Algorthmic Issues from the First RadioNet Software Forum – a synthesis

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What is RadioNet?

- Mission statement

  "RadioNet is an Integrated Infrastructure Initiative (I3), funded under the European Committee Sixth Framework Programme (FP6), that has pulled together all of Europe's leading astronomy facilities to produce a focused, coherent and integrated project that will significantly enhance the quality and quantity of science performed by European astronomers. RadioNet has 20 partners."

- 3 key joint research activities (JRA):
  - ALBUS: Advanced long baseline user software
  - AMSTAR: Advanced Millimetre and Submillimetre Technology for Astronomical Research
  - PHAROS: Phased Arrays for Reflector Observing Systems

http://www.radionet-eu.org/

The Players…

- EVN/JIVE
- eMERLIN
- ALMA
- WSRT
- LOFAR

plus the party crashers…

- NRAO (EVLA, VLBA)
- ATNF (ATCA, NTD)

Common algorithm issues

(inspired by RadioNET discussions)

Wide-field Imaging (WFI) Issues

- Players
  - low frequency arrays: LOFAR, LWA, MWA, SKA
  - also: EVLA, EVN, VLBA
- Drivers
  - high-dynamic range wide-field imaging
  - low-frequency (ionospheric) aberrations
  - using the full field-of-view in VLBI
- Issues
  - efficient gridding & transforms (faceting, w-projection)
  - full beam imaging (polarization, beam-forming)
  - direction dependent calibration (pointing, non-isoplanatism)

Imaging & Deconvolution Issues

- Players
  - EVLA, eMERLIN, LOFAR, LWA, MWA
  - also ALMA
- Drivers
  - high-fidelity imaging of extended emission
  - use of bandwidth to improve continuum sensitivity
  - imaging of spectral index and rotation measure
- Issues
  - extended emission (multi-scale deconvolution, mosaicing)
  - wide-band imaging (multi-frequency synthesis)
  - deal with WFI issues also!

Other Common Issues

- High data rates & large data volumes
  – need parallel tasking or algorithms
- Complicated interaction of effects and sky
  – serialization (e.g. “peeling”)
  – convergence?
  – approximations (for efficiency)
- Accessibility
  – standard data products
  – standard observing modes?
  – standard processing (pipelines)
  – standard data models
  – software interoperability

Key technologies

- efficient transforms and gridding for WFI
  - w-projection + faceting based methods
- direction-dependent calibration (DDC)
  - pointing calibration
  - polarization beam
- ionospheric calibration (IC)
  - corrective vs. reconstructive methods
- wide-band imaging (WBI)
  - multi-frequency synthesis (MFS)
- multi-scale deconvolution (MSD)
  - multi-scale CLEAN
  - multi-scale MFS

A way forward…

- focus groups
  - WFI, WBI, DDC, IC, MSD
- research
  - get real algorithm research groups activated
- exchanges
  - exchange of developers and scientists
  - exchange of algorithms (papers, SourceForge?)
  - software interoperability interesting but probably a dream…
- assertion:
  - “The most important currency of exchange is the algorithms; once implemented in one package, it is then relatively easy to re-implement in another. Develop in whatever environment that you are most comfortable in.”

Algorithm issues for EVLA and beyond

(slides courtesy Tim Cornwell)

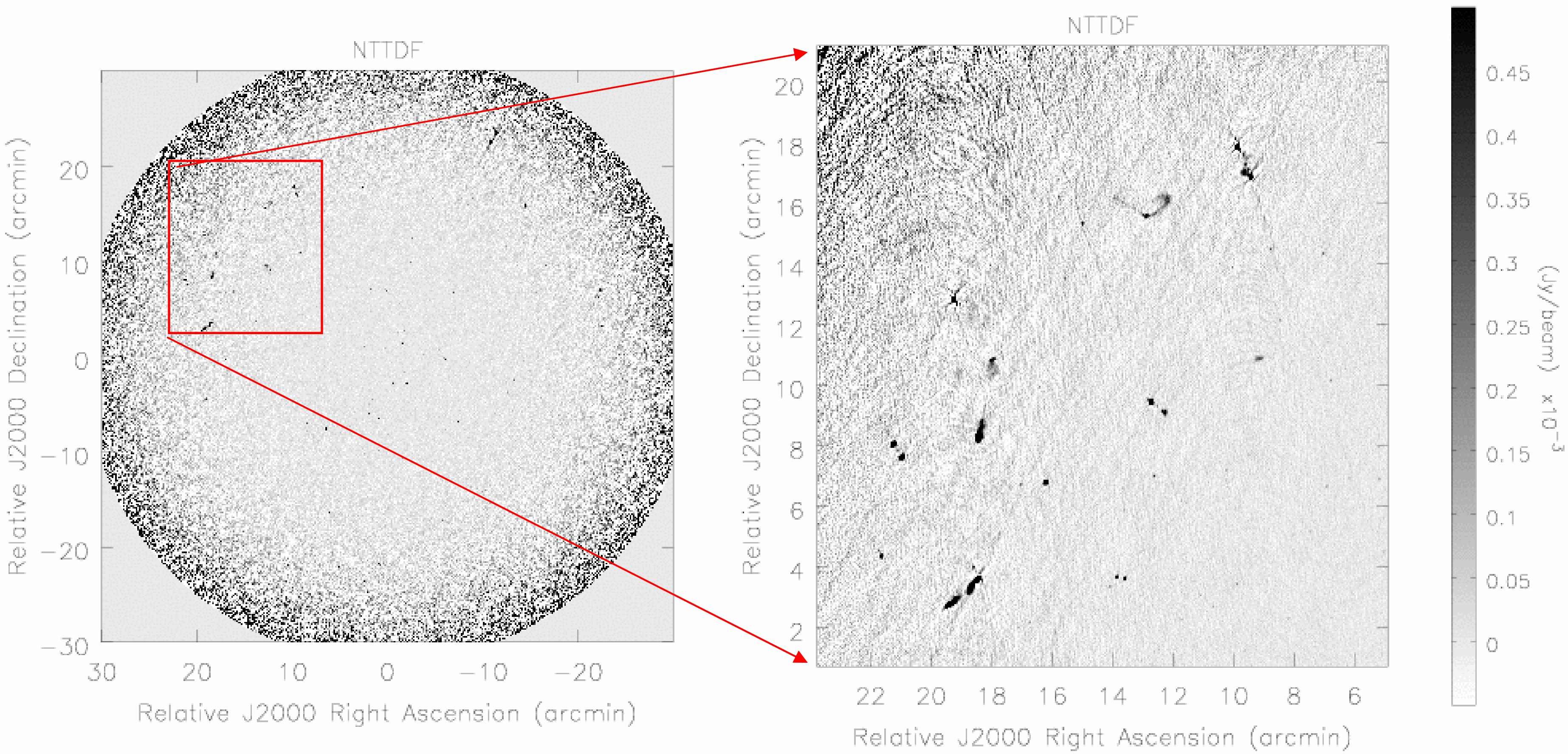
Limits to wide field imaging quality

- Deconvolution of extended emission
- Non coplanar baselines
- Pointing errors
- Time-variable primary beams/station calibration errors
- Non-isoplanatism (e.g. ionosphere)
- RFI mitigation
- Polarized primary beams
- Spectral indices and rotation measure of sources
- Missing short-spacing data
- Computing costs (software and hardware)

In some cases all of the above at the same time!

