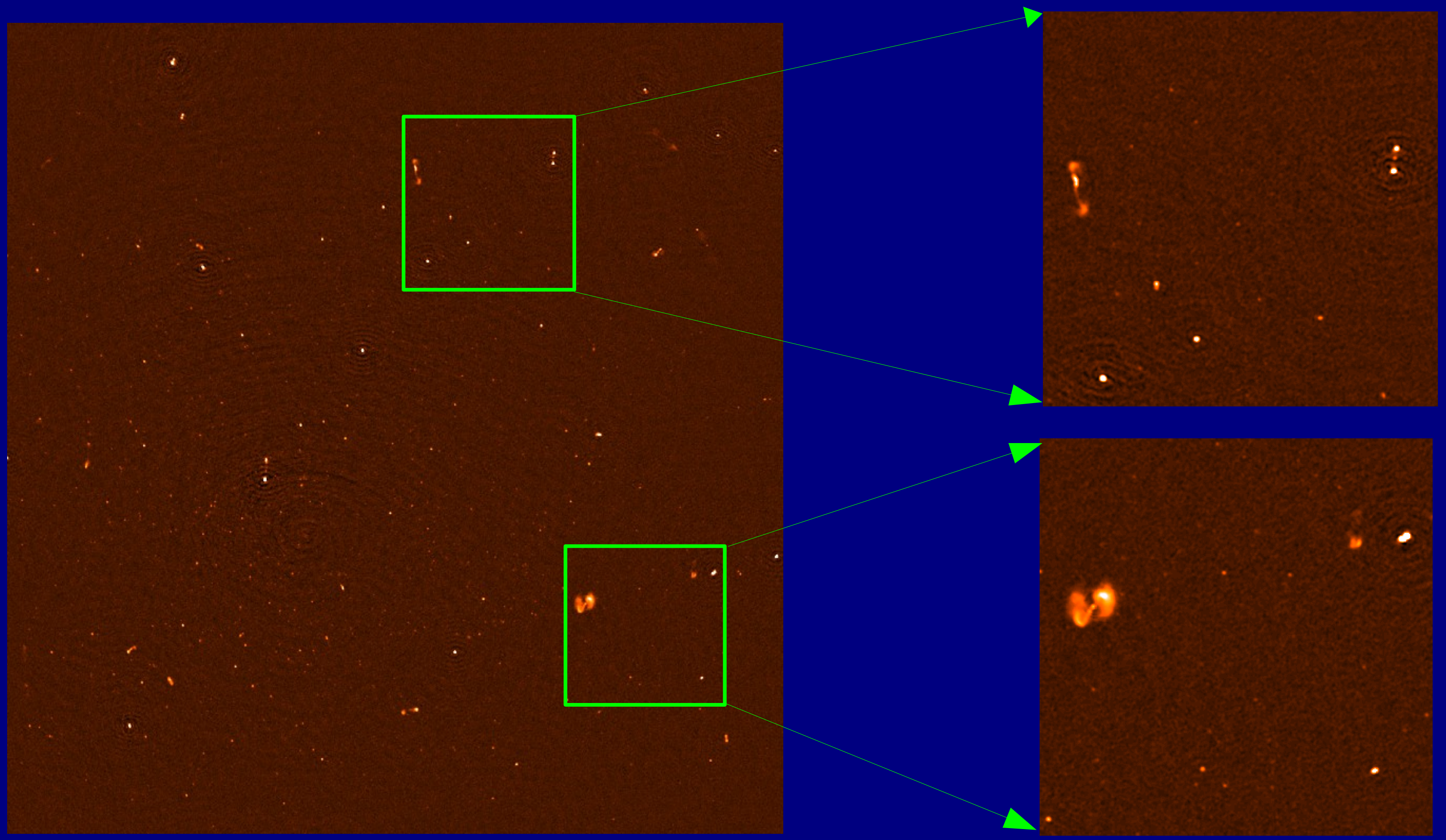
Imaging algorithms and computing



S. Bhatnagar

NRAO

Challenges

- 2:1 Bandwidth ratio
  - Primary beam effects
    - Time and frequency dependent
    - Polarization response
  - Spectral index variations across the sky
  - Deconvolution errors, Pixelation errors
- Direction dependent (DD) effects
  - Pointing errors
  - Long, non co-planar baselines (w-term)
  - Ionospheric phase screen
- Computing and I/O loads

Challenges

- Strong RFI
  - Some algorithms/schemes exist
- Weak RFI
  - Very difficult to detect and remove
  - Will/does affect high dynamic range imaging
- Near field problems
  - Remains correlated
  - Not the same at all baselines
  - Variable in time & frequency
- Self Interference

The Measurement Equation

- Generic Measurement Equation: [HBS papers]

$$V_{ij}^{Obs}(\nu) = M_{ij}(\nu, t) W_{ij} \int M_{ij}^{S}(\mathbf{s}, \nu, t) \; I(\mathbf{s}, \nu) \; e^{\iota \mathbf{s}.\mathbf{b}_{ij}} \; d\,\mathbf{s}$$

Data — Corruptions — Sky — W-term

- Corruptions: $M_{ij} = J_i \otimes J_j^*$:direction independent corruptions

  $M_{ij}^{s} = J_i^{s} \otimes J_j^{s*}$:direction dependent corruptions

- Sky: Frequency dependent sky: $I(s, \nu) = I(s, \nu_o)\left(\frac{\nu}{\nu_o}\right)^{\alpha}$

