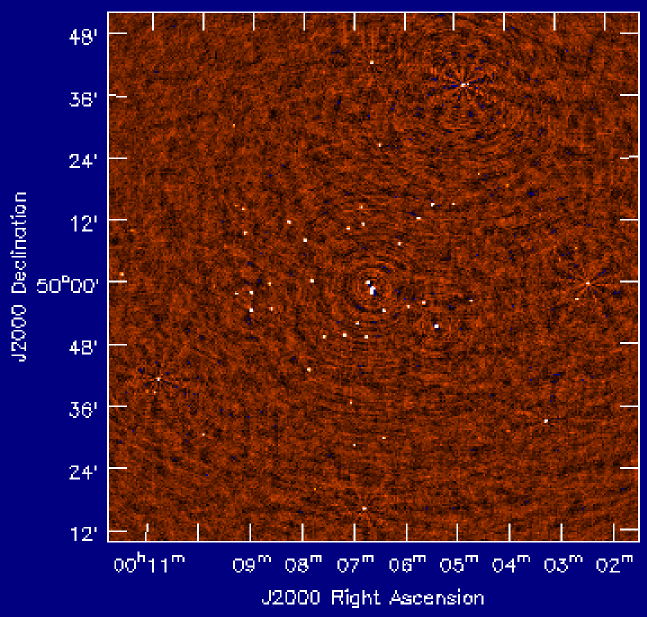
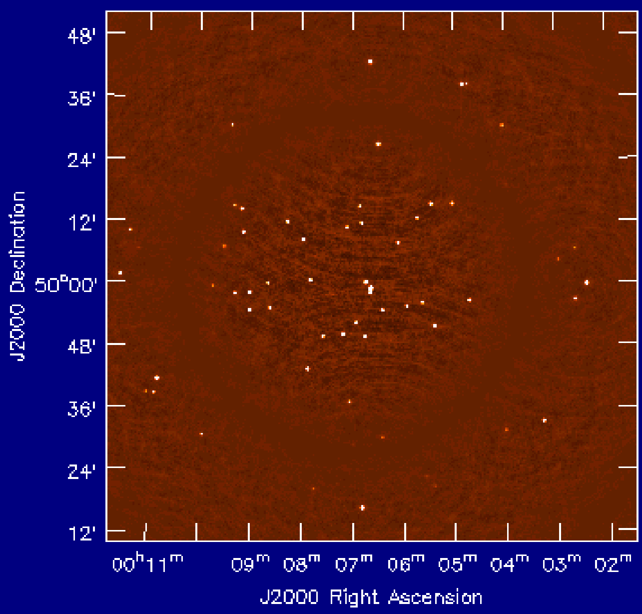
Image plane corrections





S. Bhatnagar

NRAO, Socorro

The Measurement Equation

- Generic Measurement Equation:

$$V_{ij}^{Obs}(\nu) = J_{ij}(\nu,t) \int J_{ij}^{S}(S,\nu,t) \; I(S) \; e^{\iota S.B_{ij}} \, dS$$

Data — Corruptions — Sky

$J_{ij} = J_i \otimes J_j^*$ **:direction independent corruptions.**

$J_{ij}^{s} = J_i^{s} \otimes J_j^{s*}$ **:image plane errors (direction dependent).**

- $V_{ij}^{Obs} = J_{ij} W_{ij} E_{ij} V^{o}$ where $E_{ij} = F J_{ij}^{s} F^{T}$
  - J_{ij} is multiplicative in the Fourier domain
  - J^{s}_{ij} is multiplicative in the Image domain *only if* $J^{s}_{i} = J^{s}_{j}$

Hierarchy of algorithms

- Unknowns of the problem: J_{ij}, J^s_{ij}, *and* I^M.
- $J^s_i = J^s_j$ and *independent* of time

Imaging and calibration as orthogonal operations

- $J^s_i(t) = J^s_j(t)$ (Poln. squint, PB correction, etc.) (Cornwell, EVLA Memo 62)
  - J^s_{ij} is multiplicative in the image plane for appropriate ∇T

$$\Delta I^D \propto \Re\left[\sum_n J^{s^T}(n\nabla T)\sum_{ij}[\Delta V_{ij}(\nabla T)e^{\iota S.B_{ij}}]\right]$$

Hierarchy of algorithms

- $J_i^s(t) \neq J_j^s(t)$ (Pointing offsets, PB variations, etc.)
  - Image plane effects not known a-priori
    - Pointing selfcal (EVLA Memo 84)
  - Correct for J^s_{ij} during image deconvolution
    - W-Projection, (EVLA Memo 67) PB-Projection (EVLA Memo 100)

- Simultaneous solver for J_{ij}, J^s_{ij}, *and* I^M!!

General structure of imaging algorithms

- $\vec{V}^{Obs} = A\vec{I}^{o}$ $\quad A$: The Measurement Matrix

- Solve the normal equation $A^T[\vec{V} - A\vec{I}] = 0$
  - Compute the approx. update direction: $\Delta I^D = A^T[\Delta V^R]$
  - Update the model: $I_i^M = I_{i-1}^M + \alpha\, max(\Delta I^D)$

    (Steepest Descent minimization: Clean algorithm)
  - Compute residuals: $\vec{V} - A\overrightarrow{I^M}$
- Transform implemented using FFT: $V^M = C[A\vec{I}^M]$
- Incorporate the image plane effects in the transform operator: Forward/inverse transforms: EA and $A^T E^T$
- Iteratively solve the modified normal equation:

$$B[\vec{V} - A\vec{I}] = 0 \quad \text{where } B \sim A^T$$

Motivation

- Single pointing L-Band observations limited due to pointing/PB asymmetries ~10-20microJy/beam.
  - Next generation telescopes hope to do >10x better
- Mosaicking dynamic range limited by pointing errors and azimuthally asymmetric PB/sidelobes.

- Use of pixel basis for image representation: deconvolution errors: > 10mircoJy/beam

- Frequency dependence of the sky & the instrument: 10-15microJy/beam (much greater than this when PB effects are included!)

Measured direction dependent effects

- E_{ij} as a function of direction is measured a-priori (nominal full beam polarimetric imaging)

$$V^M_{ij} = \boldsymbol{E}_{\boldsymbol{ij}} [\boldsymbol{A}\,\boldsymbol{I}^M]_{ij} \quad where \quad E_{ij}(l_i, l_j, u_{ij}; p_i, p_j)$$

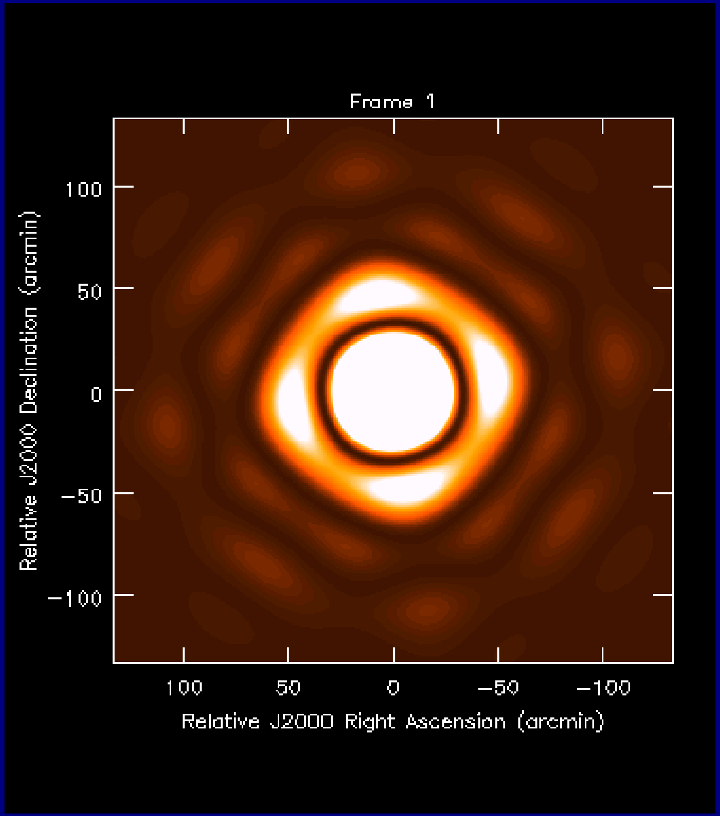
- Aperture Function: E_i *different* for each poln. product *pq* (pointing offsets correction)