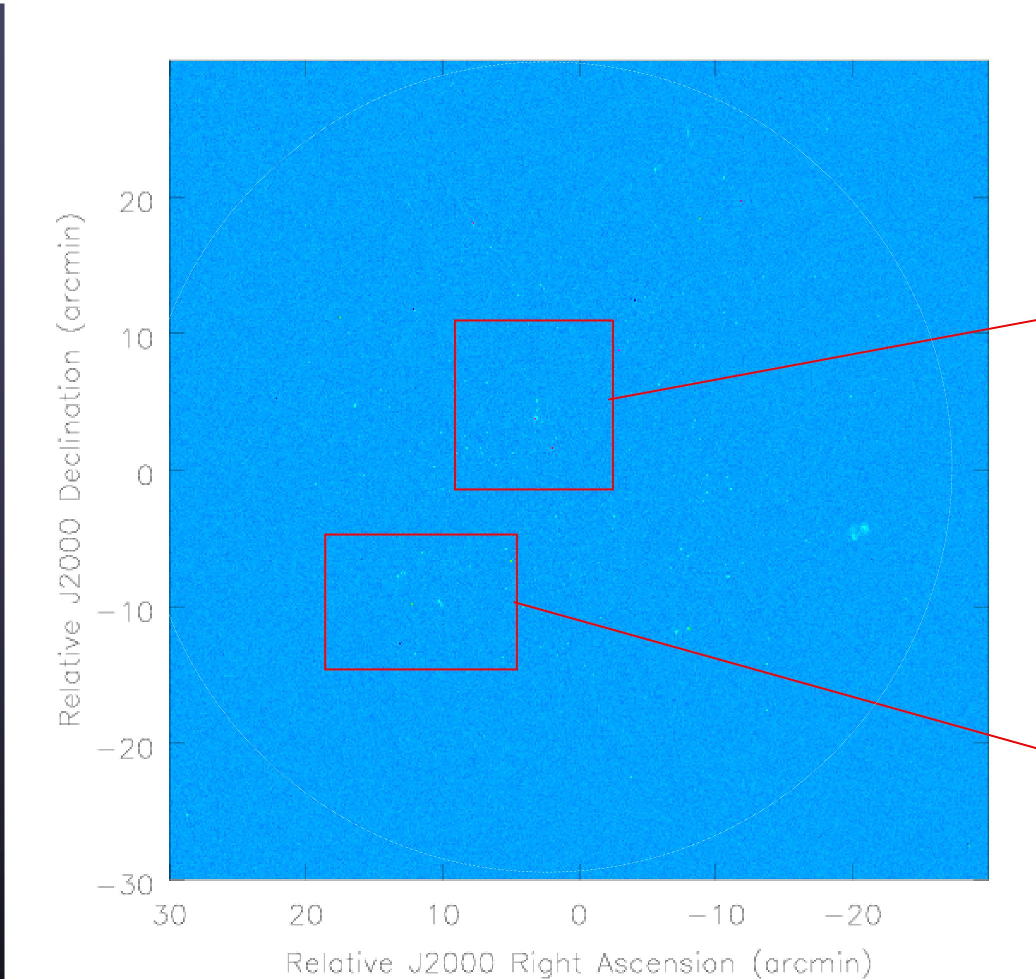
Wide-field Imaging

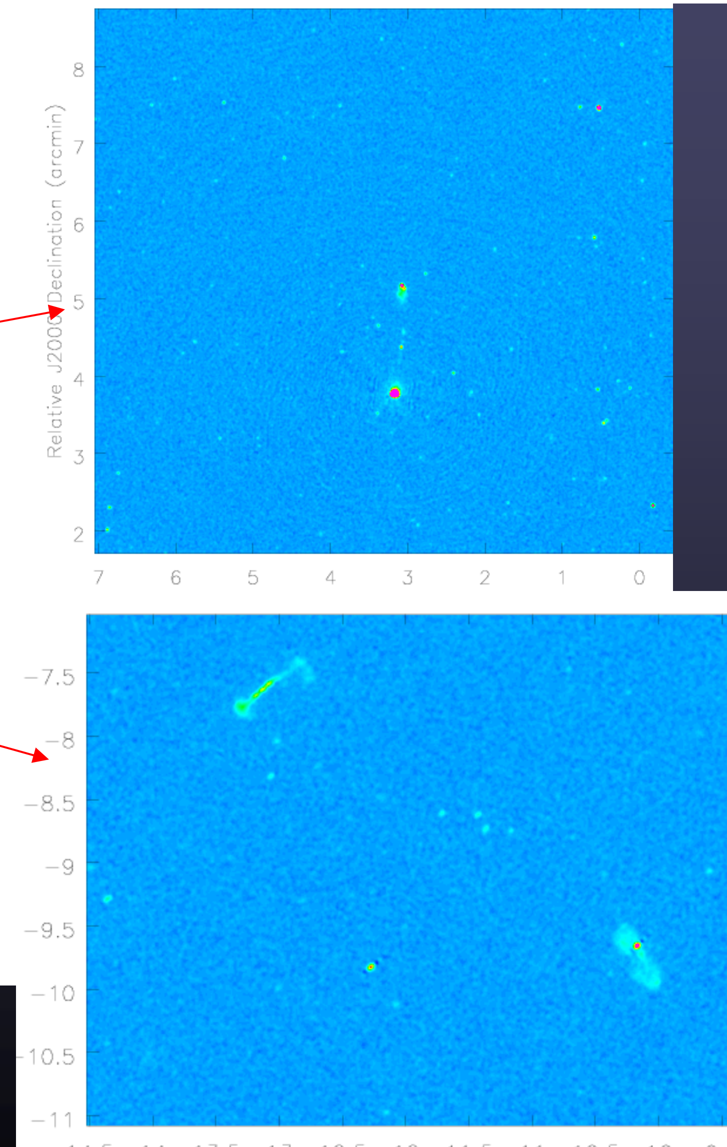
Deep Field at 4", 1.4GHz, VLA



Unfortunate location of cluster low down in the primary beam - noise limited by pointing errors

Deep VLA image at 1.4GHz: 3μJy





120h integration with Very Large Array

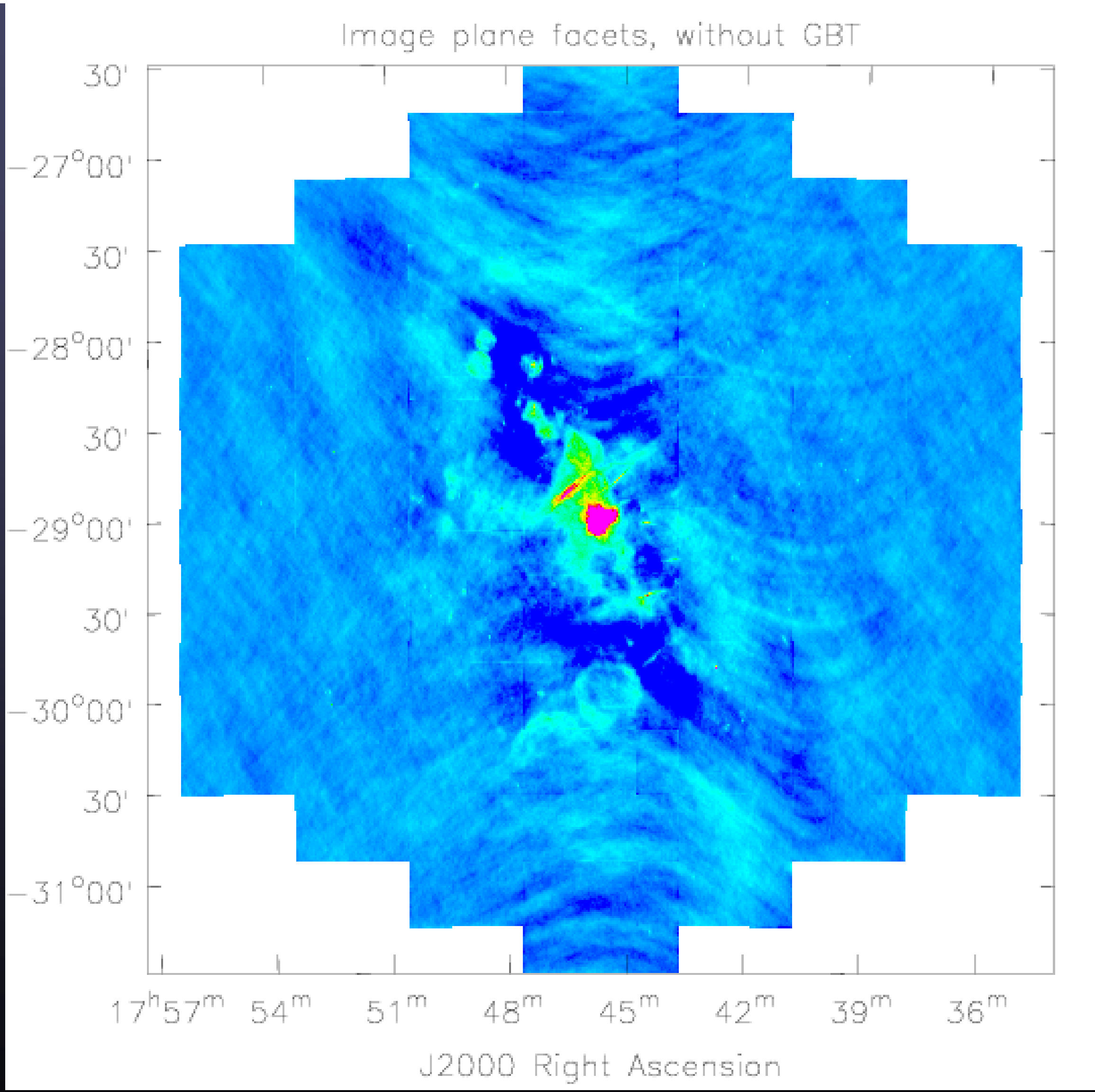
SKA will go 10 times deeper in a few hours