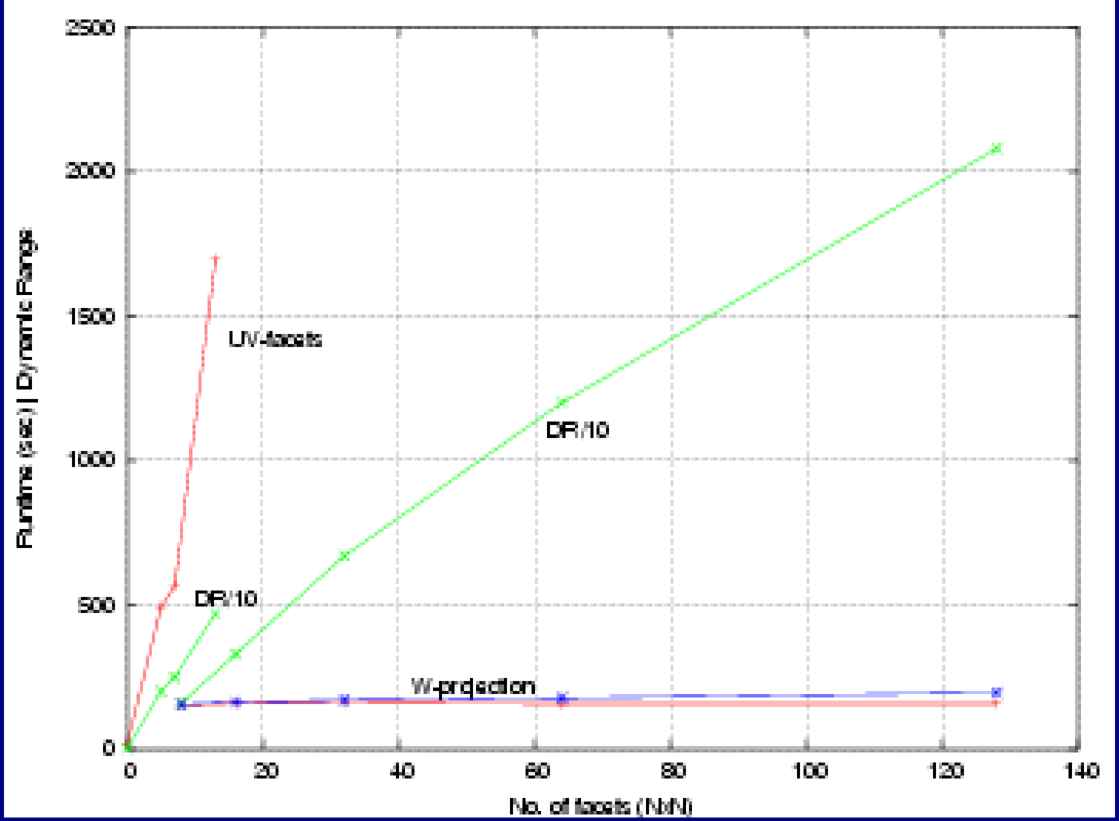
- W-term: $e^{\iota s.b_{ij}} = e^{\iota[ul + vm + w(\sqrt{1 - l^2 - m^2} - 1)]}$: Not a FT kernel

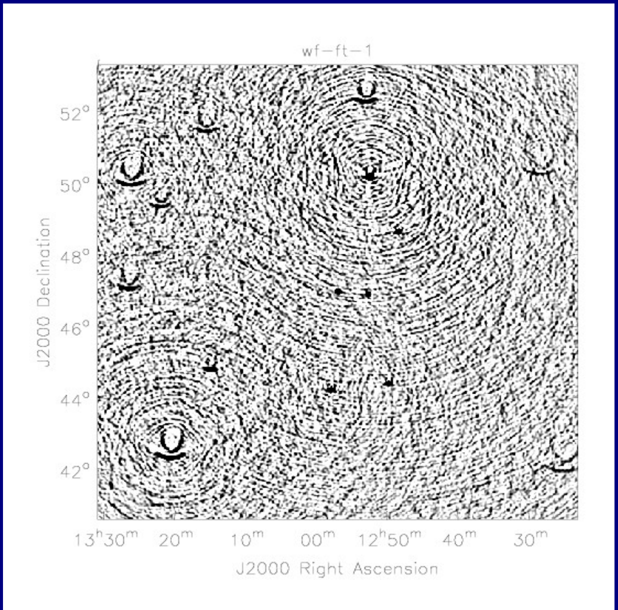
  (a.k.a. non co-planar array)

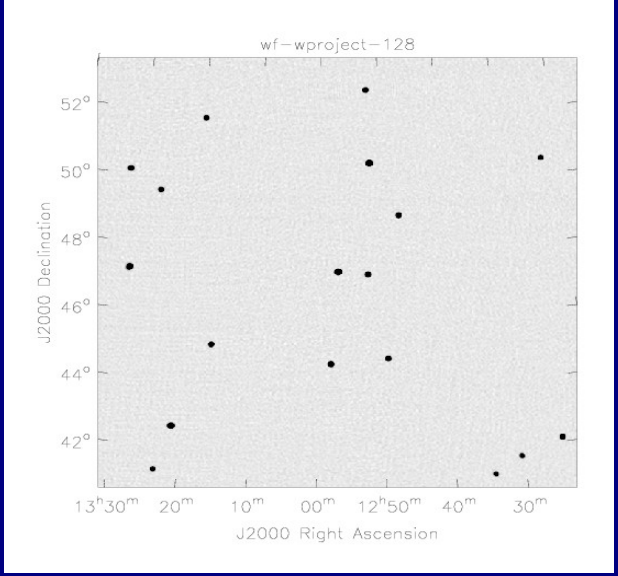
Pieces of the puzzle

- Unknowns:
  - *M_{ij}, M^s_{ij}: Electronics, Primary Beams, Antenna pointing, ionosphere,...*
  - *I^M : Extended emission, spectral index variations, polarization,...*
- Need Efficient Algorithms:
  - *Correct for image plane effects*
  - *Decompose the sky in a more appropriate basis*
    - Frequency sensitive (combine with MFS)
  - Solvers for the "unknown" direction dependent effects (pointing, PB shape, ionospheric effects,...)
    - <u>As expensive as imaging!</u>
- Needs (Computing):
  - Parallel computing & I/O
  - Scalable algorithms & software

W-projection algorithm: Scaling laws







W-projection: $(N^2_{wproj} + N^2_{GCF})\, N_{vis}$

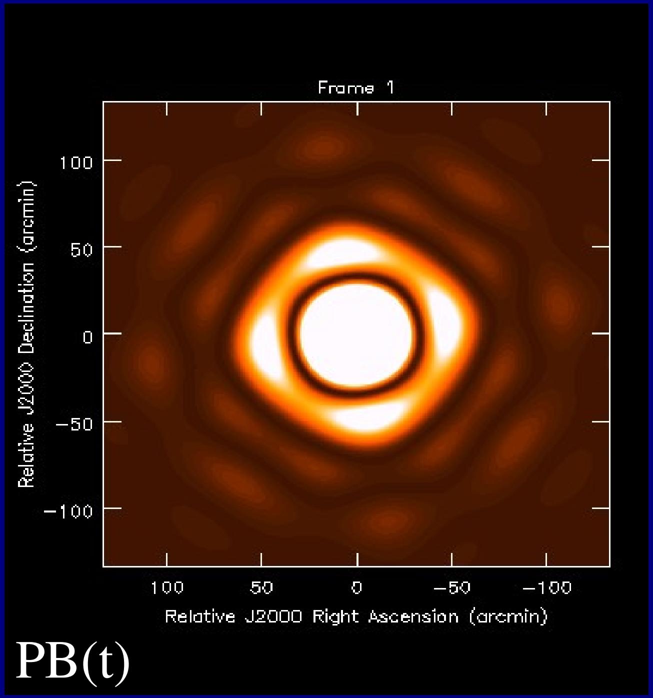
UV-facet: $N^2_{facets}\, N^2_{GCF}\, N_{vis}$

