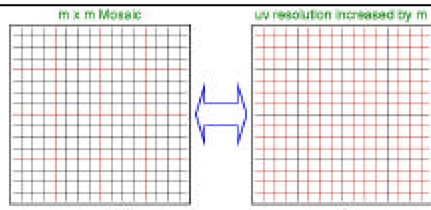


$\Delta x = \Delta\theta$ $\Delta u = L^{-1}$

$L = n\Delta\theta$ $U_{max} = \Delta\theta^{-1}$

- image plane and aperture (uv) planes are conjugate

Mosaicing



$\Delta x = \Delta\theta$

$L' = m \cdot n\Delta\theta = mL$

$\Delta u = (mL)^{-1}$

- synthesizing wider field narrows *uv* plane resolution

Image or Aperture Plane?

- errors obey Fourier transform relations:
  - narrow features transform to wide features (and visa versa)
  - symmetries important (real/imag, odd/even, point/line/ring)
- the transform of a serious error may not be serious!
  - effects are diluted by the number of other samples
  - watch out for short scans or effect on calibration solutions
- some errors more obvious in particular domain
  - switch between image and uv planes

The 2D Fourier Transform

- *x,y* (radians) in tangent plane relative to phase center
- spatial frequency *u,v* (wavelengths)
- adopt the sign convention of Bracewell:

$$I(x,y) \leftrightarrow \bar{I}(u,v)$$

$$I(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} du\, dv\, \bar{I}(u,v)\, e^{2\pi i(ux+vy)}$$

$$\bar{I}(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dx\, dy\, I(x,y)\, e^{-2\pi i(ux+vy)}$$

The Fourier Theorems

- shift in one domain is a **phase gradient** in the other

$$F(x-x_0, y-y_0) \Leftrightarrow e^{-2\pi i(ux_0+vy_0)}\bar{F}(u,v)$$

- multiplication in one domain is **convolution** in the other

$$F * G(x,y) \Leftrightarrow \bar{F}\bar{G}(u,v)$$

$$FG(x,y) \Leftrightarrow \bar{F} * \bar{G}(u,v)$$

$$F * G(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F(x',y')\,G(x-x', y-y')\,dx'\,dy'$$

Intensity and Visibility

- for a phase center at the pointing center $\boldsymbol{x}_p$

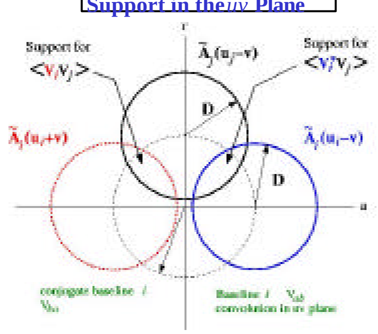
primary beam — pointing center — phase center

$$V(\boldsymbol{u}) = \int\int d^2\boldsymbol{x}\, A_\nu(\boldsymbol{x}-\boldsymbol{x}_p)\, I_\nu(\boldsymbol{x})\, e^{-2\pi i\,\boldsymbol{u}\cdot(\boldsymbol{x}-\boldsymbol{x}_p)}$$

$$= \int\int d^2\boldsymbol{v}\, \bar{A}_\nu(\boldsymbol{u}-\boldsymbol{v})\, \bar{I}_\nu(\boldsymbol{v})\, e^{2\pi i\,\boldsymbol{u}\cdot\boldsymbol{x}_p}$$

transform of primary beam — frequency dependent — true transform of sky brightness