Already limited by pointing errors?

add in extended structure…

Galactic plane at 90cm

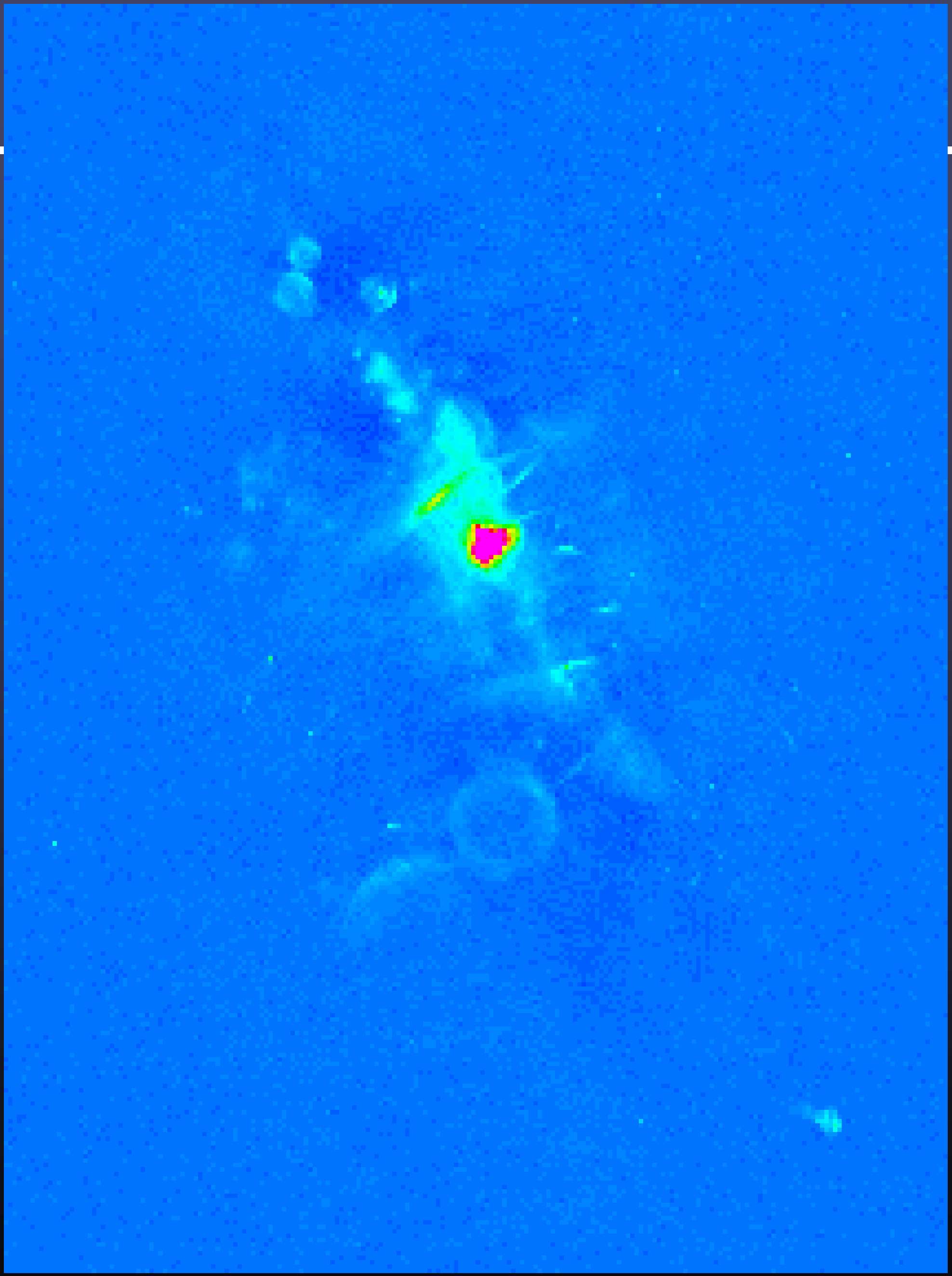
- Nord *et al.* observations
- AIPS IMAGR program using faceted transforms (Cornwell and Perley 1992)
- Poor deconvolution of extended emission
- Facet boundaries obvious



some progress…

State of the art wide-field image

- VLA B,C,D
- λ90cm
- Imaged using W projection to counter non-coplanar baselines effect
- Deconvolved using Multi-scale CLEAN