(Cornwell, Kolap & Bhatnagar, Special Issue IEEE)

Primary Beam Effects (Available in CASA)

- EVLA full beam, full band, single feed

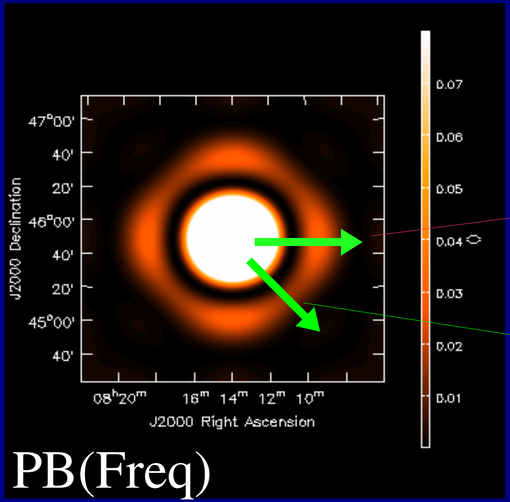
PB rotation, pointing errors



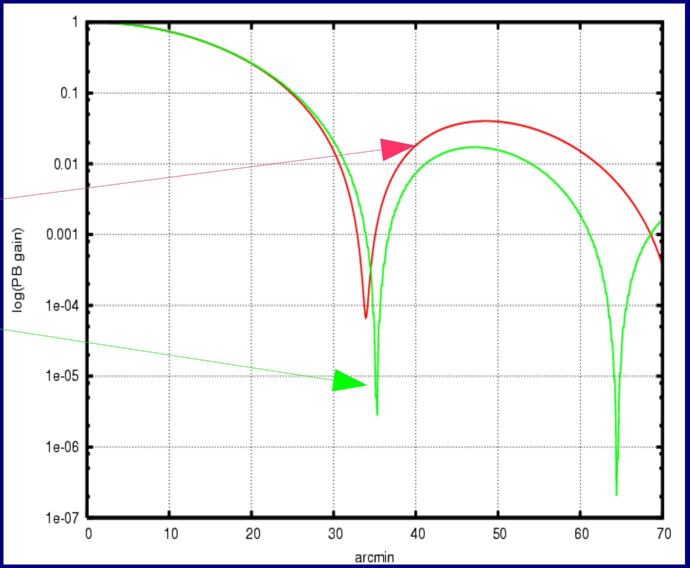
PB(t)

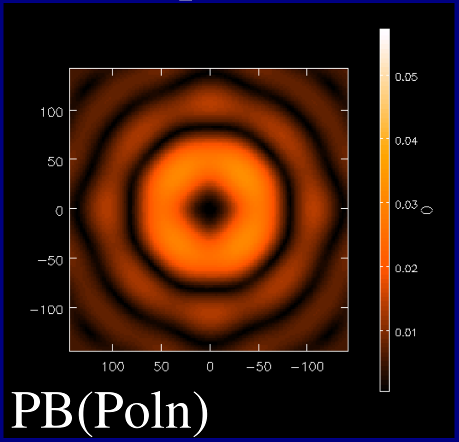
PB variation across the band

EVLA: Sources move from main-lobe to side-lobes



PB(Freq)