Support in the *uv* Plane



- visibility = *uv* plane convolved with aperture x-cor

Fourier Symmetries

- symmetries determined by Fourier kernel

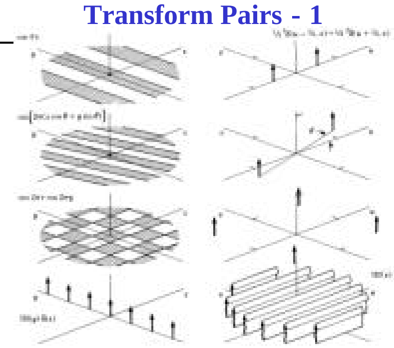
$$\exp(i\phi) = \cos\phi + i\sin\phi$$

  - Real ⇔ Real Even + Imag Odd
  - Imag ⇔ Real Odd + Imag Even
  - Real & Even ⇔ Real & Even
  - Real & Odd ⇔ Imag & Odd
  - Even ⇔ Even   Odd ⇔ Odd

→ image errors with odd symmetry or asymmetric often due to phase errors

- real sky brightness ⇔ Hermitian *uv* plane
  - *complex conjugate* of visibility used for inverse baseline

Transform Pairs - 1



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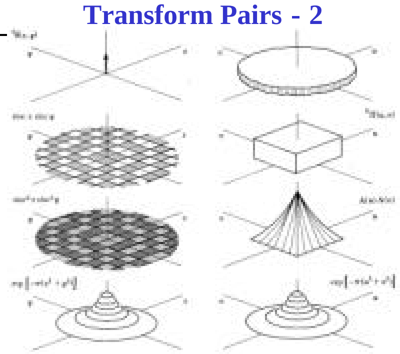
Transform Pairs - 2



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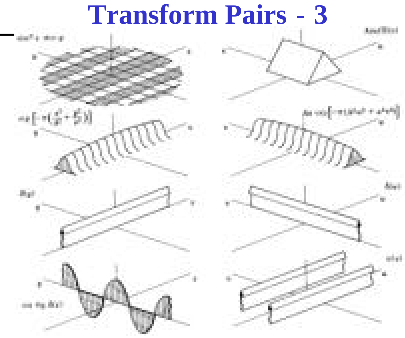
Transform Pairs - 3



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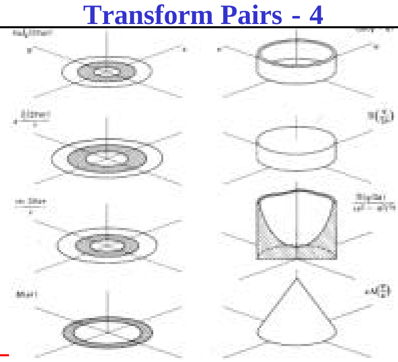
Transform Pairs - 4



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Error Diagnosis

- amplitude or phase errors:
  - phase errors usually asymmetric or odd symmetry
  - amplitude errors usually symmetric (even)
- short duration errors:
  - localized in *uv* plane ⇔ distributed in image plane
  - narrow ⇔ extended orthogonal direction in image
- long timescale errors:
  - ridge in *uv* plane ⇔ corrugations in image
  - ring in *uv* plane ⇔ concentric "Bessel" rings in image

Additive or Multiplicative?

$$V + \varepsilon \Leftrightarrow I + \mathcal{F}\varepsilon$$

- some errors *add to* visibilities
  - additive in conjugate plane
  - examples: noise, confusion, interference, cross-talk

$$V\varepsilon \Leftrightarrow I * \mathcal{F}\varepsilon \qquad V * \varepsilon \Leftrightarrow I\,\mathcal{F}\varepsilon$$

- others *multiply* or *convolve* visibilities
  - multiplication ⇔ convolution in conjugate planes
  - examples: sampling, primary beam, gain errors, atmosphere

Antenna Based Errors

- often easier to diagnose in *uv* plane
- typically due to single antenna:
  - short duration = pattern of baselines (six-pointed for VLA)
  - long duration = rings (concentric corrugations in image)
- effect in image plane diluted by other antennas
  - factor N_{bad} / N_{tot} of baselines affected
- many antenna-based errors obey *closure relations* and are *self-calibratable*