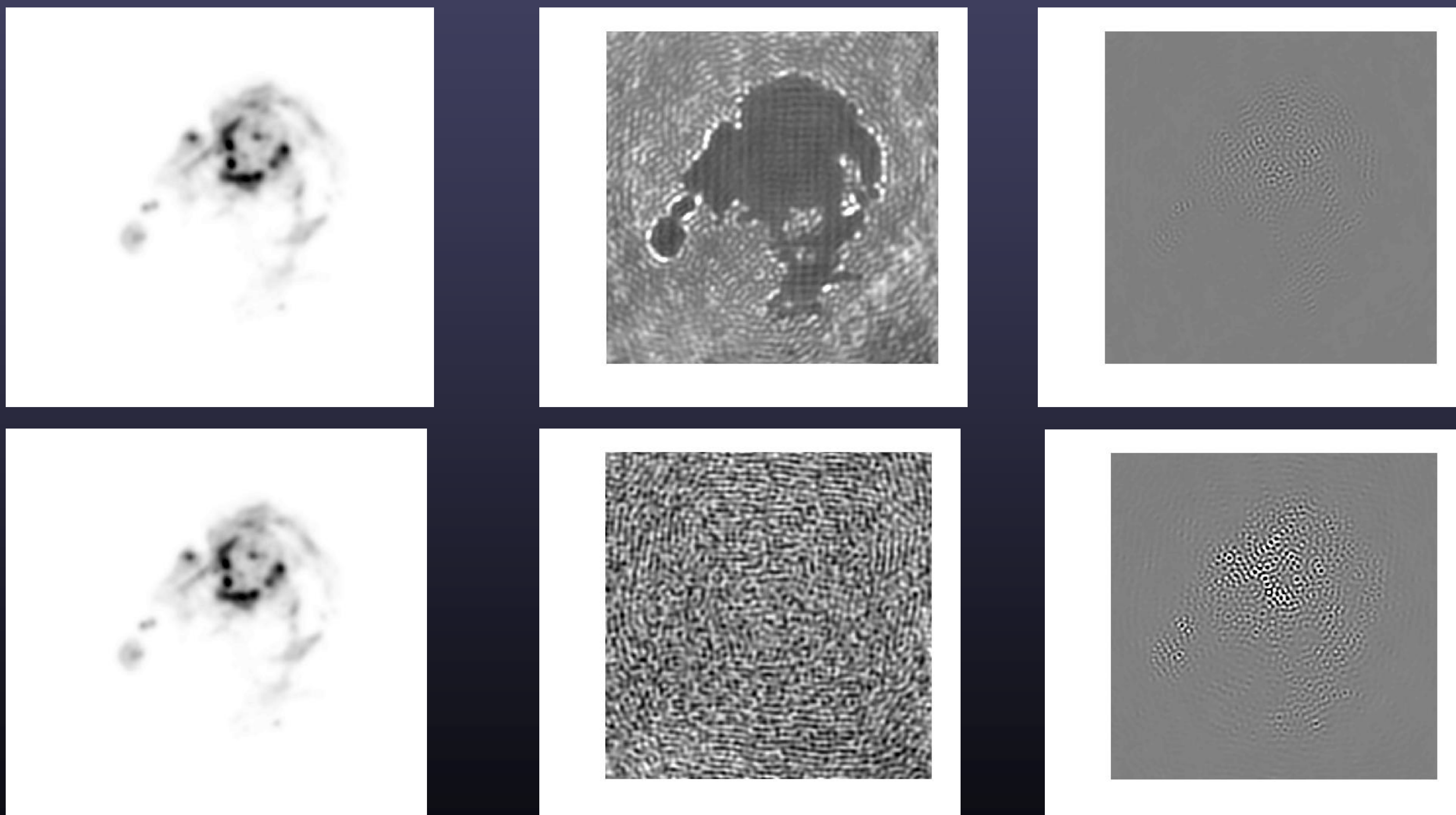
Multi-scale methods promising…

Max Entropy vs. Multi-scale CLEAN

Restored | *Residual* | *Error*

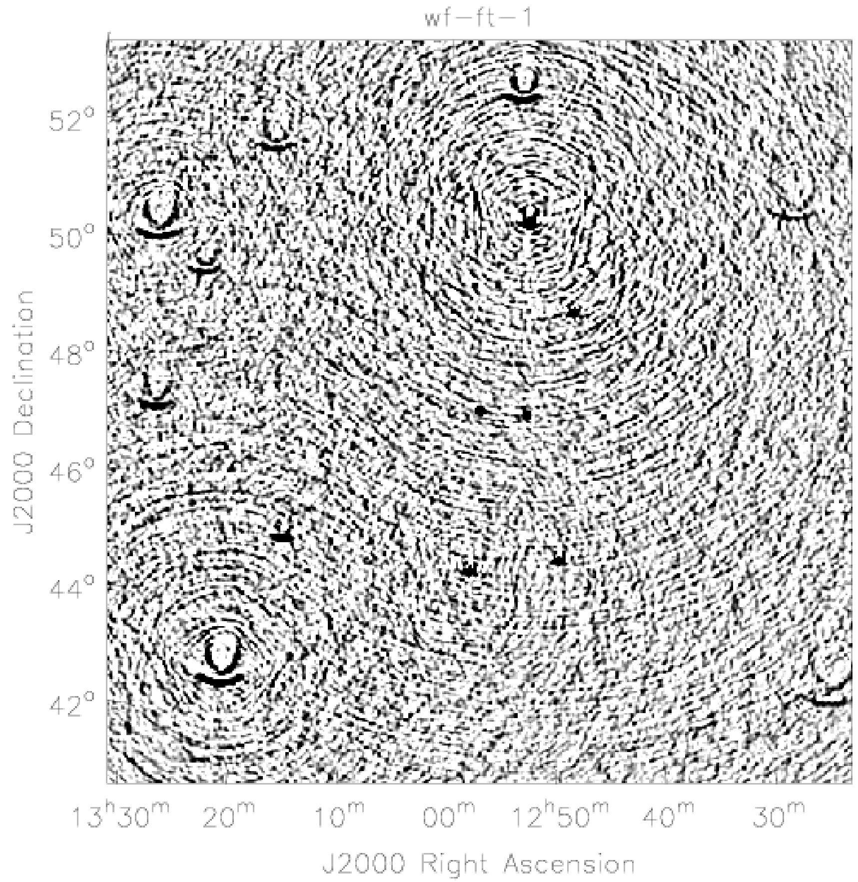
Maximum Entropy

MS Clean



WFI: Non coplanar baselines

- For wide fields, the relationship between sky and visibility is no longer a Fourier transform
- If we use a Fourier transform, point sources away from the phase center of a radio synthesis image are distorted
- Bad for long baselines, large field of view, and long wavelengths



$$V(u,v,w)=\int I(l,m)e^{j2\pi\left(ul+vm+w\left(\sqrt{1-l^2-m^2}-1\right)\right)}dldm$$

The essence of W projection

- Evaluate this integral (and transpose) for regular grid in *(l,m)* and irregularly spaced samples in *(u,v)*

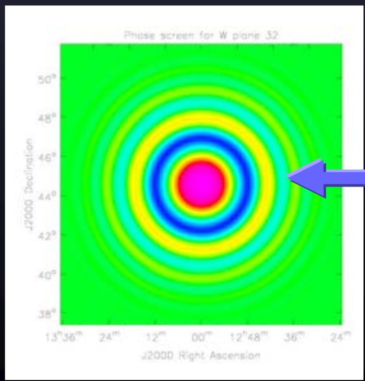
$$V(u,v,w)=\int I(l,m)e^{j2\pi\left(ul+vm+w\left(\sqrt{1-l^2-m^2}-1\right)\right)}dldm$$

- Image space computation = multiplicative function

$$V(u,v,w)=\int G(l,m,w)I(l,m)e^{j2\pi(ul+vm)}dldm$$

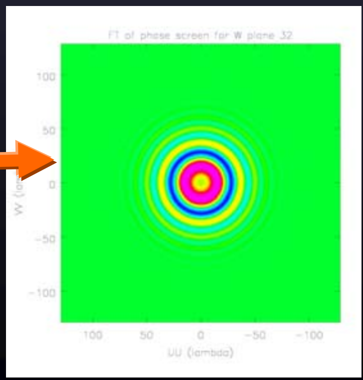
- Fourier space computation = convolution kernel

$$V(u,v,w)=G(u,v,w)\otimes V(u,v,w=0)$$



$$e^{j2\pi w\left(\sqrt{1-l^2-m^2}-1\right)}$$

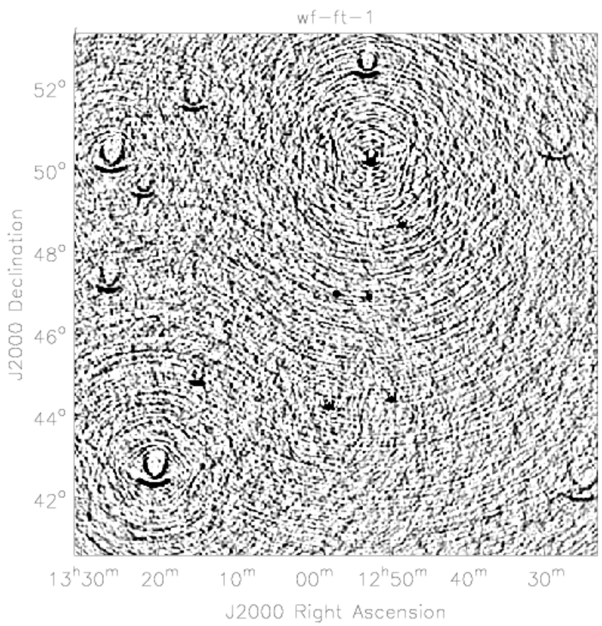
$$\approx e^{-j\pi w(u^2+v^2)}$$

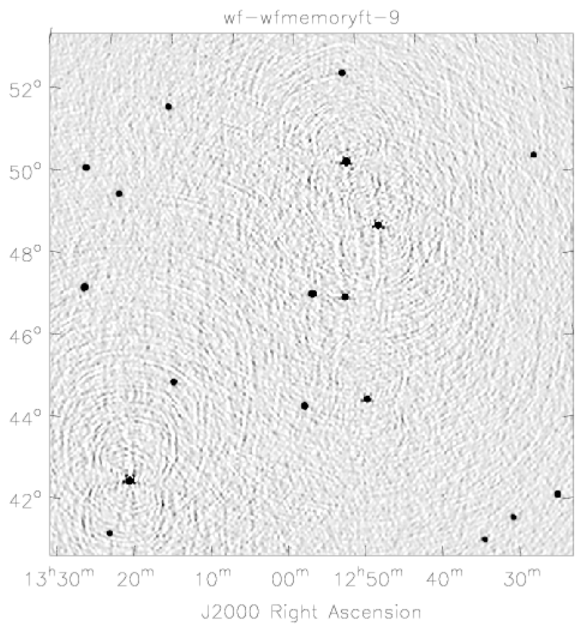


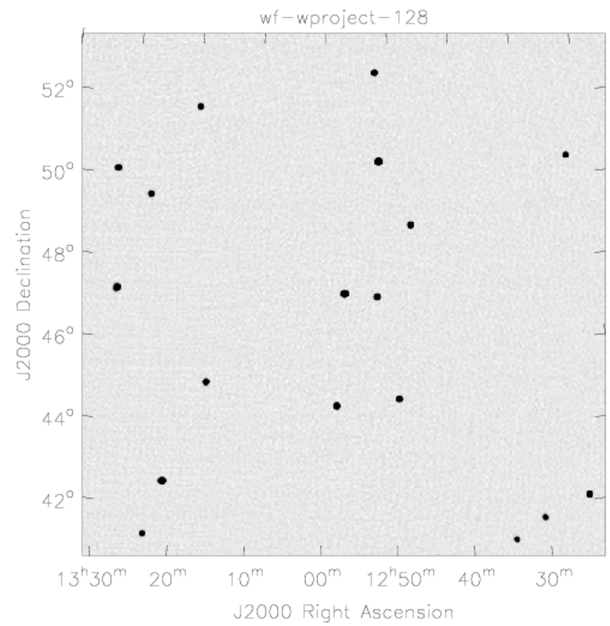
W-projection: A synthetic example

- Simulation of ~ typical 74MHz field
  - Sources from WENSS
  - Long integration with VLA