  Needs a solver: Pointing SelfCal

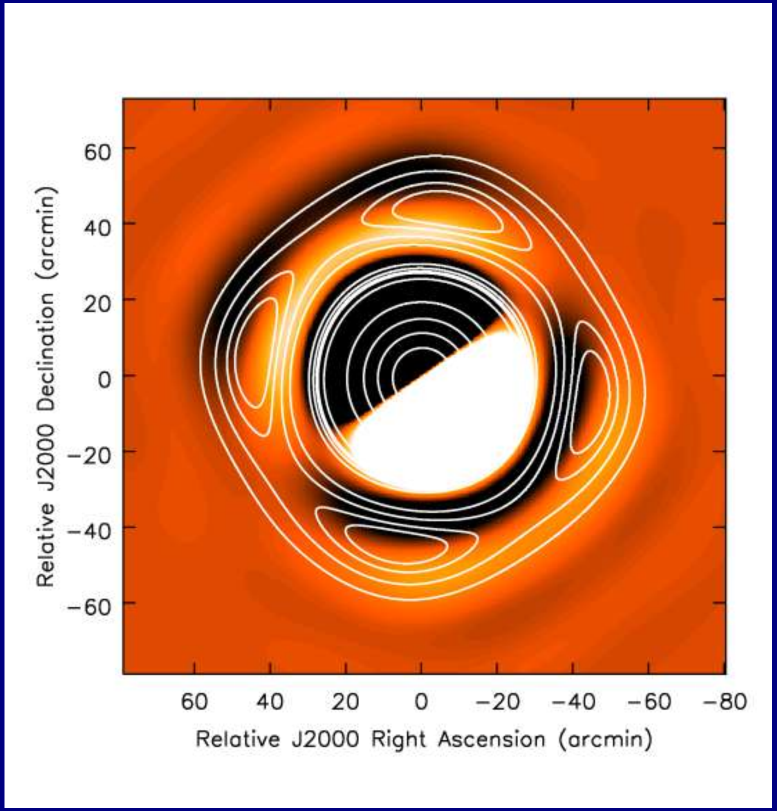
- Asymmetric Primary Beams:

Power patterns

Model for VLA antenna power patters at L-band
(modeling code courtesy W.Brisken)

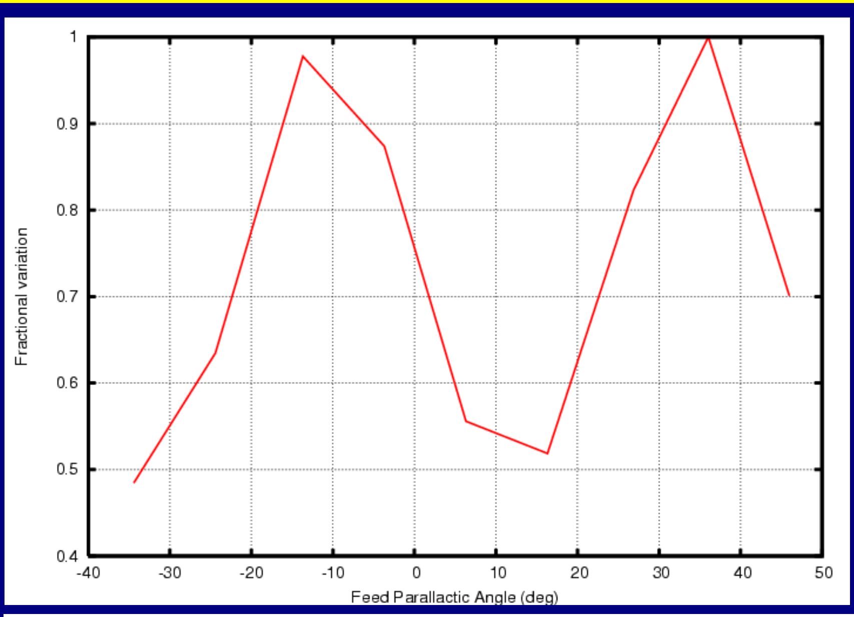


Stokes-I

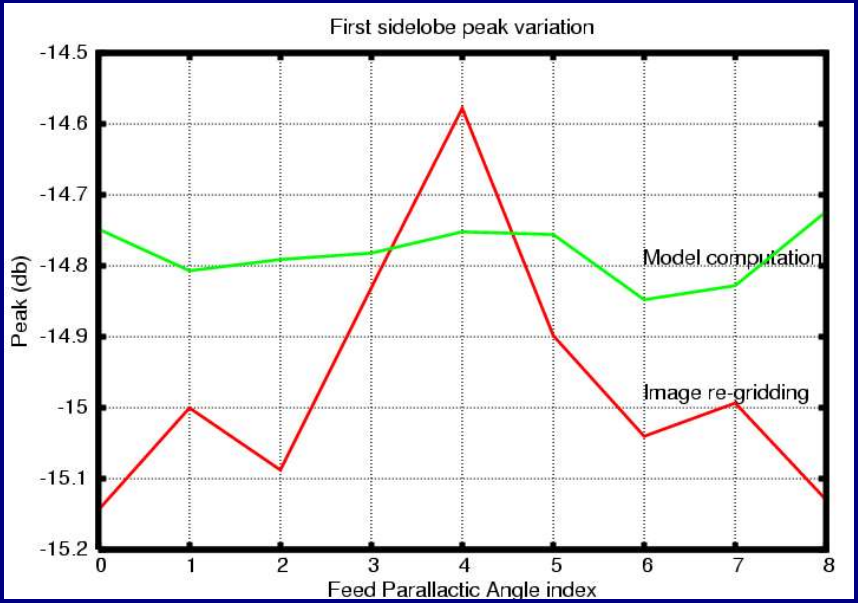


Stokes-V

Variable side-lobe gain



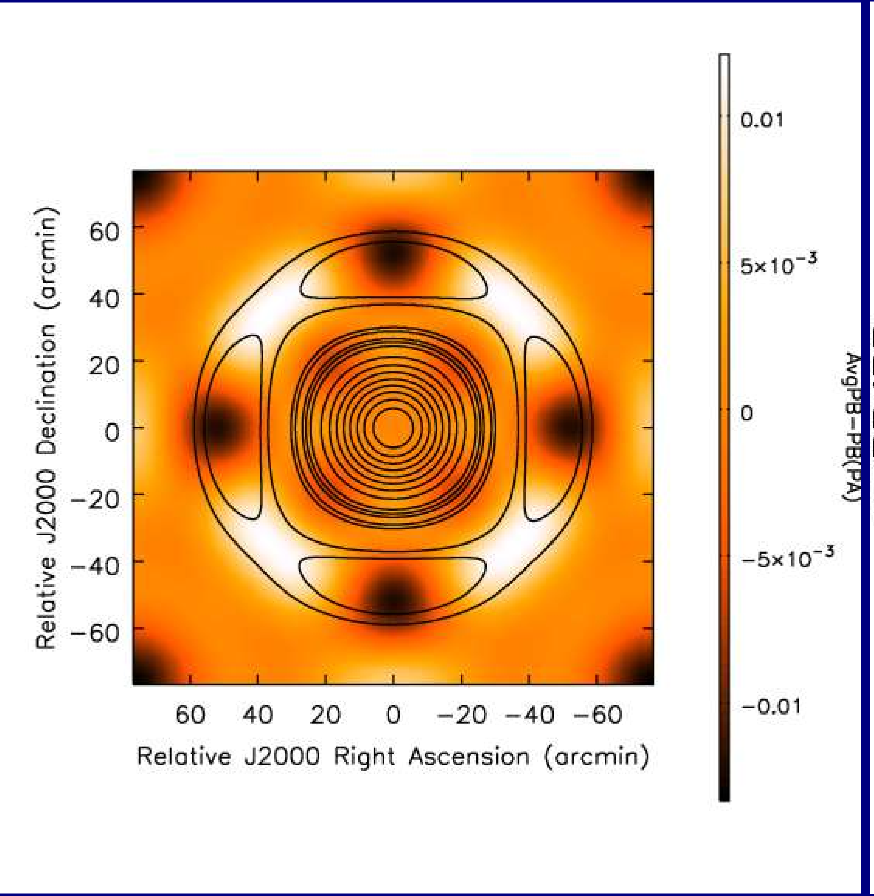
Maximum gain variations at the location of the sidelobes