Closure Relations

- complex antenna voltage gain errors

$$\tilde{V}_{ij} = g_i g_j^* V_{ij} = a_i a_j V_{ij} e^{i(\phi_i - \phi_j)}$$

$$g_j = a_j e^{i\phi_j}$$

- cancel out in special combinations of baselines:

$$\tilde{V}_{ij}\tilde{V}_{jk}\tilde{V}_{ki} = a_i^2 a_j^2 a_k^2 V_{ij} V_{jk} V_{ki}$$

$$\frac{\tilde{V}_{ij}\tilde{V}_{kl}}{\tilde{V}_{il}\tilde{V}_{kj}} = \frac{V_{ij}V_{kl}}{V_{il}V_{kj}}$$

Additive Errors

- adds to visibilities ⇔ transform adds to image
  - unconnected to real sources in the image
  - may make "fake" sources
- sources of additive errors:
  - interference (sources outside beam, RFI, cross-talk)
  - baseline-dependent errors
  - noise
- short strong gain errors can appear to be additive

Noise in Images

- computable from radiometer equation
  - you should know expected noise level given the conditions
  - unexpectedly high noise levels may indicate problems
- additive, same *uv* distribution as data
  - will show same sidelobe pattern as real sources!
- issues:
  - deconvolution will modify noise characteristics – beware!
  - self-calibration on weak sources can manufacture a fake source from noise (especially with short solution intervals)

Multiplicative Errors 1

- multiplies visibilities ⇔ convolved with image
  - will appear to be "attached" to sources in the image
- antenna gain calibration errors
  - sidelobe pattern (e.g. Y for short durations, ripples or rings for longer durations)
- troposphere and ionosphere
  - troposphere: 8+ GHz, water vapor content plus dry atmosphere
  - ionosphere: < 8 GHz, total electron content (TEC)
  - antenna-based errors (usually closing), calibratable

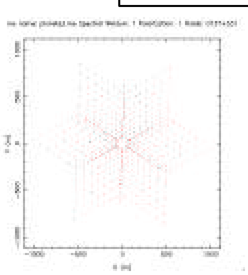
Multiplicative Errors 2

- atmosphere and ionosphere (continued)
  - worse on longer baselines
  - short-term (sub-integration) errors smear image
  - long-term large-scale structures cause image shifts/distortions
    - phase gradient ⇔ position shift (Fourier shift theorem)
    - equivalent to optical "seeing"
    - need *phase referencing* to calibrator(s) for astrometry
    - but, keep track of turns of phase!
  - wide-field: higher-order distortions over field of view
  - VLBI: incoherent between antennas – phase referencing needed

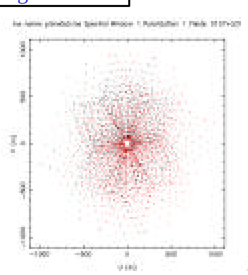
Multiplicative Errors 3

- *uv* sampling
  - sampling multiplicative with true uv distribution
  - sampling function ⇔ dirty beam convolved with image
  - considered under *Imaging* & *Deconvolution*
- primary beam and field-of-view
  - multiplicative in image plane ⇔ convolves *uv* distribution
  - for baseline = cross-correlation of aperture voltage patterns
  - compact in *uv* plane ⇔ extended sidelobes in image plane
  - can be corrected for in image plane by division (**PBCOR**)
  - can be compensated for in *uv* plane by *mosaicing*

uv Coverage



snapshot coverage



8 scans over 10 hours

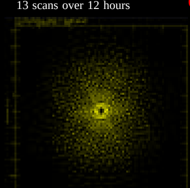
Radially Dependent Errors

- not expressible as simple operations in image/*uv* plane
  - sometimes convertible to standard form via coordinate change
- smearing effects
  - bandwidth: radial - like coadding images scaled by frequency
  - time-average: tangential – baselines rotated in *uv* plane
- pointing
  - dependent on source position in the field
  - polarization effects worse (e.g. beam squint)

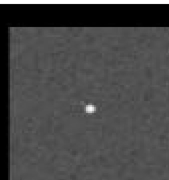
Example Error - 1

- point source 2005+403
  - process normally
  - self-cal, etc.
  - introduce errors
  - clean