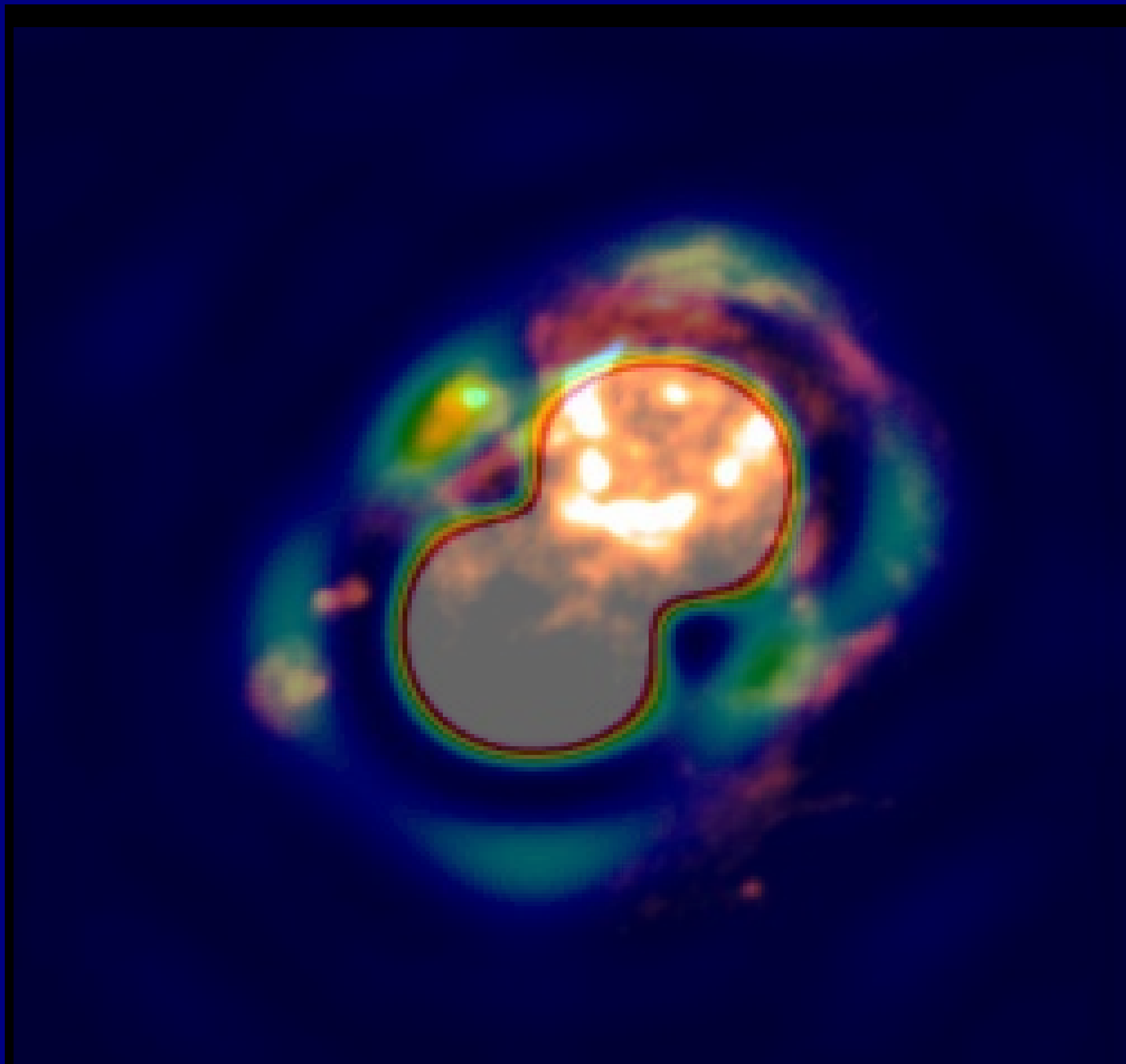


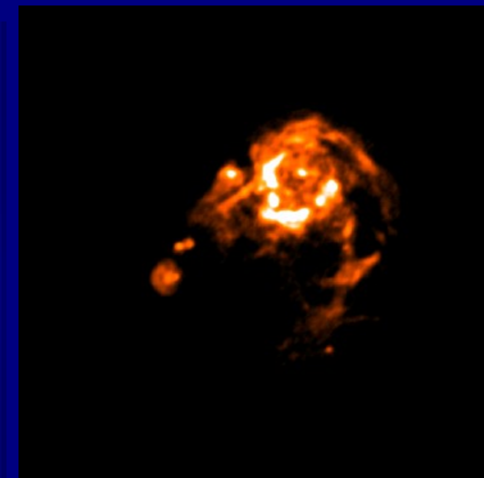
PB(Poln)