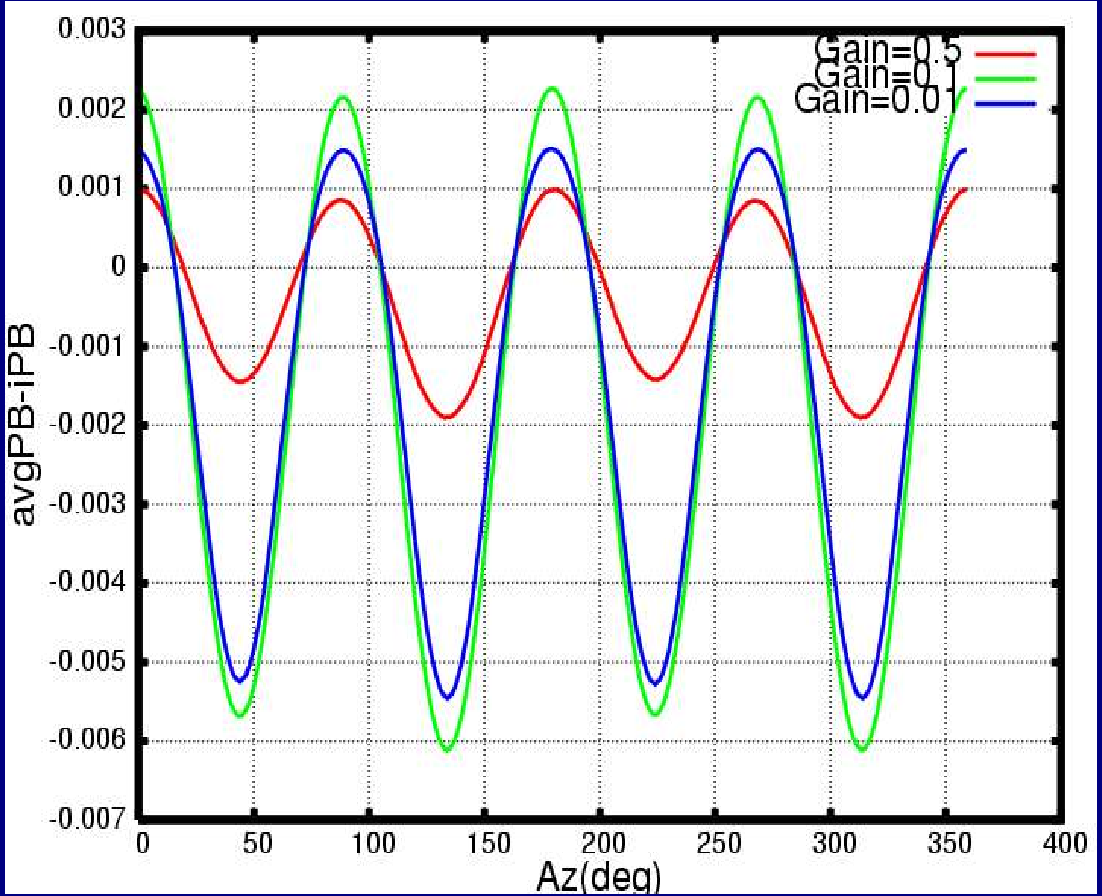


Numerical errors: Variations in the peak of the sidelobe.

Image re-gridding vs. direct evaluation

Error patterns



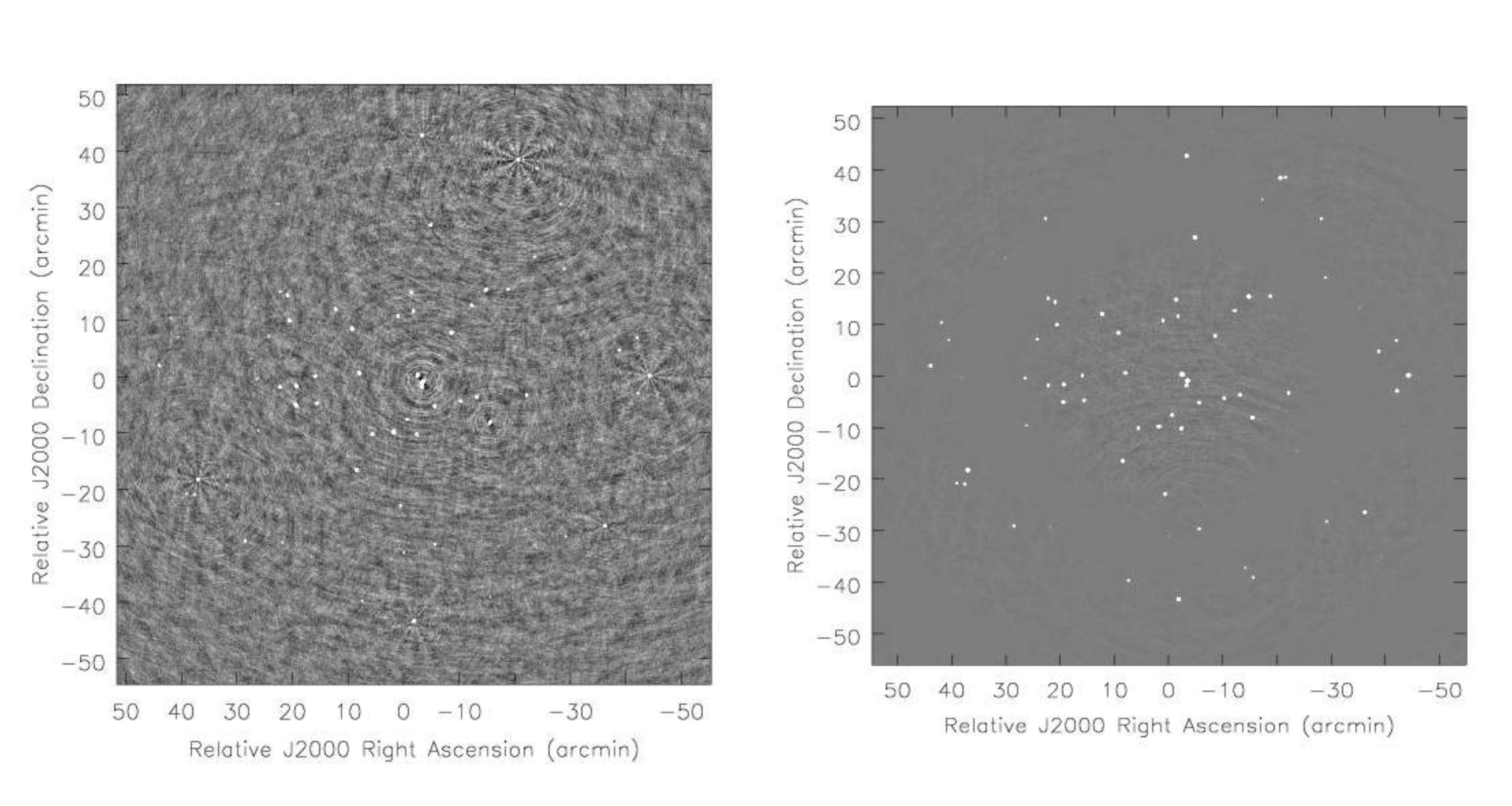


AvgPB - PB(t_o)