13 scans over 12 hours

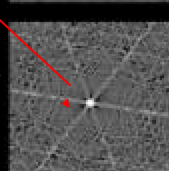


no errors:
max 3.24 Jy
rms 0.11 mJy



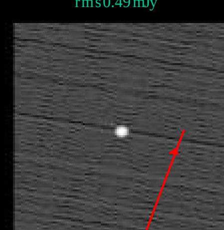
6-fold symmetric pattern due to VLA "Y"

10% amp error
all ant 1 time
rms 2.0 mJy



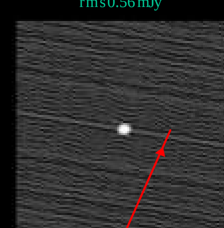
Example Error - 2

10 deg phase error 1 ant
1 time
rms 0.49 mJy



anti-symmetric ridges

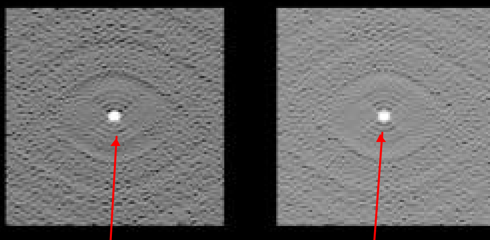
20% amp error 1 ant
1 time
rms 0.56 mJy



symmetric ridges

10 deg phase error 1 ant
all times
rms 2.0 mJy

20% amp error 1 ant
all times
rms 2.3 mJy



rings – odd symmetry

rings – even symmetry

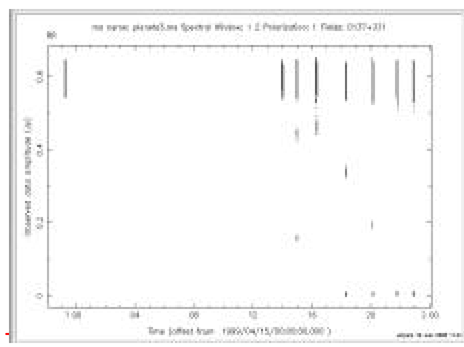
Editing – Search & Destroy!

- For calibrators: be ruthless!
  - single errors can propagate to bad solutions which will affect longer intervals
  - may want to flag target source data around flagged calibrator scans
- For target sources: keep in mind image-plane effect
  - single bad integrations highly diluted in image
  - long-term offsets can be more serious

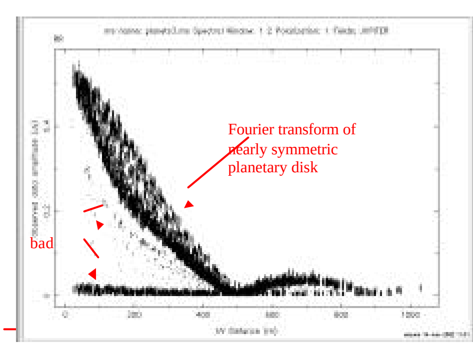
Editing – What?

- plot amplitude & phase versus time:
  - plot baselines versus a given antenna, look for outliers etc.
  - discriminates antenna-based and baseline-based errors
  - **TVFLG** (AIPS), **msplot** (aips++), **vplot** (difmap)
- check different IF and polarization products
  - may be best to delete all data to a given antenna
  - for polarization observations, flag cross-hands (e.g. RL,LR) also when editing parallel hands (e.g. RR,LL)