Single Fourier transform | Faceted Fourier transforms | W projection







ALMA: Mosaicing as a convolution

- Other problems suitable to convolutional approaches!
- e.g. measurement equation for mosaicing:

$$V(u,v) = \int A(l,m) I(l,m) e^{j2\pi(ul+vm)} dl dm$$

- in terms of antenna voltage patterns

$$V_{i,j}(u,v) = \int E_i(l,m) E_j^*(l,m) I(l,m) e^{j2\pi(ul+vm)} dl dm$$

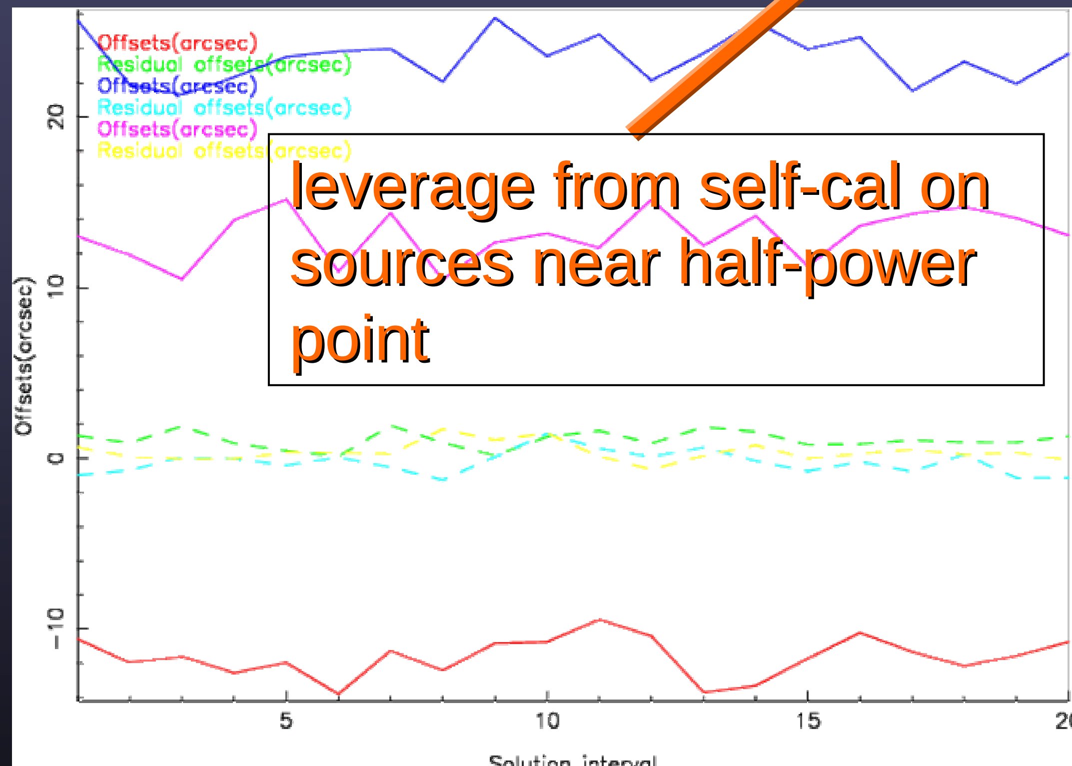
- Fourier space computation

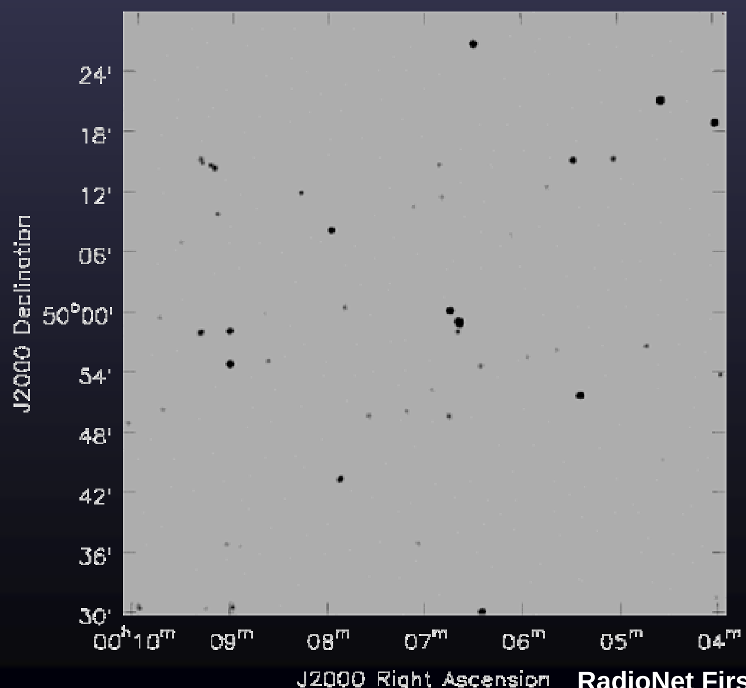
$$V_{i,j}(u,v) = \tilde{E}_i \otimes \tilde{E}_j^* \otimes V(u,v)$$

DDC: Pointing self-calibration

- Determines pointing errors directly from visibilities and component model
- Model = 59 sources from NVSS: 2 to 200mJy
- Bottom shows pointing offsets and residuals

$$\tilde{E}_i \otimes \tilde{E}_j^* = \left[\frac{1}{\sigma}\sqrt{\frac{\pi}{2}}\, e^{-\frac{u^2\pi^2}{2\sigma^2}}\right]\left[e^{-\frac{(\Delta \mathbf{l}_i - \Delta \mathbf{l}_j)^2\sigma^2}{2}}\right] e^{-i\pi \mathbf{u}\cdot(\Delta \mathbf{l}_i + \Delta \mathbf{l}_j)}$$