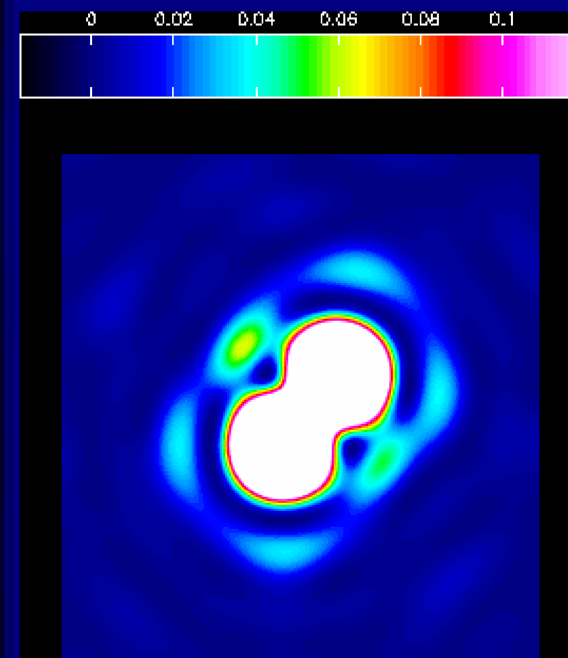
Cross hand power pattern

PB gain varies as a function time, frequency and direction in the sky

Dominant errors in mosaicing: PB effects





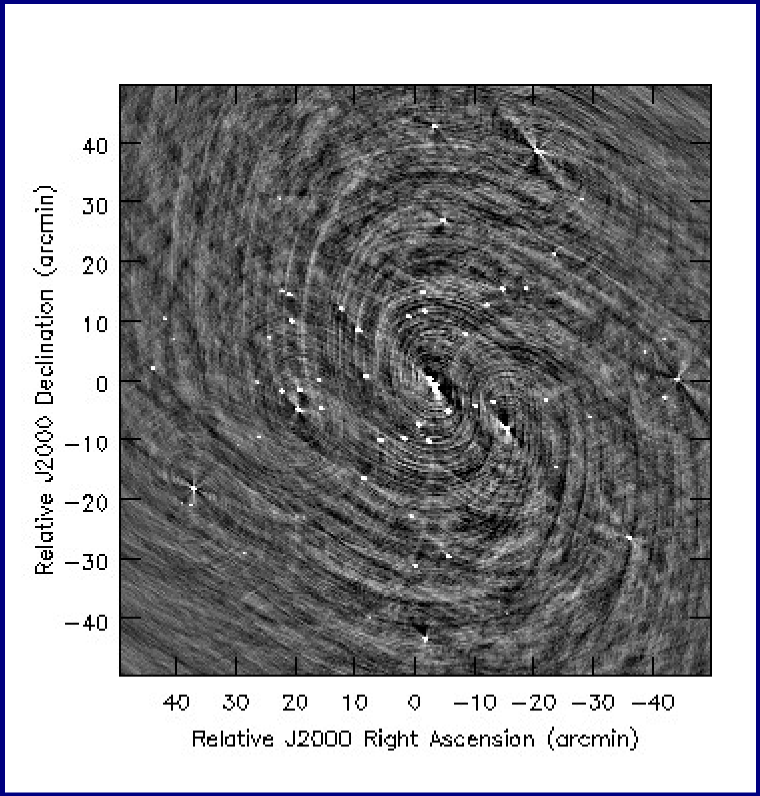


Dominant sources of error: Single Pointing

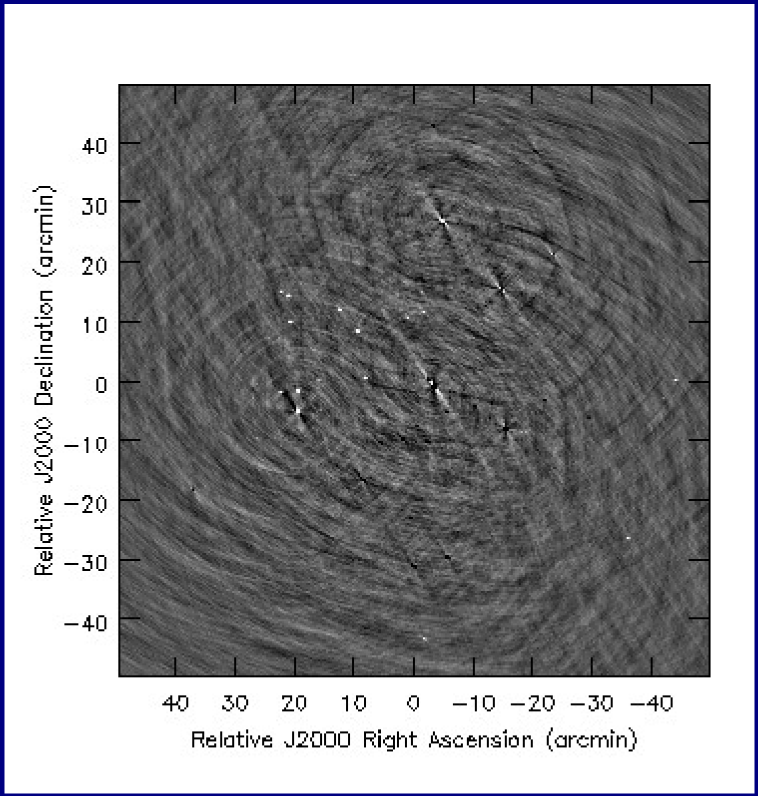
Requirements: "...full beam, full Stokes, wide-band imaging at full sensitivity".

- EVLA full beam
  - Estimated Stokes-I imaging Dynamic Range limit: $\sim 10^4$

Stokes-I



Stokes-V



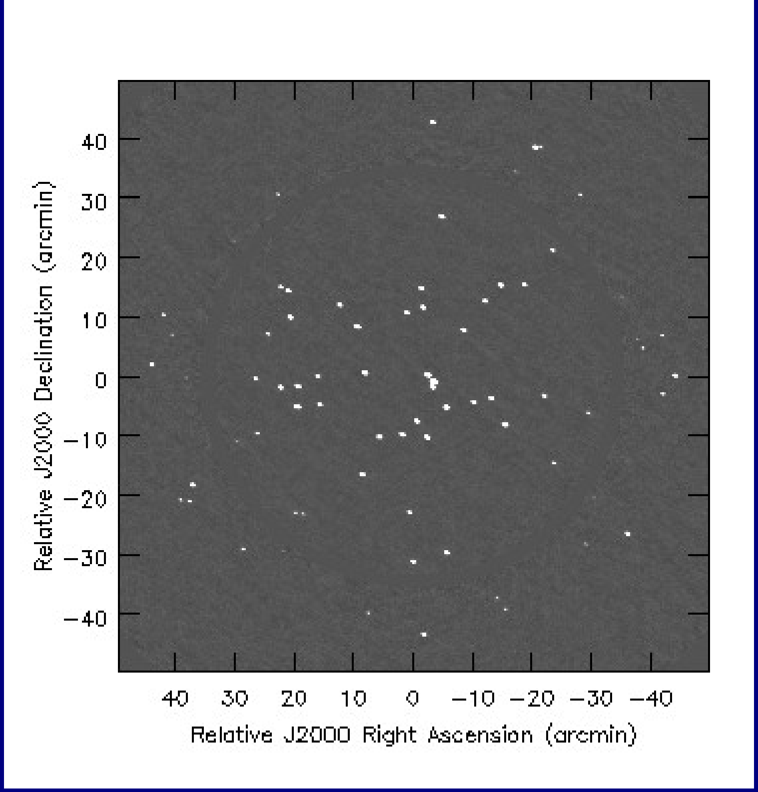
RMS ~15μJy/beam

Dominant sources of error: Single Pointing

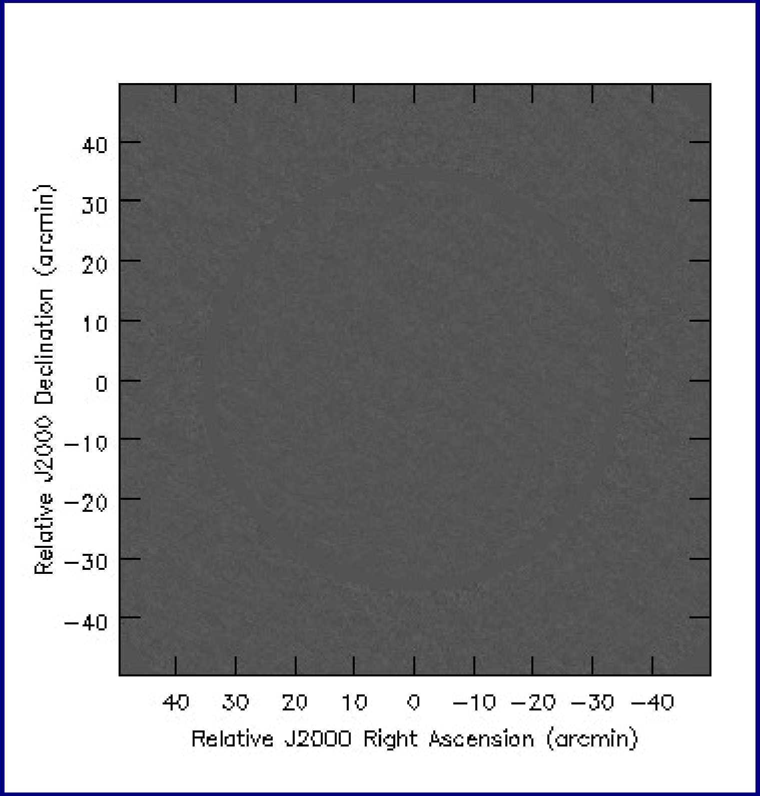
Requirements: "...full beam, full Stokes, wide-band imaging at full sensitivity".