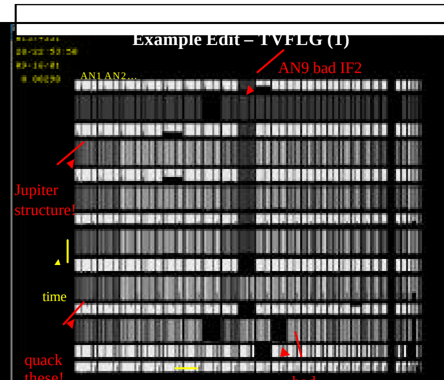
Example Edit – **msplot (1)**

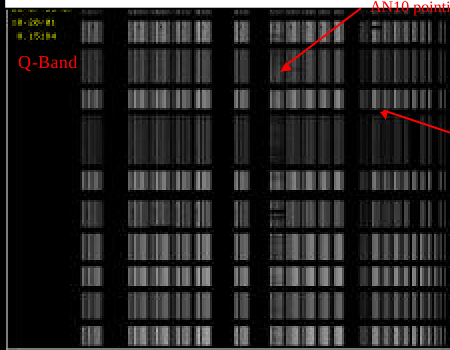


Example Edit – **msplot (2)**



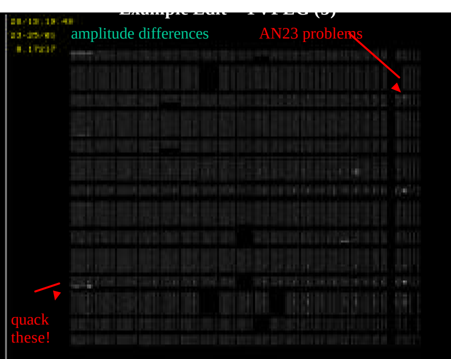
Example Edit – TVFLG (1)

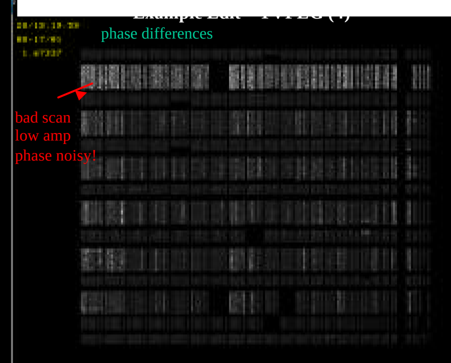




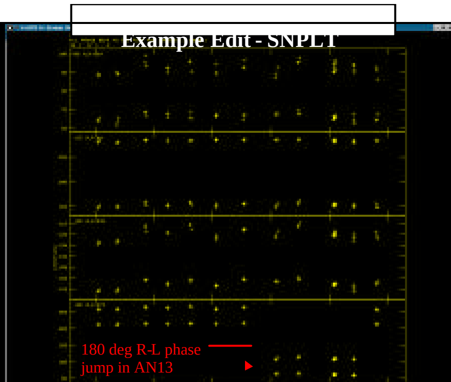
More on Editing

- editing tricks
  - also plot versus *uv* distance (e.g. **UVPLT, msplot**)
  - plot differences versus running mean (amplitude & phase)
  - antenna temperatures: e.g. **TYPLT** (AIPS)
  - calibration solutions: **SNPLT** (AIPS), **plotcal** (aips++)
    - also check IF 1-2 and R-L for anomalous jumps
- special cases
  - spectral line: continuum versus line channels
  - VLBI: channels, delay and rate solutions
  - autocorrelations





Example Edit - SNPLT



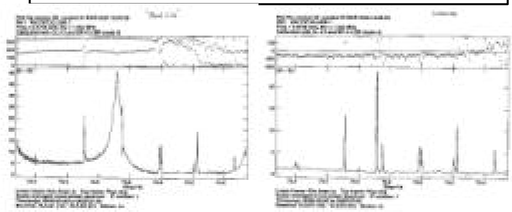
Interference 1

- strong additive errors
  - most often seen on short baselines
- bright sources in sidelobes
  - Sun (and Cyg-A at low frequencies) can be seen even though the source may be offset by many primary beams!
  - watch for aliasing near map edge
- **cross-talk** between antennas
  - short baselines, especially when **shadowing** occurs
  - delete baslines where an antenna is shadowed

Interference 2

- radio frequency interference (RFI)
  - variable, often short duration bursts, sometimes CW
  - predominantly on baselines with low fringe rate (e.g. N-S) and when pointed at low elevation
  - usually **narrow band** - avoidable or excisable in high spectral resolution modes when isolated to a few channels
  - system must have high degree of **linearity** to deal with strong signals without saturation

Example RFI



The spectrum above left shows VLA 74 MHz spectral data in the presence of a broad RFI feature. After **hanning smoothing** the data with time, the broad feature is effectively removed, leaving only narrow easily excisable features in the plot at the right.