Azimuthal cuts at 50%, 10% and 1% of the Stokes-I error pattern AvgPB - PB(t_o)

Simulations: Stokes-I

Stokes-I imaging with and without PB effects
(Polarization squint, Pointing offsets, PB rotation)

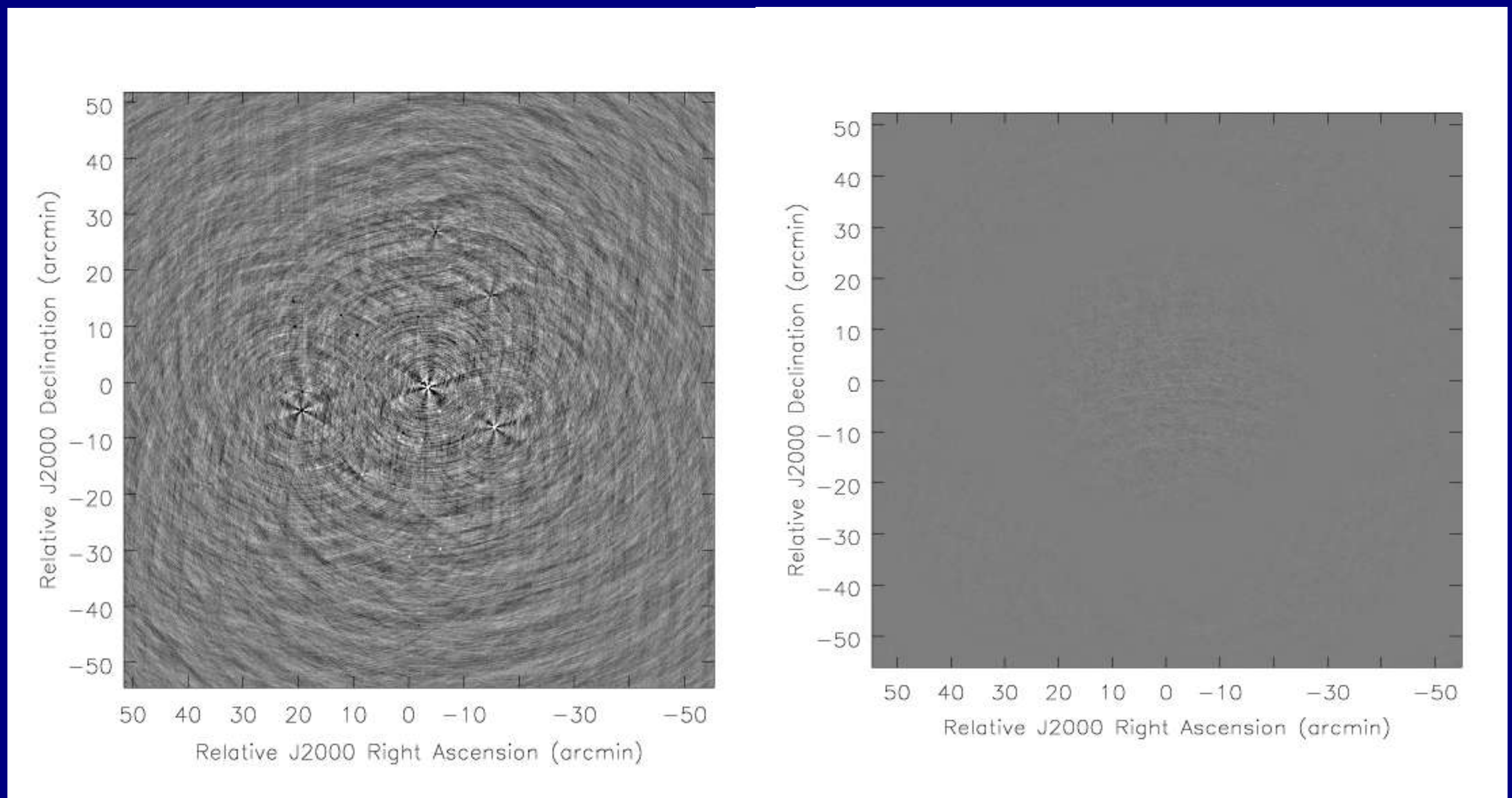


RMS ~15μJy/beam RMS ~1μJy/beam

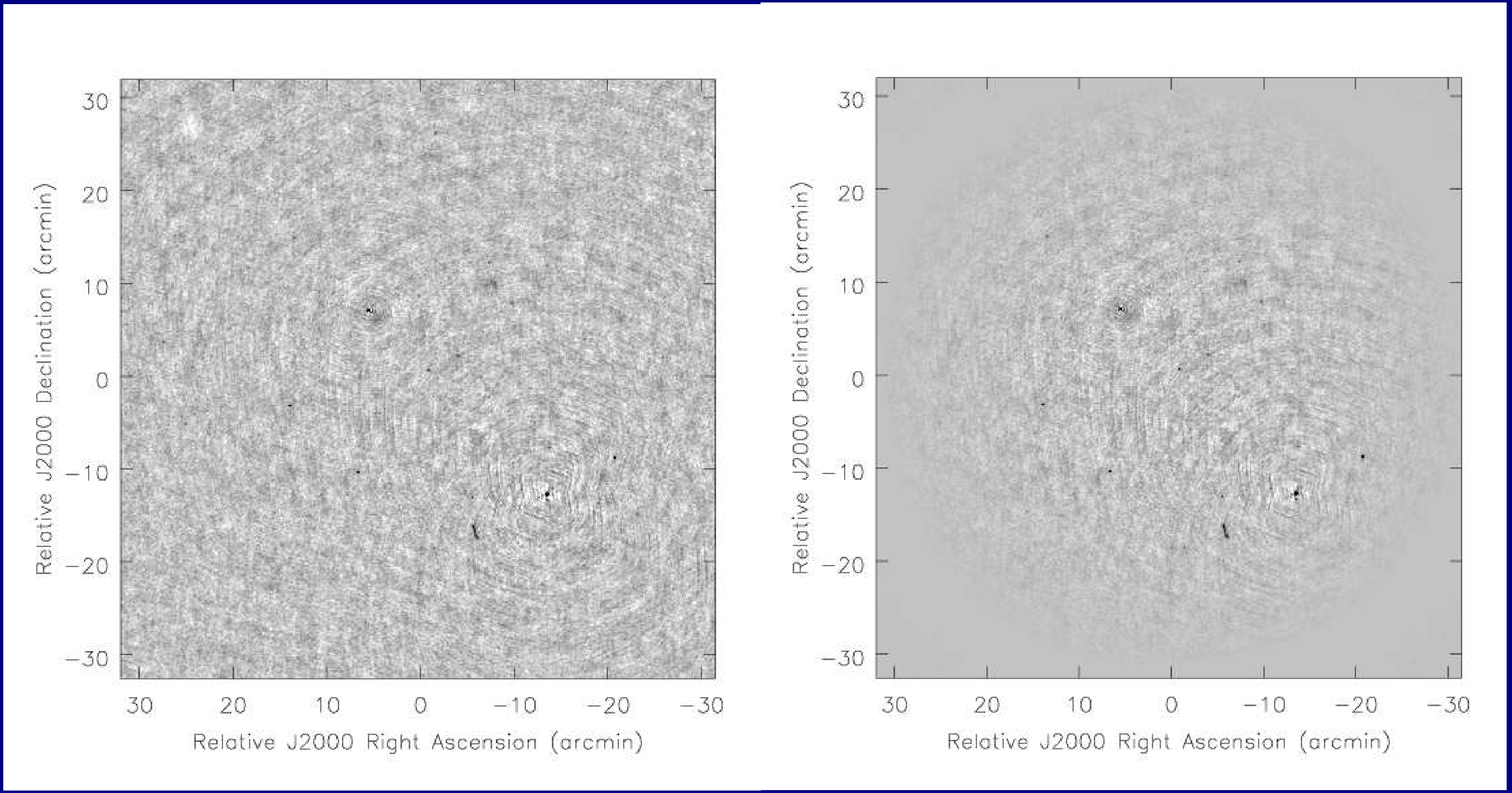
Simulations: Stokes-V

Stokes-V imaging with and without PB effects