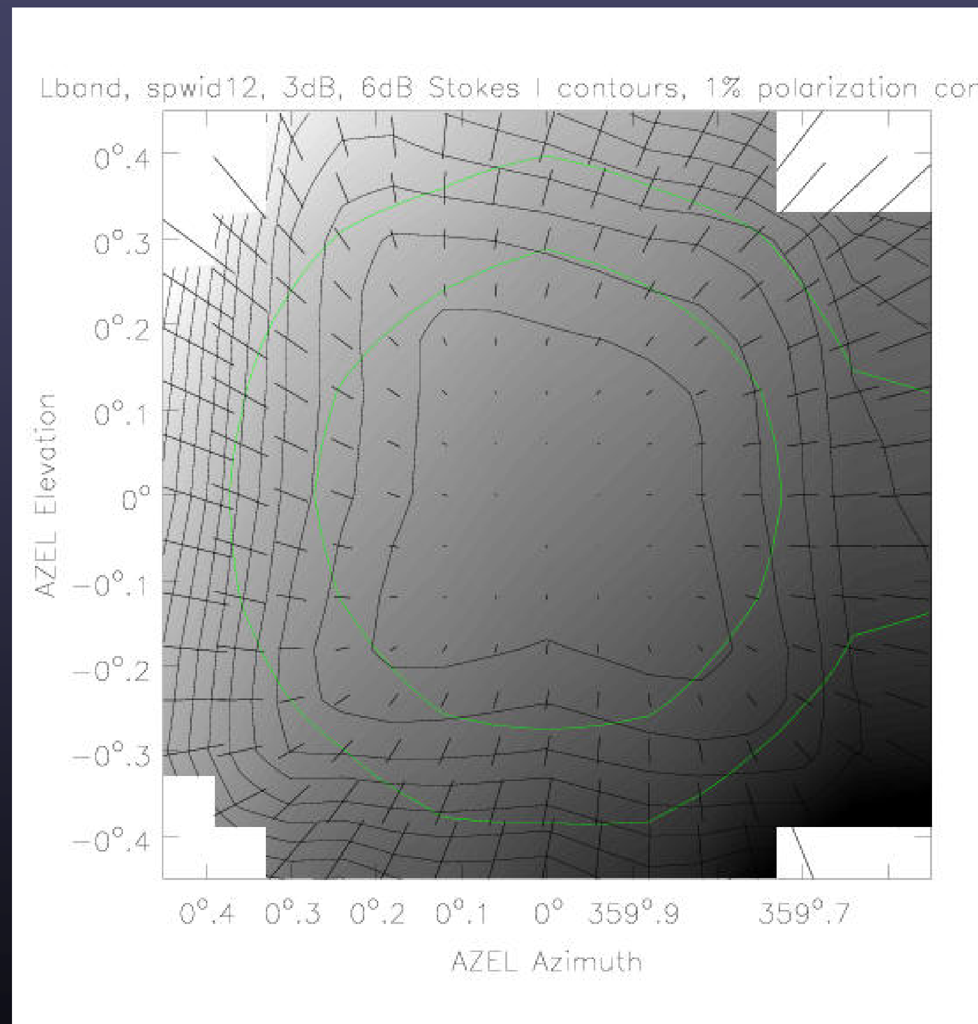




- See Bhatnagar, Cornwell, and Golap, *EVLA memo 84*

DDC: Full field polarization imaging

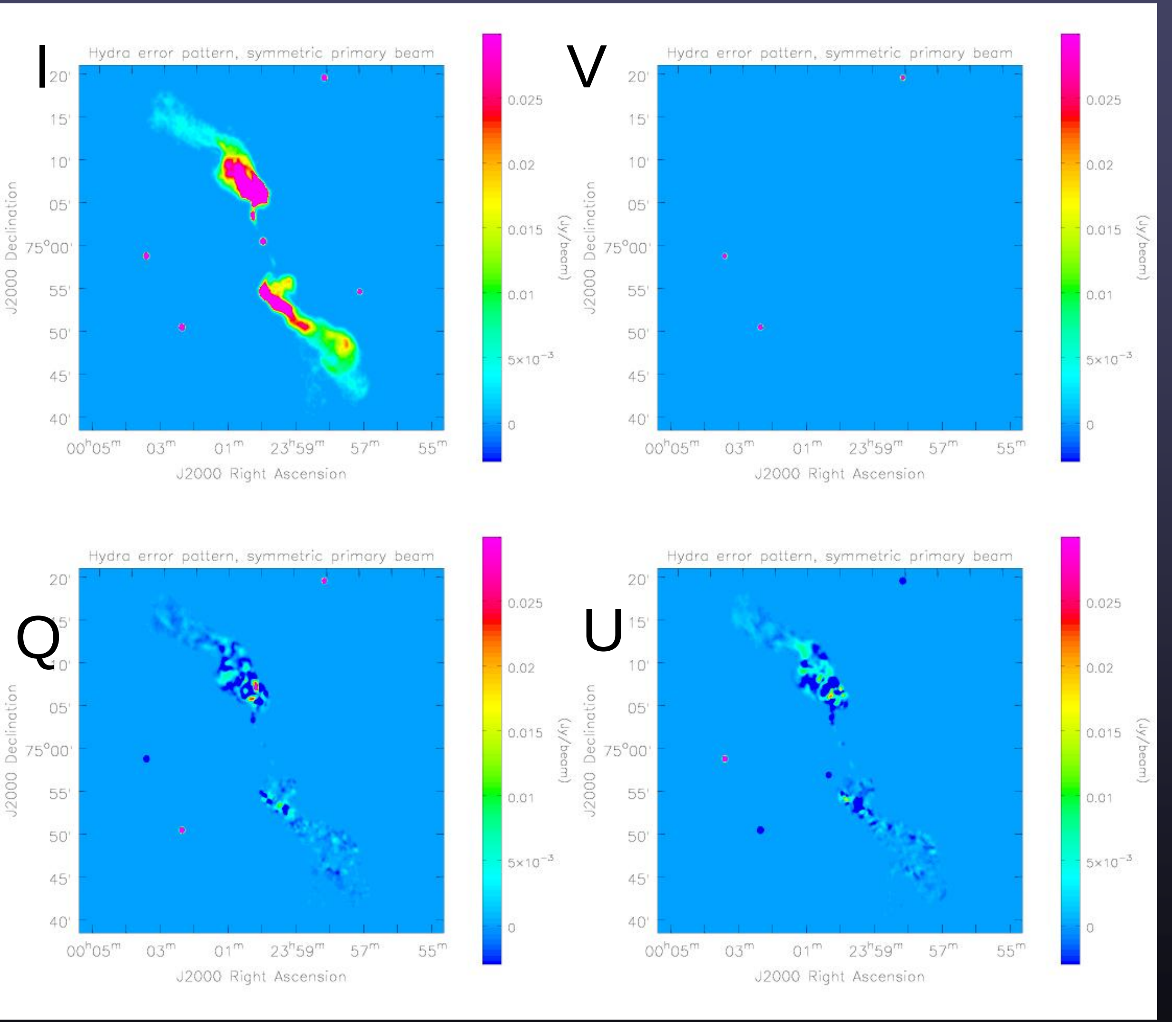
- VLA primary beams
  - Beam squint due to off-axis system
  - Instrumental polarization off-axis
  - Az-El telescopes
- Instrumental polarization patterns rotate on sky with parallactic angle
  - Limits polarization imaging
  - Limits Stokes I dynamic range (via second order terms)



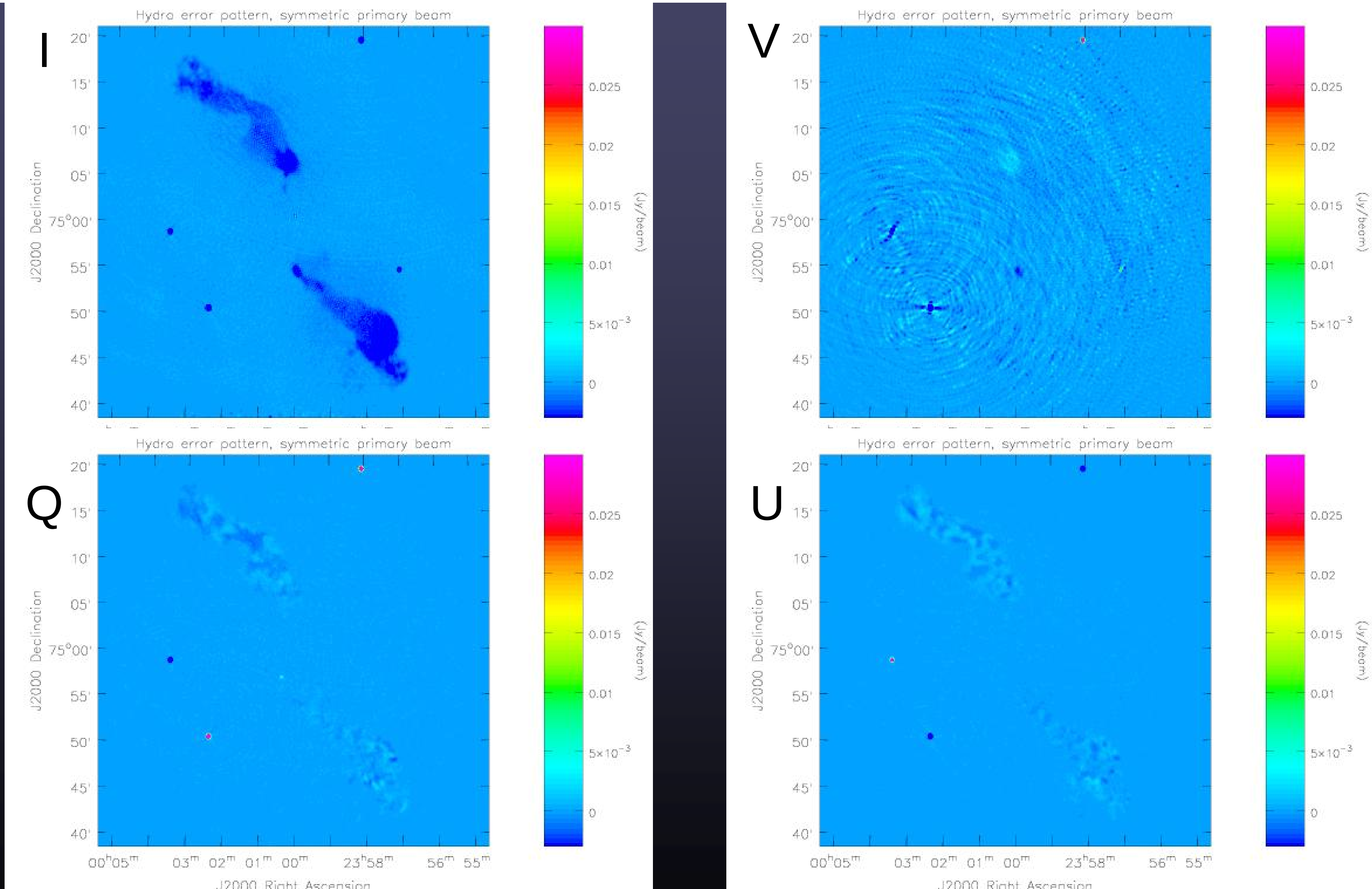
Green contours: Stokes I 3dB, 6dB, black contours: fractional polarization 1% and up, vectors: polarization position angle, raster: Stokes V