Spectral plots provided by Rick Perley

Other Problems

- wide-field imaging and mosaicing
  - particularly susceptible to pointing errors and smearing
- high-dynamic range imaging
  - all these problems will be exacerbated!
  - even weak errors (especially non-closing) will affect data
  - the most difficult type of problem
- other issues or hints :
  - detection experiments for weak source forgiving

Other Suggestions

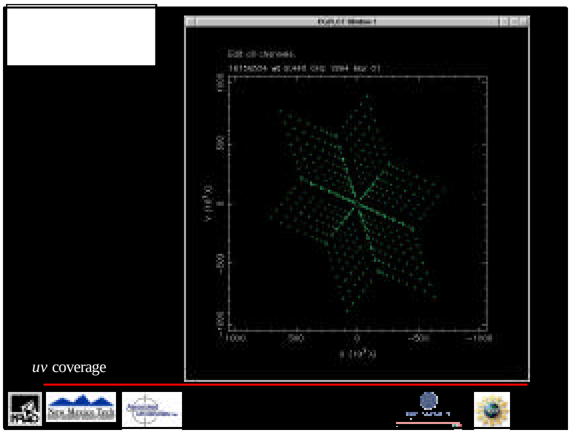
- polarization as a diagnostic
  - polarization images of unpolarized sources useful
  - V images sometimes useful (depends on cal scheme)
  - also, look at differences between IFs or channels
- low-resolution images good first step
  - image full field-of-view and sidelobes
  - find confusing sources or signature of RFI
- FT errors in image back to *uv* plane
  - identify source (antennas, baselines, or integrations)

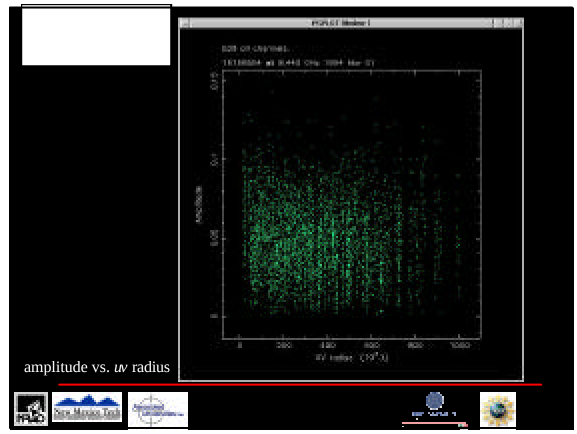
Summary

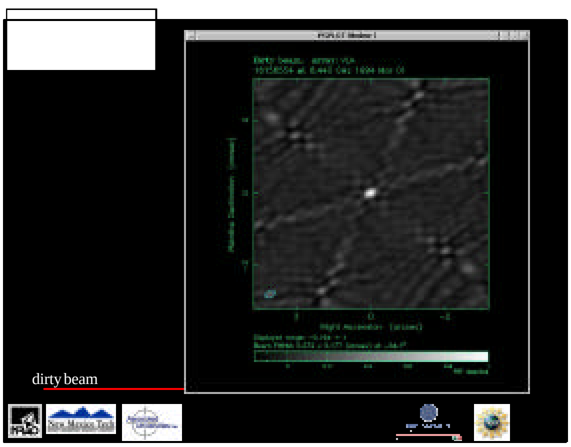
- effect in image depends on effect in *uv* plane or time stream
  - understand the properties of the Fourier transform
  - errors may be additive, multiplicative, radially dependent
  - move between image and *uv* plane
- effective editing
  - know expected noise levels, gauge severity in image
  - edit calibration scans carefully
  - image the full beam to look for confusing sources or RFI
  - use visualization tools (getting better all the time)
  - know the effects of the imaging & calibration algorithms