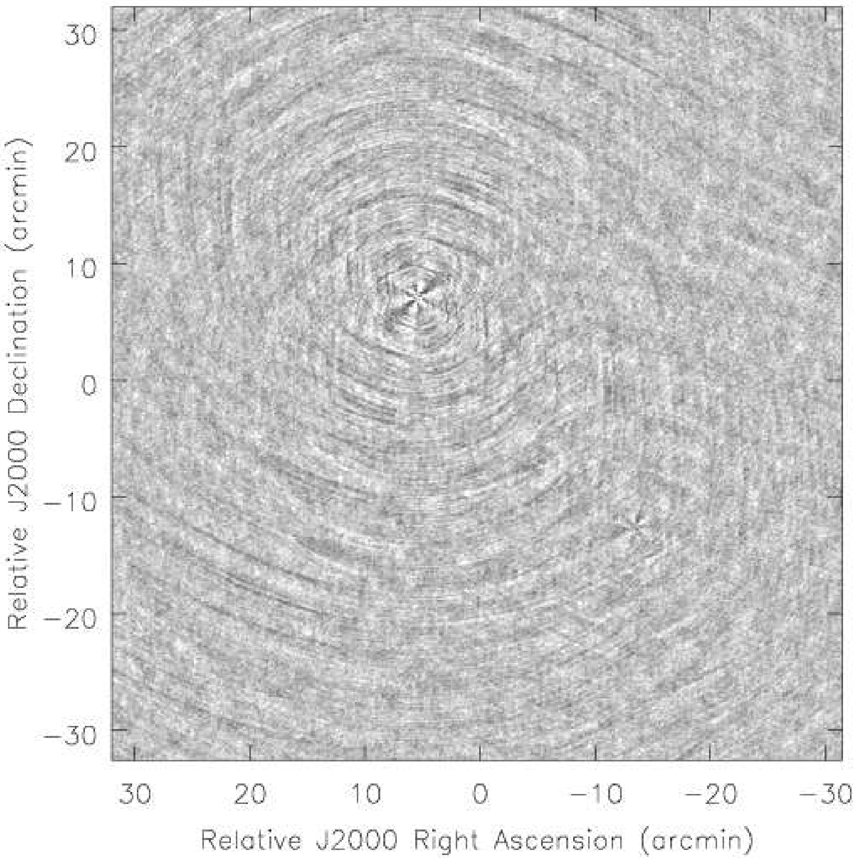
(Polarization squint, Pointing offsets, PB rotation)

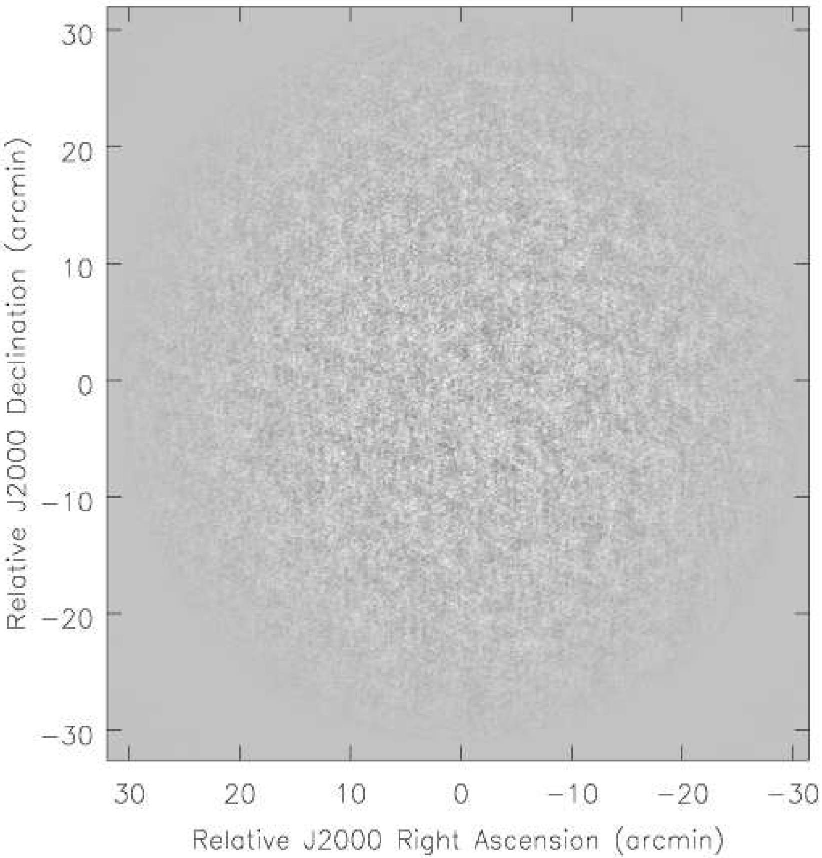


VLA L-Band C-array: Stokes-I

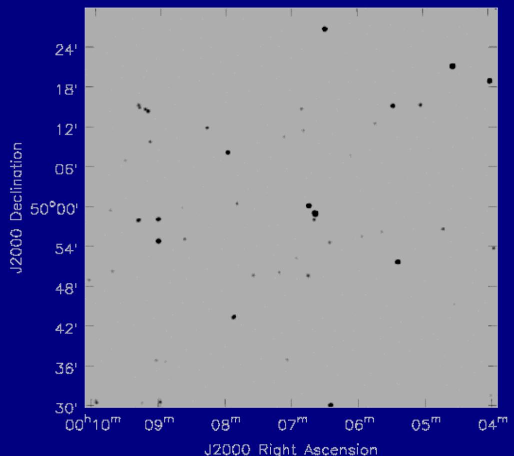


VLA L-Band C-array: Stokes-V





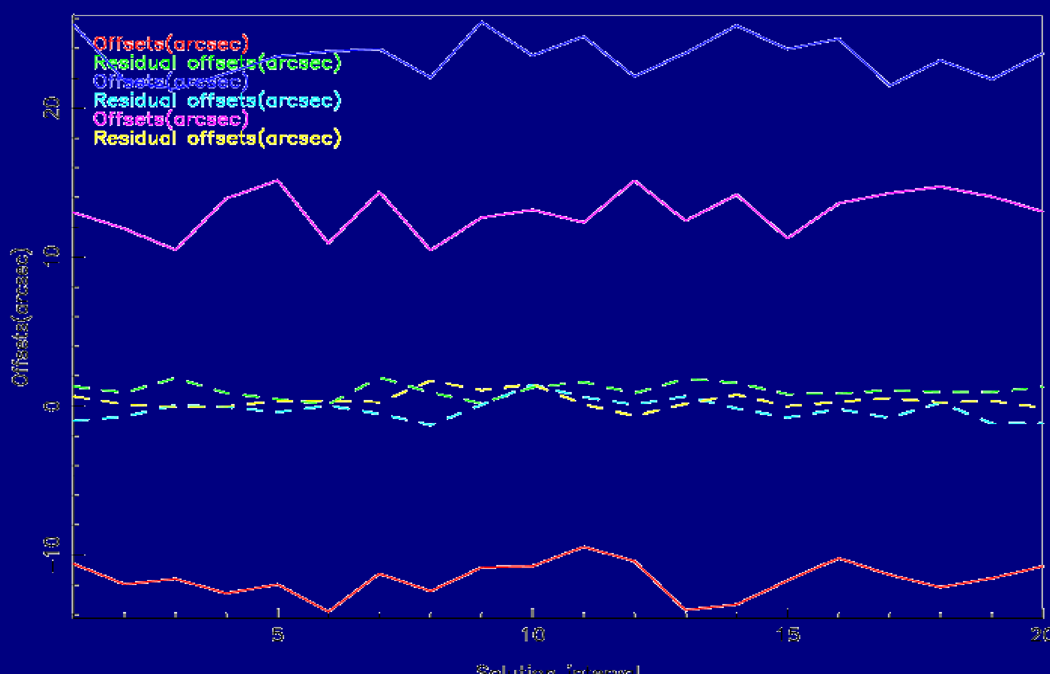
Pointing correction



Model image using 59 sources from NVSS.
Flux range ~2-200 mJy

Details in EVLA Memo 84 (2004)