Simulations on a complex model

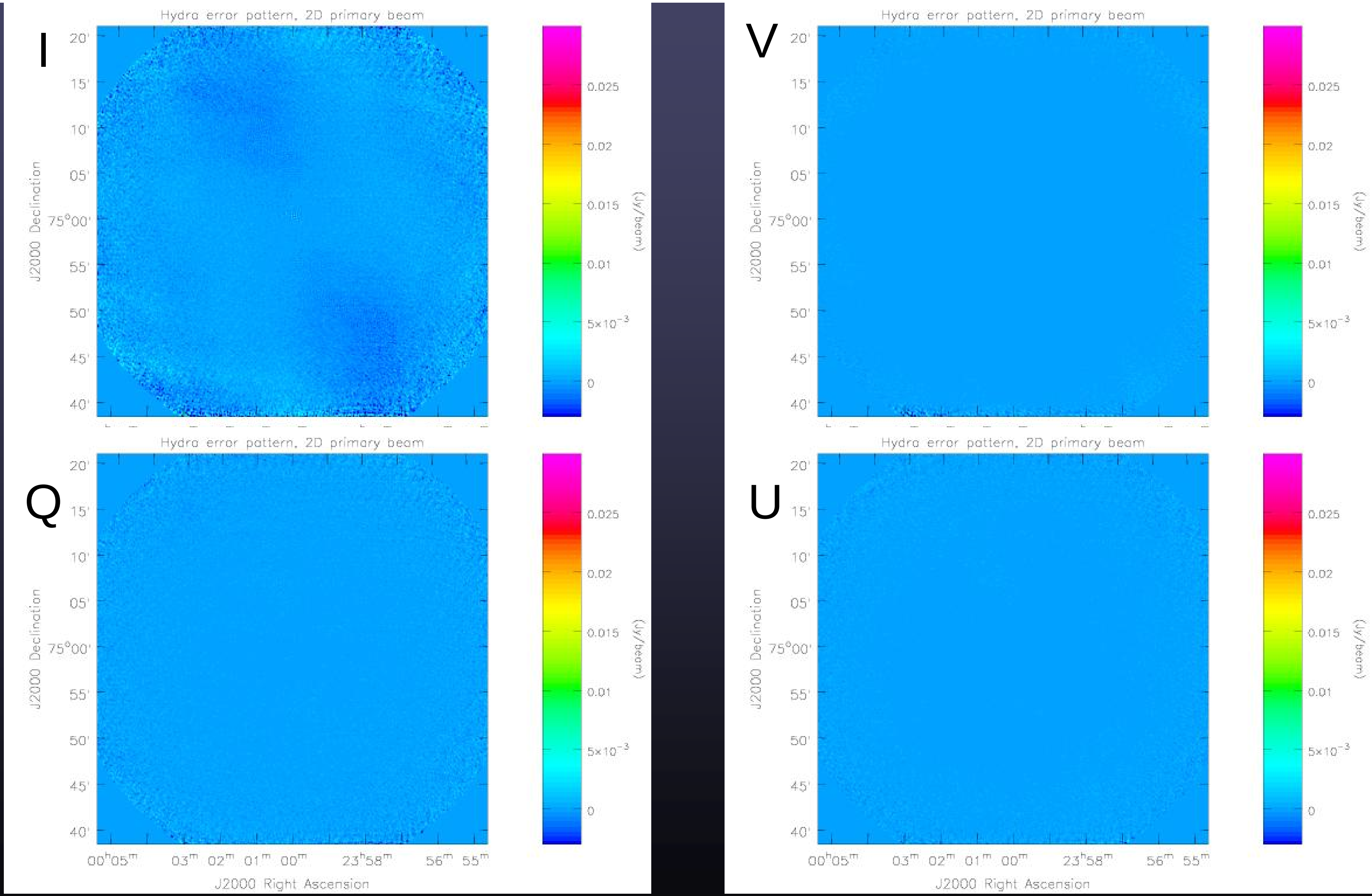
- VLA simulation of ~ 1 Jy point sources + large source with complex polarization (“Hydra A”)
- Long integration with full range of parallactic angles
- equivalent to weak 1.4GHz source observed with EVLA
- Antenna primary beam model by W. Brisken
- See EVLA memo 62



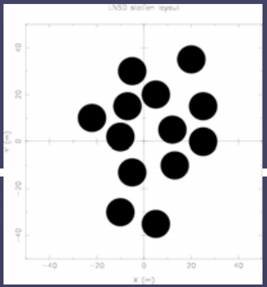
Polarization dynamic range ~ 200 when using symmetrical antenna beam model



Polarization dynamic range ~ 10,000 when using two-dimensional primary beam model

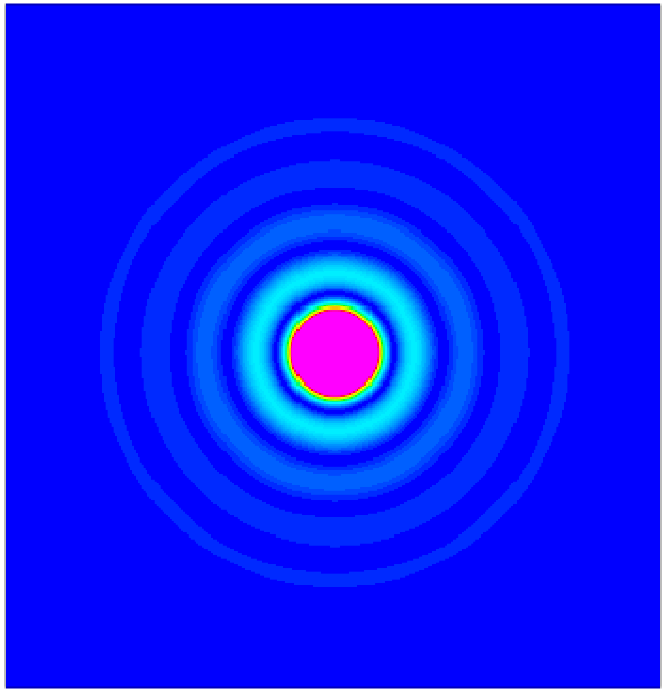


Special Problem: Station Beams

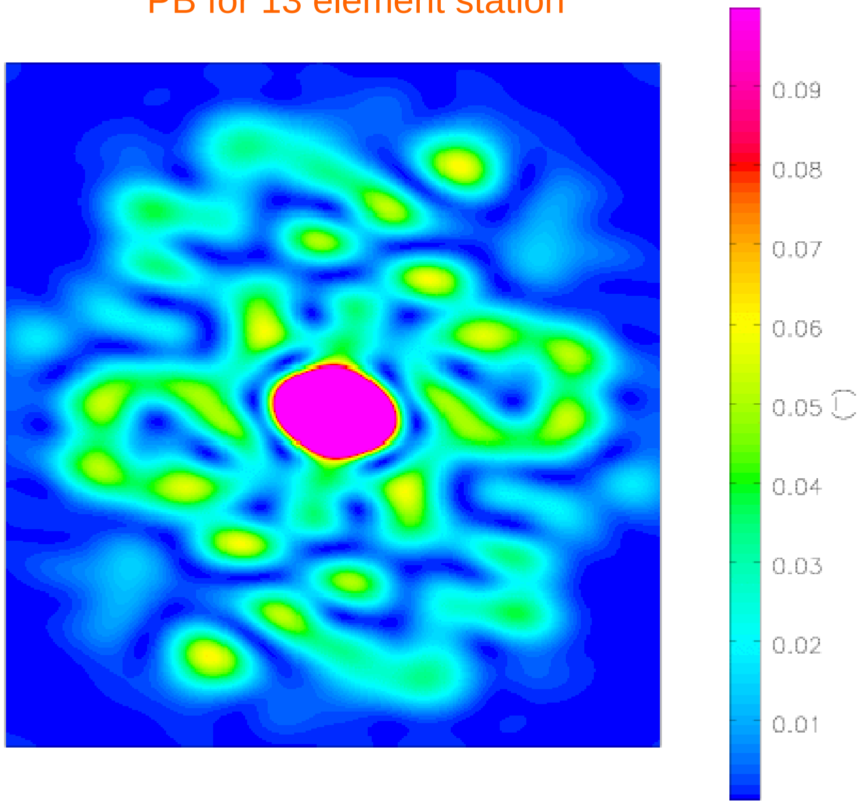


SKA LNSD station beam compared to ideal primary beam – also LWA, LOFAR, etc.