- EVLA full beam
  - Estimated Stokes-I imaging Dynamic Range limit: ~10^4

Stokes-I

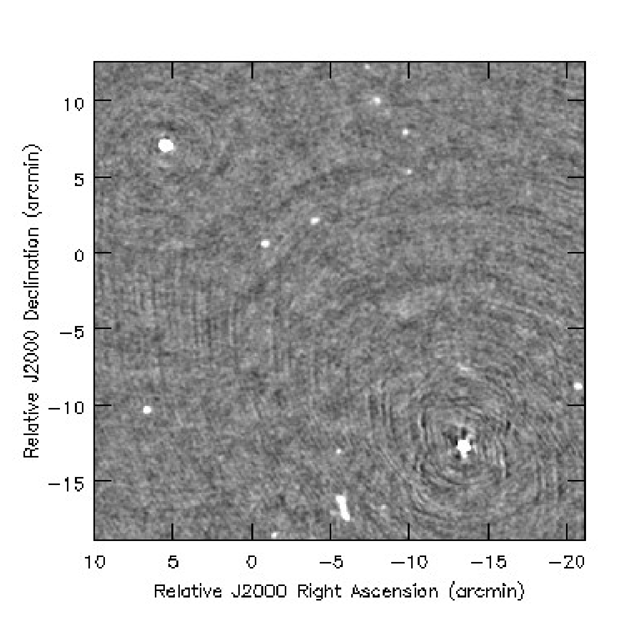


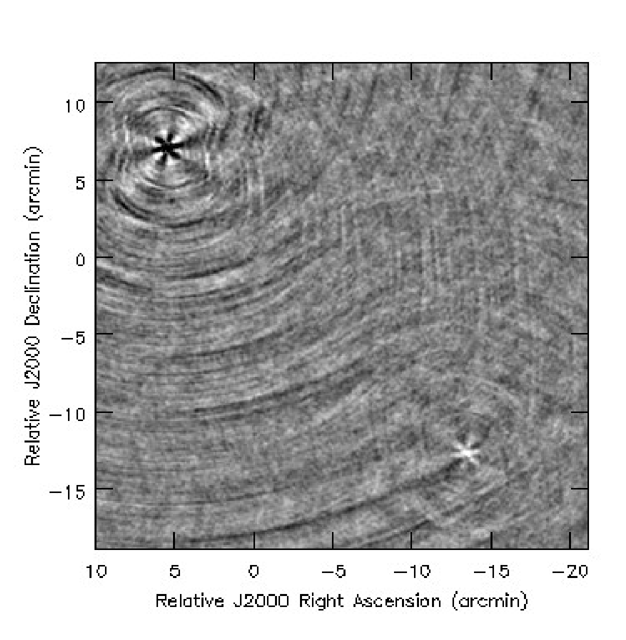
Stokes-V

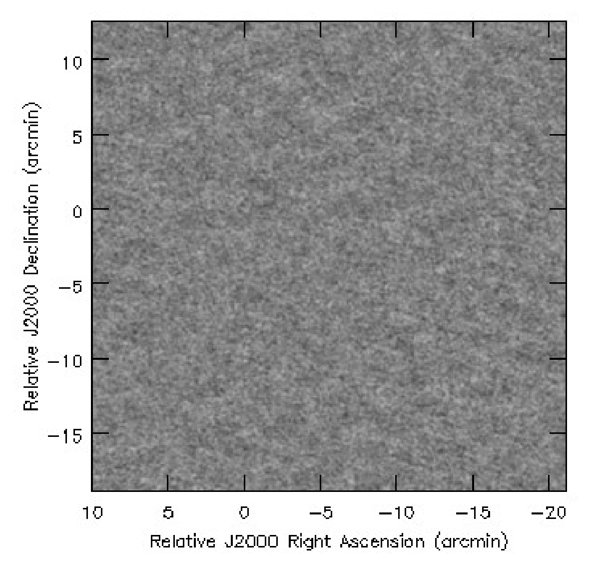


RMS ~1μJy/beam

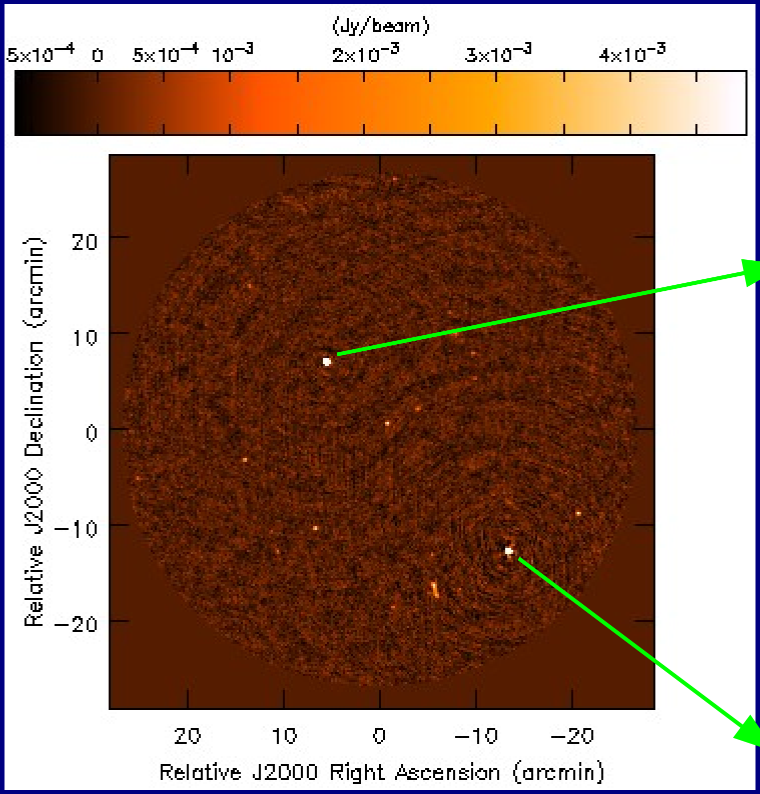
Direction Dependent Corrections

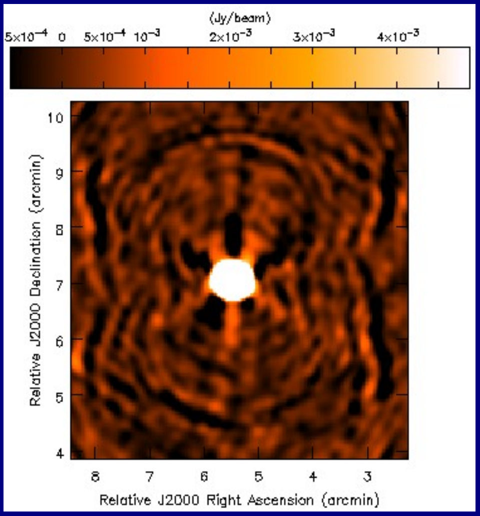


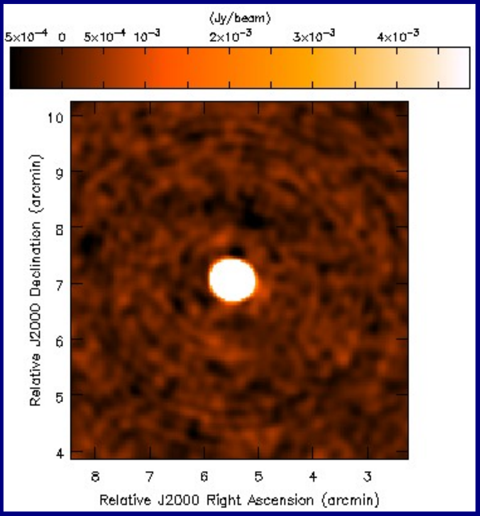