http://www.aoc.nrao.edu/evla/geninfo/memoseries/evlamemo84.pdf

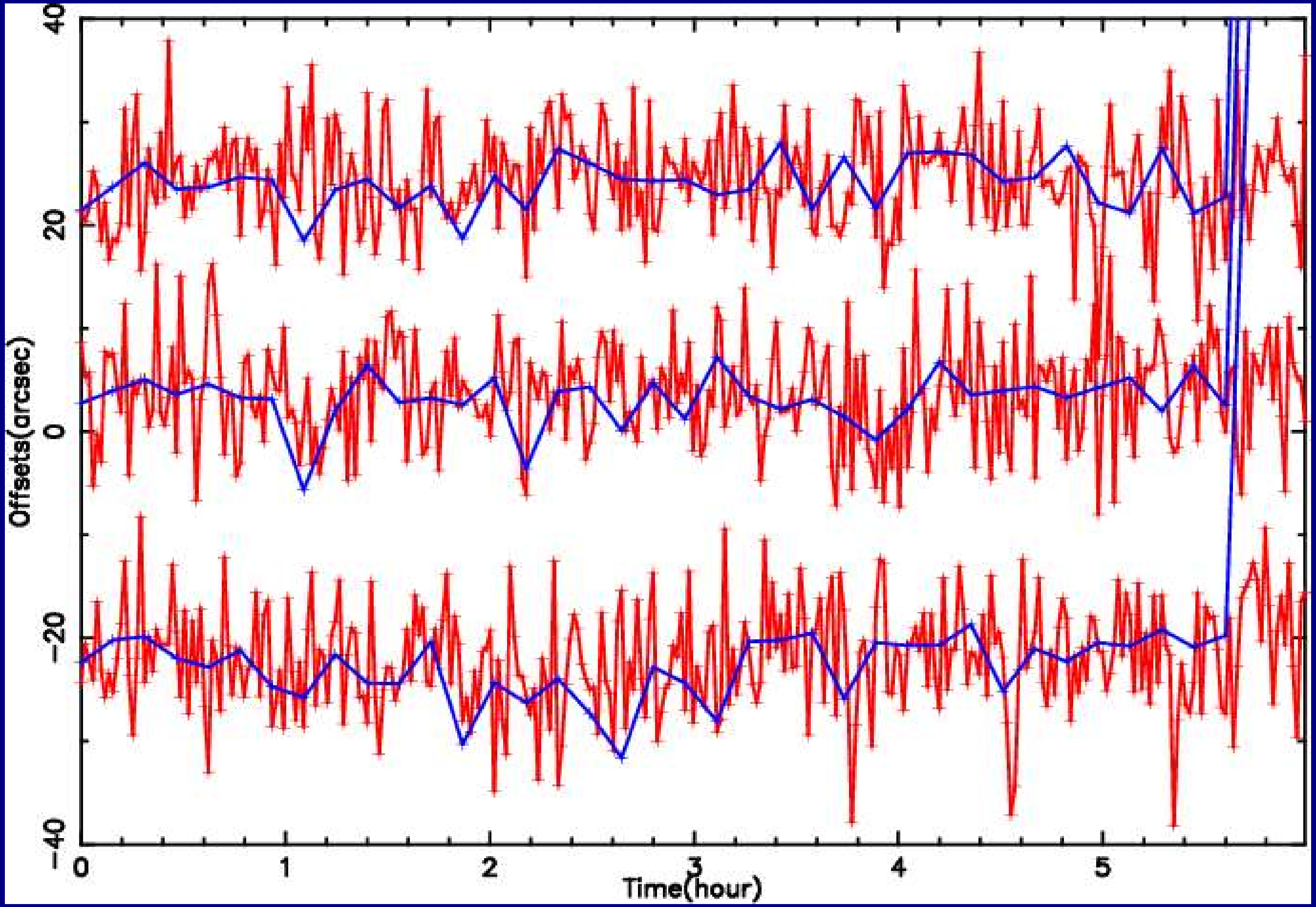


Continuous lines: Typical antenna pointing offsets for VLA as a function of time (Mean between +/- 25” and RMS of 5”).

Dashed lines: Residual pointing errors. RMS ~1”.

Pointing SelfCal: "Unit" test

Test for the solver using simulated data



Red: Simulated pointing offsets τ=60sec

Blue: Solutions τ=600sec

Time lines: Research

- Note on algorithm research, Aug. 2004

  http://www.aoc.nrao.edu/~sbhatnag/Talks/AlgoDevelopment.ps

- Major areas of work:
  - Scale sensitive deconvolution (Asp paper, 2004[2003])
  - Correction of PB effects (Poln., pointing, sidelobes,etc.)

    Basic algo: Pointing Selfcal (2004), Imaging (early 2005)
  - Wideband imaging (will require the above)

- Difficult to translate research into Project Management lingo (“deliverables”, etc.!) - still made an attempt!
  - “Demonstrable” progress: ~1 year
  - Tricky details: ~3 years (probably more)

Time lines: Development

- Code development time much longer
  - Complexity – code base
    - Partly unavoidable
    - Improvements: Possible & Necessary
    - Use of simpler UI (UNIX command-line, inp/set/save/go)
      - Currently usable on real data (minus data selection)
  - Complexity – algorithm
    - Very difficult to predict (more difficult in evolving code-base)
    - Can run into dead-ends
- Optimization and stability/robustness
  - From "working algorithm" to "usable implementation"
  - Stability/robustness/numerical testing: Time consuming & related to the code-base complexity/stability/evolution.

Progress so far

- Use aperture function / eliminate re-gridding [Done]
- Write the imaging and solver code [Done]
- SelfCal <-> imaging iterations [Testing]
- Component image model (Asp-Clean + PB-Projection + W-Projection) [Next!]

- Is current deep L-band imaging pointing-error limited?
- Mosaicking dynamic range limited by pointing errors?
- Wide-band imaging
  - Use PB-projection to correct for PB scaling
  - MSF extensions: Freq. sensitive image plane modeling (Component based imaging)

Interesting extensions

- Fast mosaicking
  - Use the pointing vector as the “offset” (Golap): Azimuthally symmetric PB
  - Use model for aperture illumination as a function of PA and pointing errors
  - Variable PB-sidelobes and pointing errors constitute the dominant error for mosaicking: Not included in existing simulations/imaging performance estimates
- Wide band imaging
  - PB scaling contributes the dominant error: Not included in existing simulations
  - Use it with Component based sky model

Computing and I/O costs

- Significant increase in run-time due to more sophisticated parameterization
  - Deconvolution: Fast transform (both ways)
    - E.g. limits the use of MCMC approach
  - Calibration: Fast prediction

- Cost of computing residual visibilities is dominated by I/O costs for large datasets (~200GB for EVLA)
  - Deconvolution: Approx. 20 access of the entire dataset
  - Calibration: Each trial step in the search accesses the entire dataset