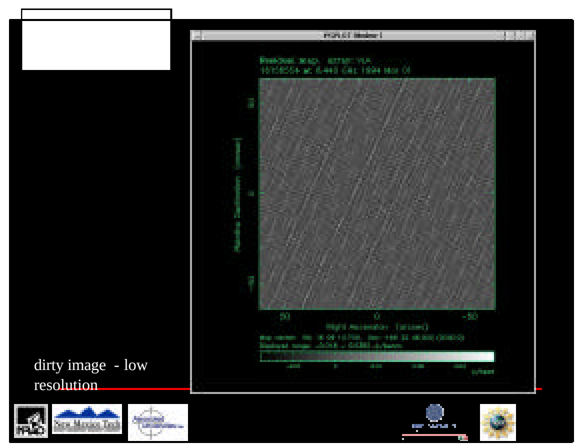
Extra - Snapshot Sequence

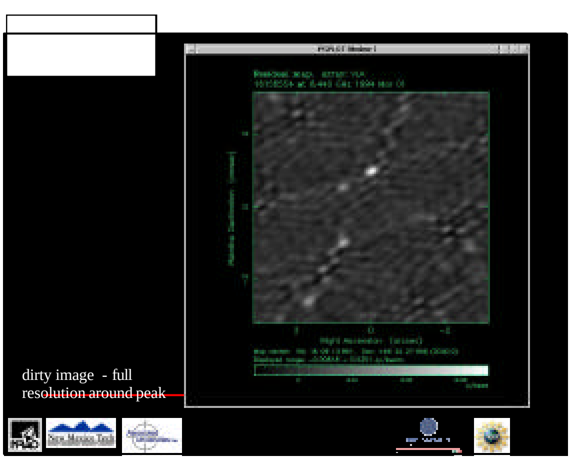
- imaging and self-calibrating VLA snapshot
  - A-config, 8.4 GHz, 30 sec, 0.2” resolution, 0.4mJy rms
  - processed in **difmap**
- special problems for snapshots:
  - poor *uv* coverage = high sidelobes
  - weak source, must be careful in self-calibration
  - modelfitting instead of cleaning – see talk by Pearson
  - point source nature makes this easier!