During vs. Post deconvolution PB correction

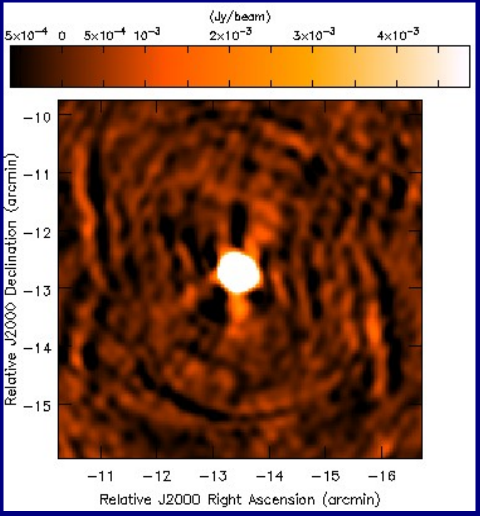


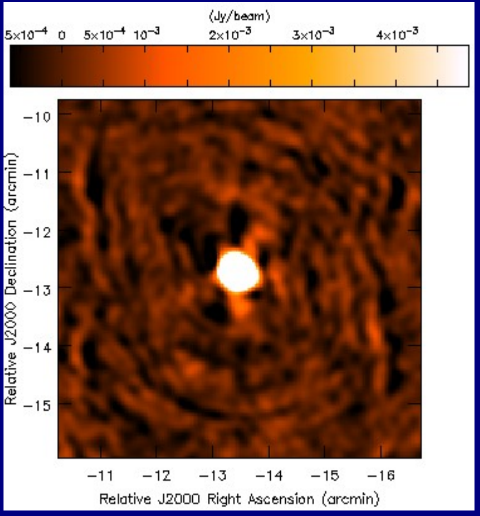




Post-deconvolution PB correction

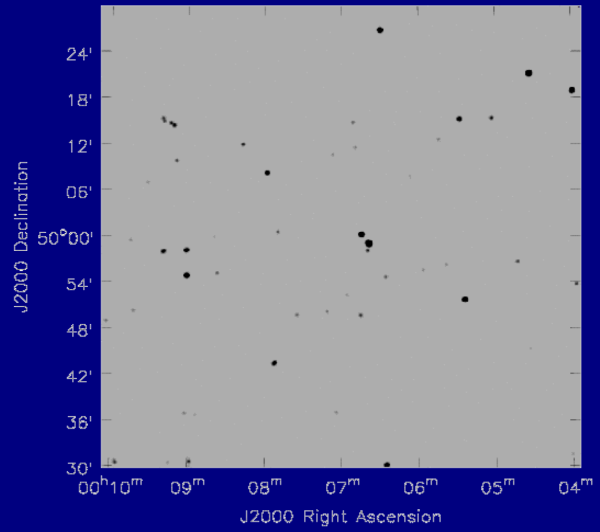
PB correction during deconvolution



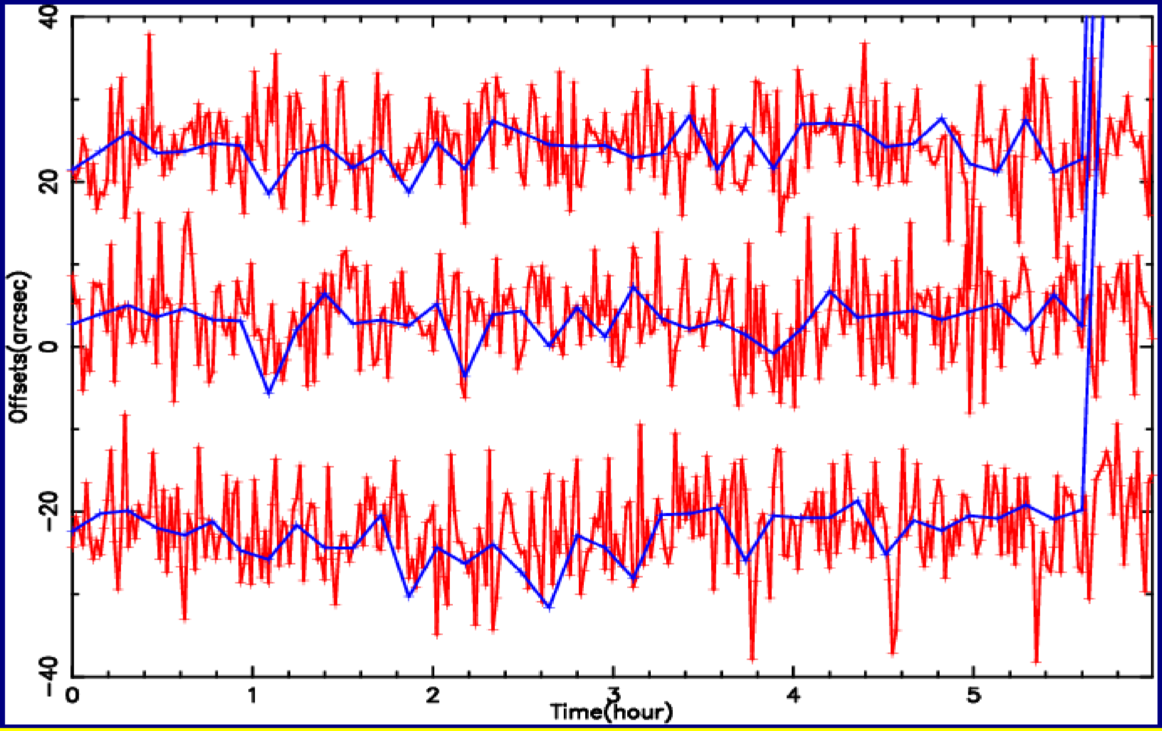


- PB errors can easily limit imaging DR
- Errors are non-random
- Stable PB will be helpful
  - Dipole arrays vs. rigid structure