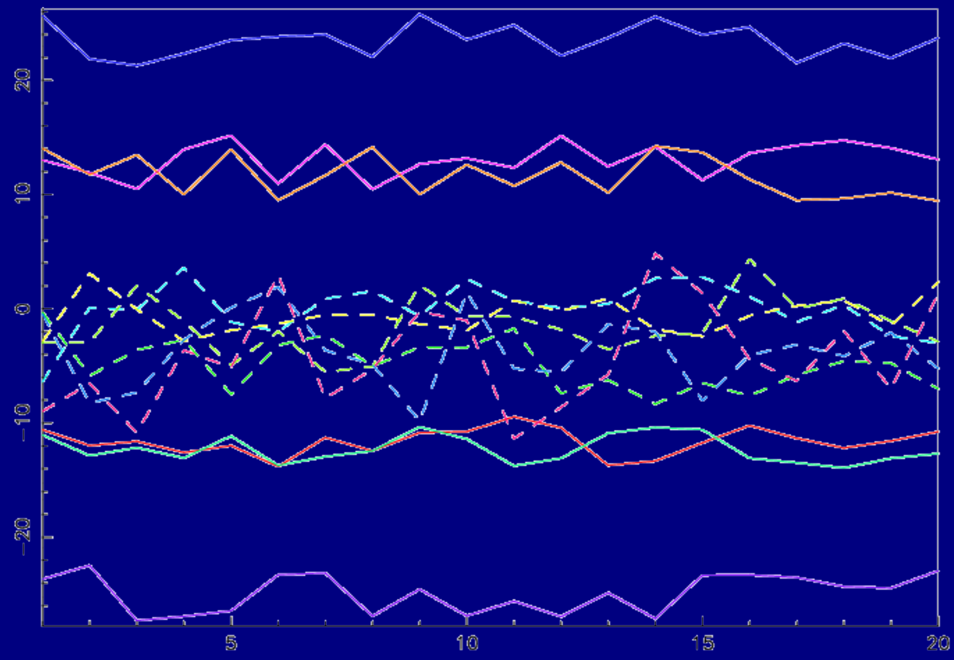
References

1. Hamaker, Bregman & Sault, 1996, A&AS, 117, 137
2. Cornwell, 1995, The Generic Interferometer: II Image Solvers, AIPS++ Note 184
3. Bhatnagar & Cornwell, 2004, Scale sensitive deconvolution of interferometric images, A&A, 426, 747-754, 2004 (astro-ph/0407225)
4. Cornwell, Golap & Bhatnagar, 2003, W-Projection: A new algorithm for non-coplanar baselines, Tech. rep., EVLA Memo 67
5. Brisken, 2003, Using Grasp8 To Study The VLA Beam, Tech. rep., EVLA Memo 58
6. Bhatnagar, Cornwell & Golap, 2004, Solving for the antenna based pointing errors, Tech. rep., EVLA Memo 84
7. Bhatnagar, Cornwell & Golap, 2006., Image plane corrections, EVLA Memo 100

http://www.aoc.nrao.edu/~sbhatnag/talks.html

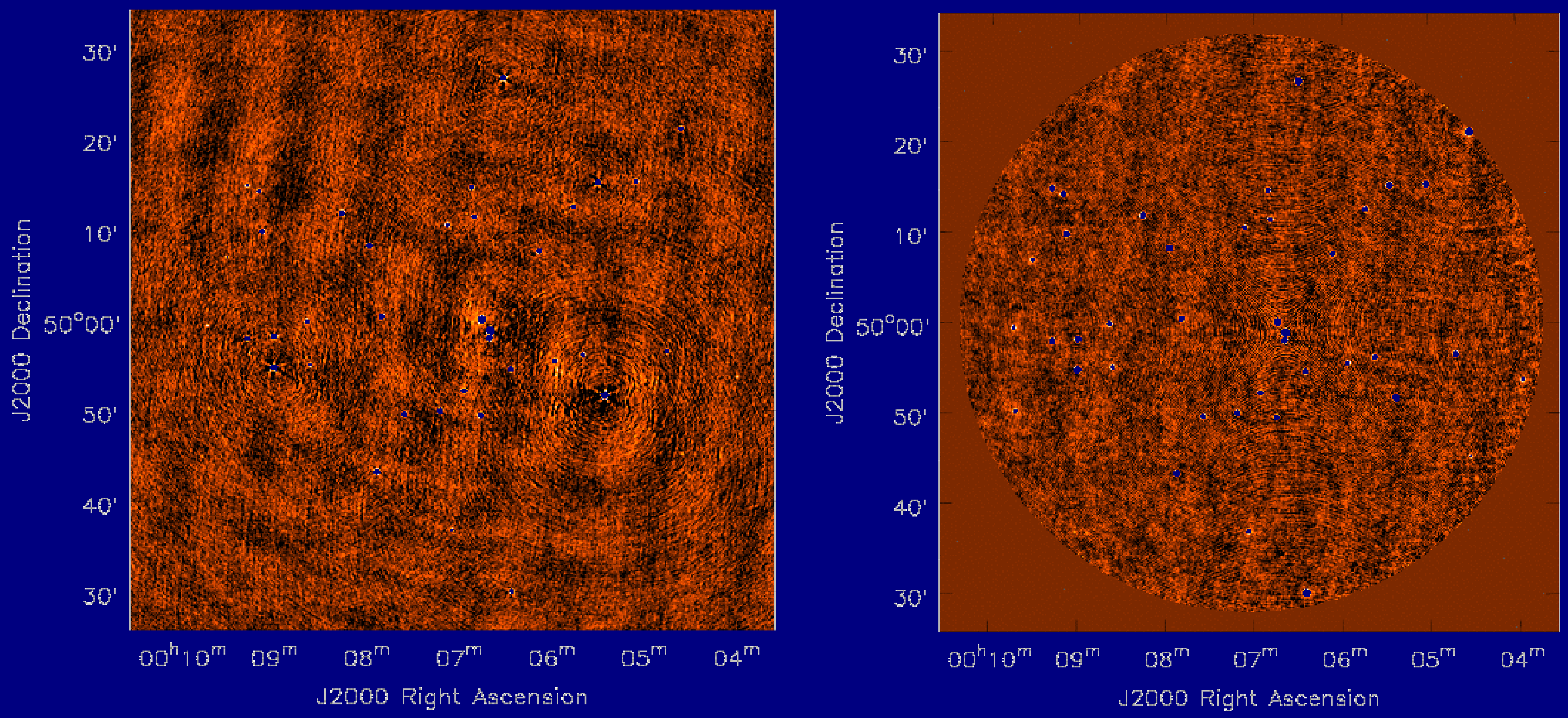
Pointing SelfCal

- Model image: deconvolved using entire data
- Pixelated model image



Pointing SelfCal

- Stokes-I imaging: Before and after pointing correction



Pieces of the puzzle

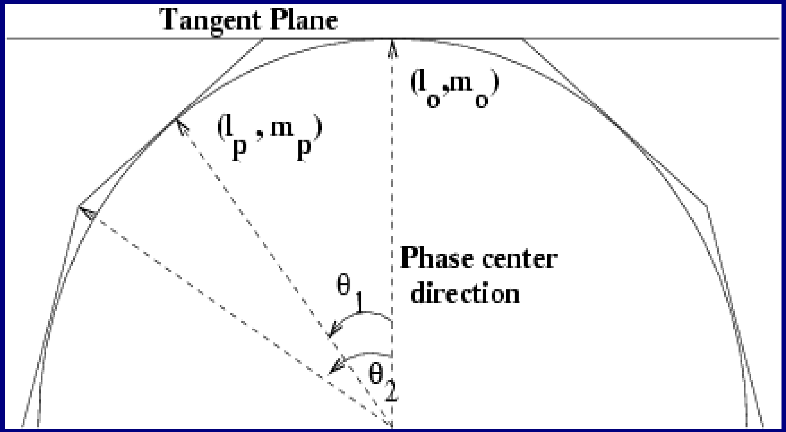
- Efficient algorithms to correct for image plane effects
  - Approximate inverse transform (Vis -> Image)
  - Forward transform (accurate)
- Decomposition of the sky in a more appropriate basis
  - Frequency sensitive
- Solvers for the “unknown” image plane effects
  - As expensive as imaging!
- Larger computers! (More memory, CPU power, fast I/O)