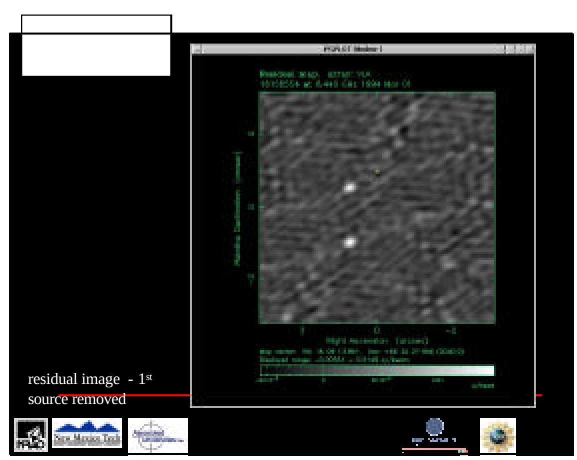

uv coverage

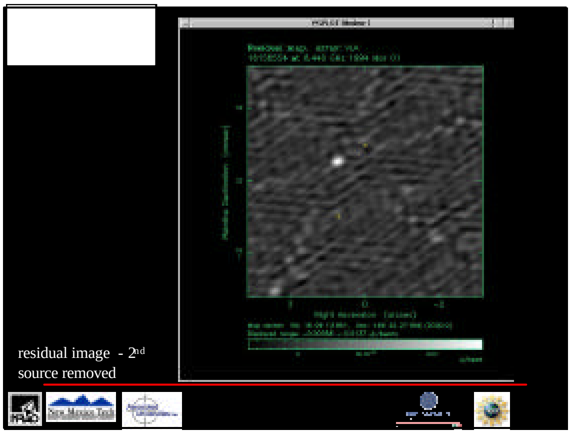

amplitude vs. *uv* radius

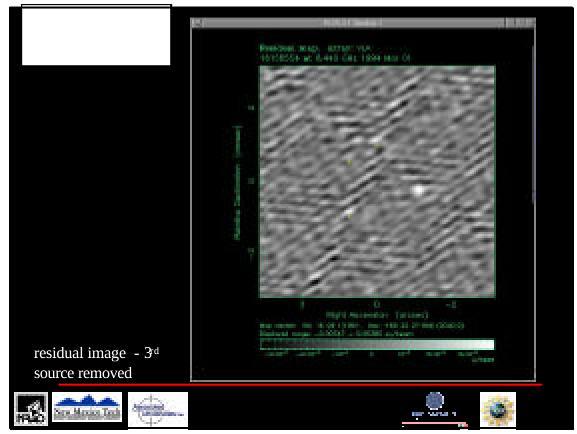

dirty beam

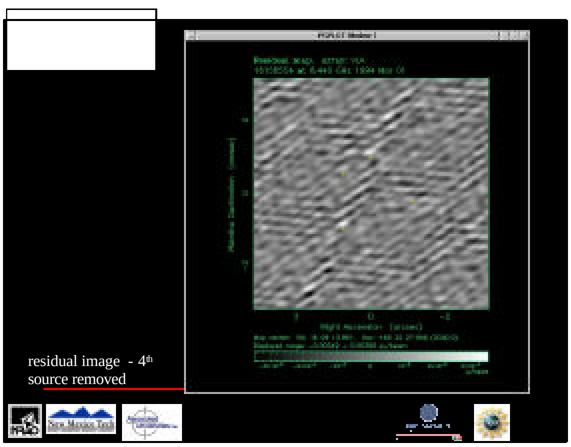

dirty image - low
resolution

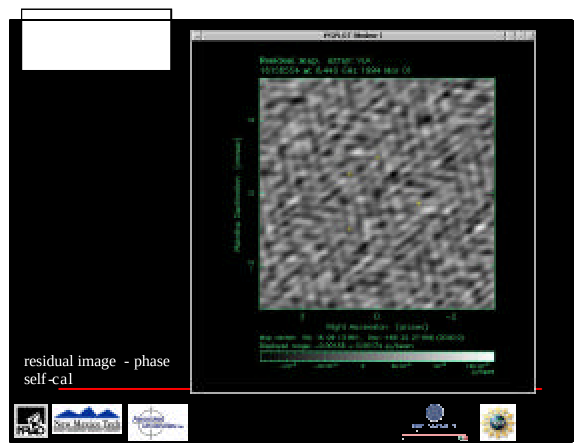

dirty image - full
resolution around peak

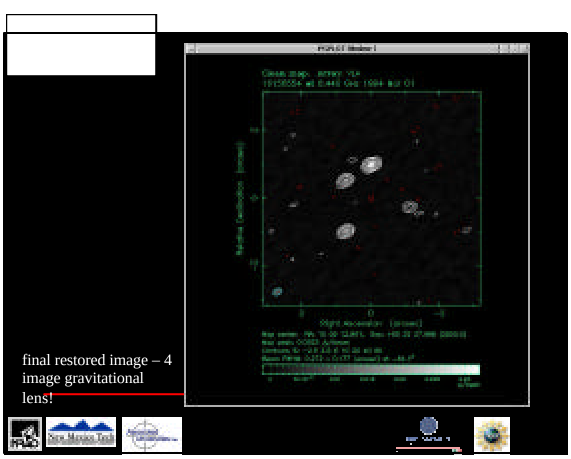

residual image - 1st
source removed


residual image - 2nd
source removed


residual image - 3rd
source removed


residual image - 4th
source removed


residual image - phase
self-cal


final restored image – 4
image gravitational
lens!