PB for 80m filled aperture



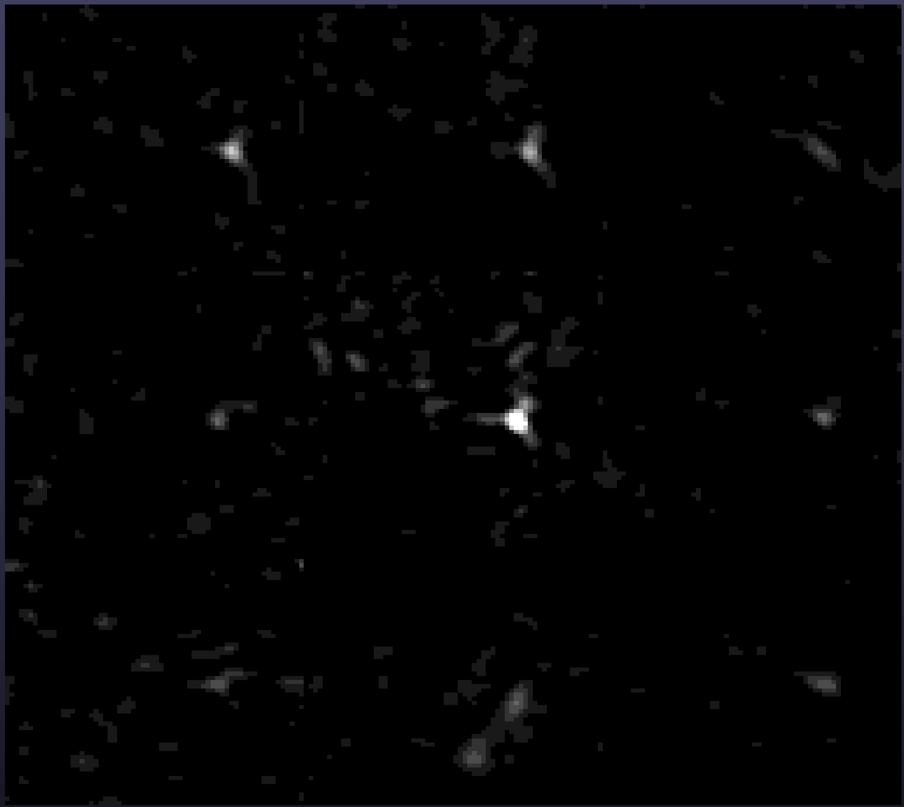
PB for 13 element station



Calibration errors will move the main lobe and sidelobes around

IC: ionospheric non-isoplanatism

- VLA refractive wander at 74MHz
  - Cotton's Field Based Calibration algorithm can correct
- Defocusing on baselines >10km
  - No known algorithm
- Will limit dynamic range at meter wavelengths
- Likely to be very expensive computationally
- Critical for LWA, LOFAR
- New approaches
  - reconstruct ionospheric volume above array?



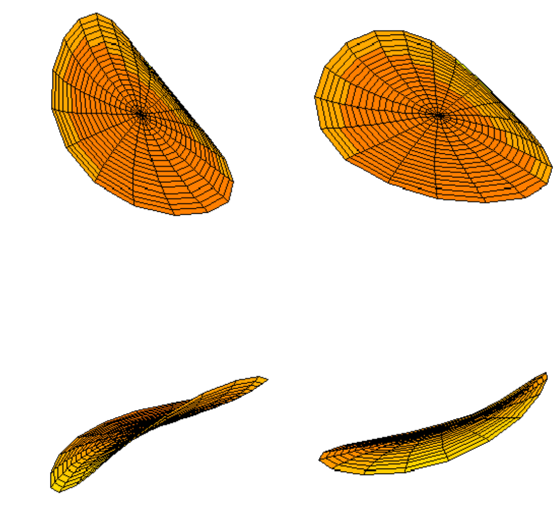
Example: Correcting the Ionosphere

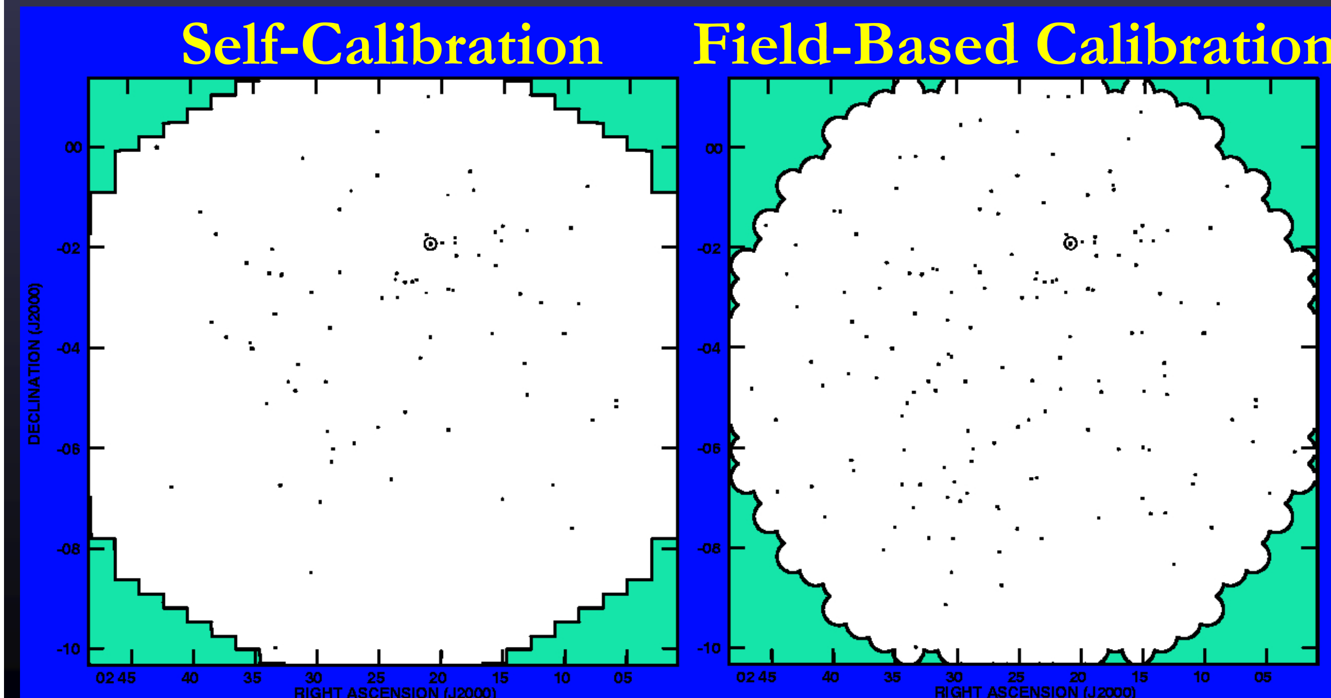
Problem

- At 74 MHz, phase distortions vary across the FOV

Solution: Field Based Calibration

- Take snapshot images of bright sources in the field and compare to NVSS positions
- Fit a 2nd order Zernike polynomial phase delay screen for each time interval
- Apply time varying phase delay screens while imaging





Work by Cotton and Condon

Slide from Aaron Cohen

WBI: MFS and beyond?

- Many next generation instruments rely upon increased bandwidth for improved continuum sensitivity
- Source spectral index and polarization variations over band and position
- Solve for spectral index or rotation measure images
  - fewer parameters than channels
  - but effective array (uv-coverage) changes over band!
- Multi-frequency synthesis
  - construct derivative image (e.g. d**I**/dν)
  - e.g. Conway, Cornwell & Wilkinson (1990)
- Critical for EVLA, eMERLIN, others…

The tip of the iceberg

- A number of challenging issues identified
- Some possible solutions and avenues for exploration identified
- Many problems in common for next generation instruments
  - wide-field wide-band high-dynamic range high-fidelity…
  - extremely high data rates and volumes
- Opportunities for collaboration!
- My own view
  - challenges are mostly algorithmic at this point
  - software package agnostic – develop in whatever you are comfortable with!
  - new frameworks & data models MAY allow interchange