Known direction dependent effects

- Non-coplanar baselines

$$V(u,v,w) = \iint I(l,m)\,G(l,m,w)\,e^{2\pi\iota(ul+vm)} \frac{dl\,dm}{\sqrt{1-l^2-m^2}}$$

- Traditional approach: Faceting



- W-projection: Visibility filtering (>10x faster)

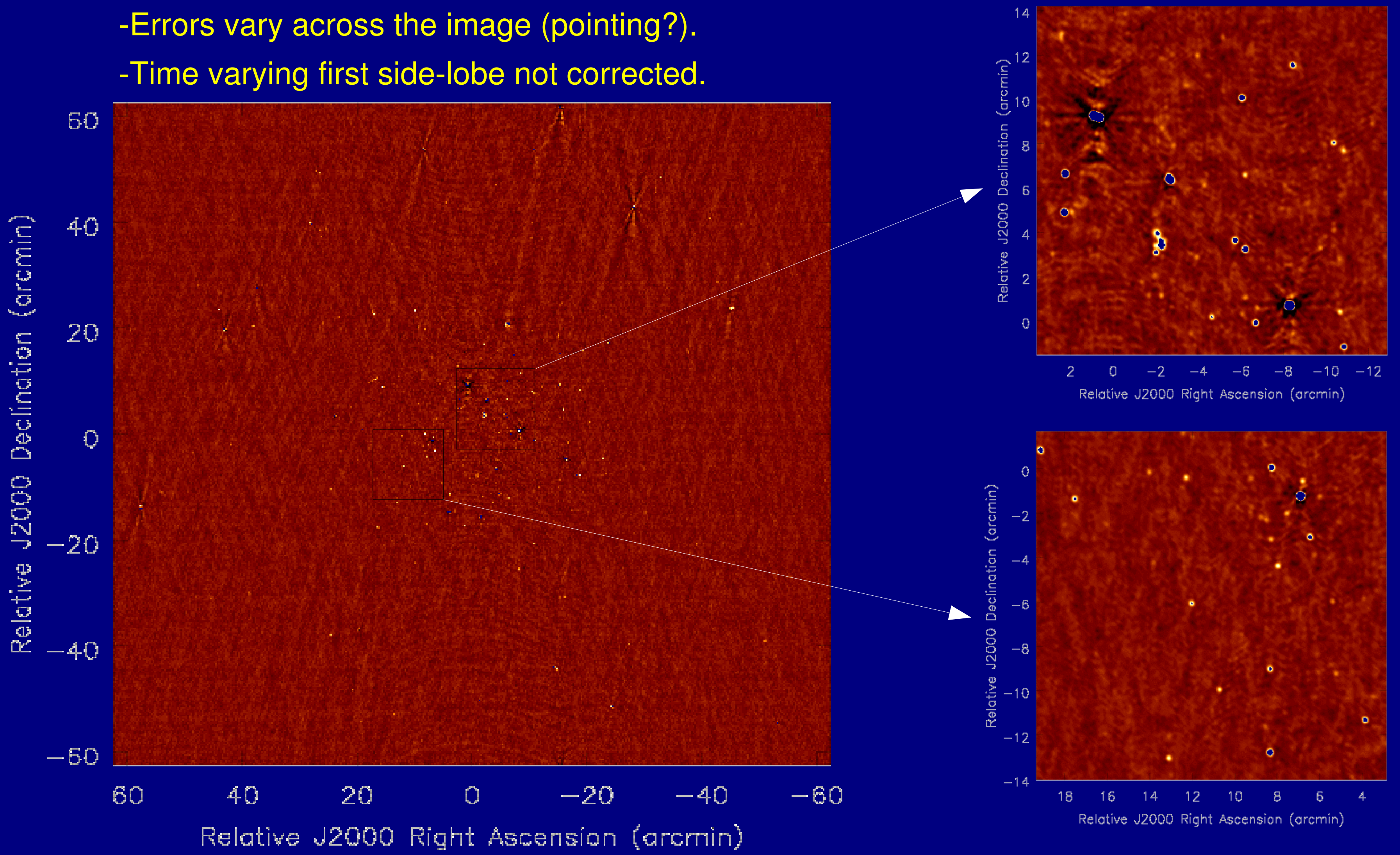
W-projection: Example

L-Band, VLA C-array, ~40hr. integration (Fomalont et al.)

-RMS: ~15microJy, Peak: 40mJy

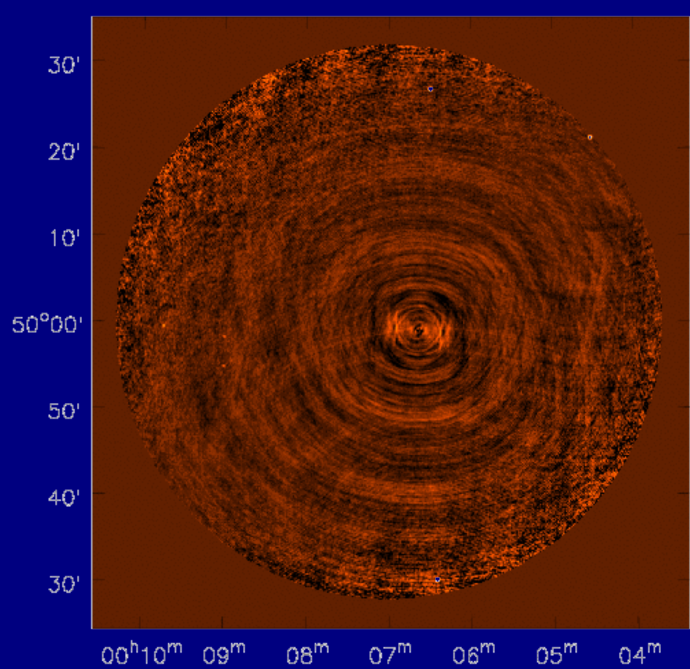
-Errors vary across the image (pointing?).

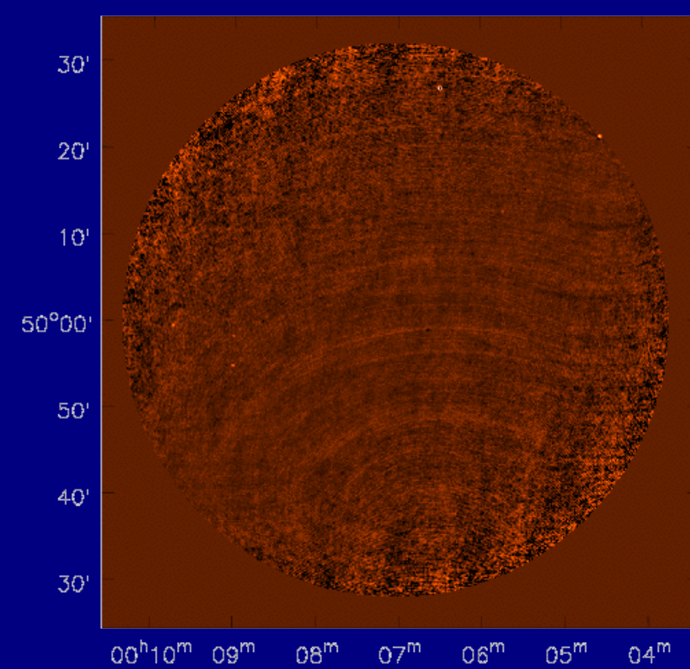
-Time varying first side-lobe not corrected.



Pointing SelfCal

- Stokes-V imaging: Need to use component imaging?





Scale sensitive imaging: Asp-Clean

- Pixel-to-pixel noise in the image is correlated

$$I^D = PI^o + PI^N \quad \text{where} \quad P = \text{Beam Matrix}$$

- The scale of emission *fundamentally* separates signal *(I^o)* from the noise *(I^N).*

- Asp-Clean (Bhatnagar & Cornwell, A&A,2004)
  - Search for local scale, amplitude and position