Pointing SelfCal: Example (Available in CASA)



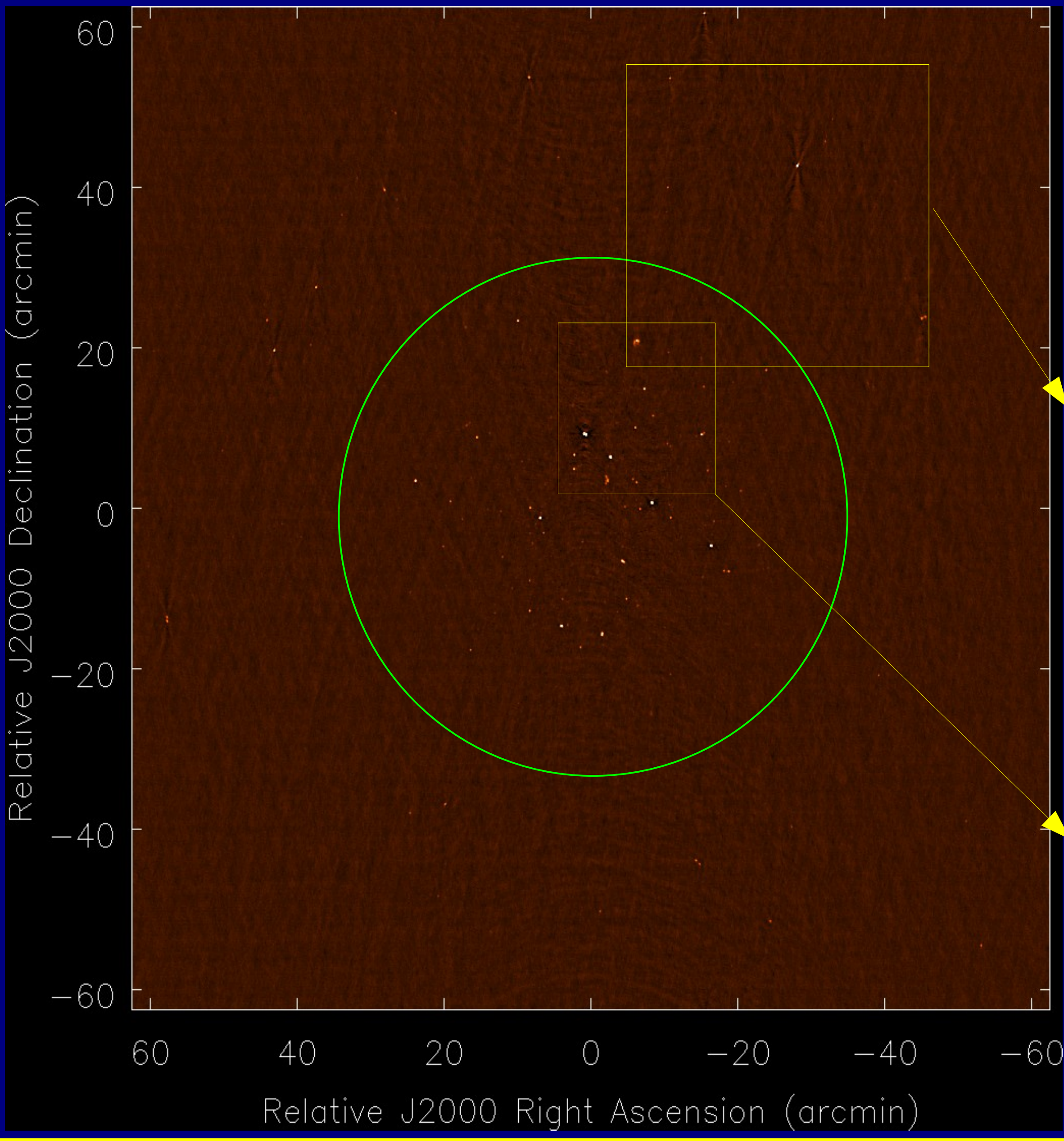
Model image: 59 sources from NVSS. Flux range ~2-200 mJy/beam



Red: Typical antenna pointing offsets for VLA as a function of time

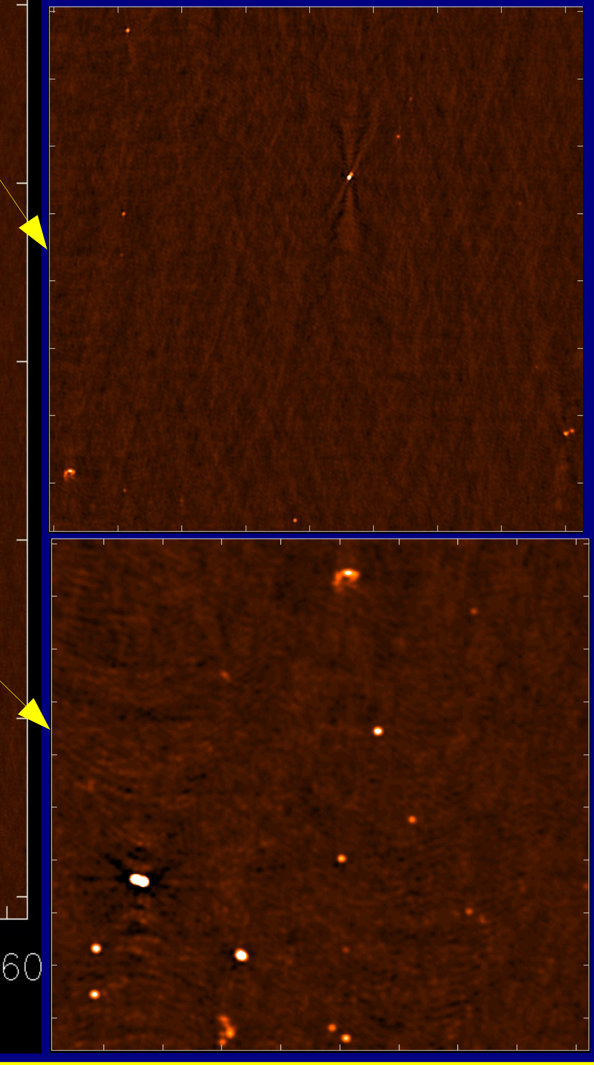
Blue: Solved antenna pointing errors

Sky: More complex than point sources

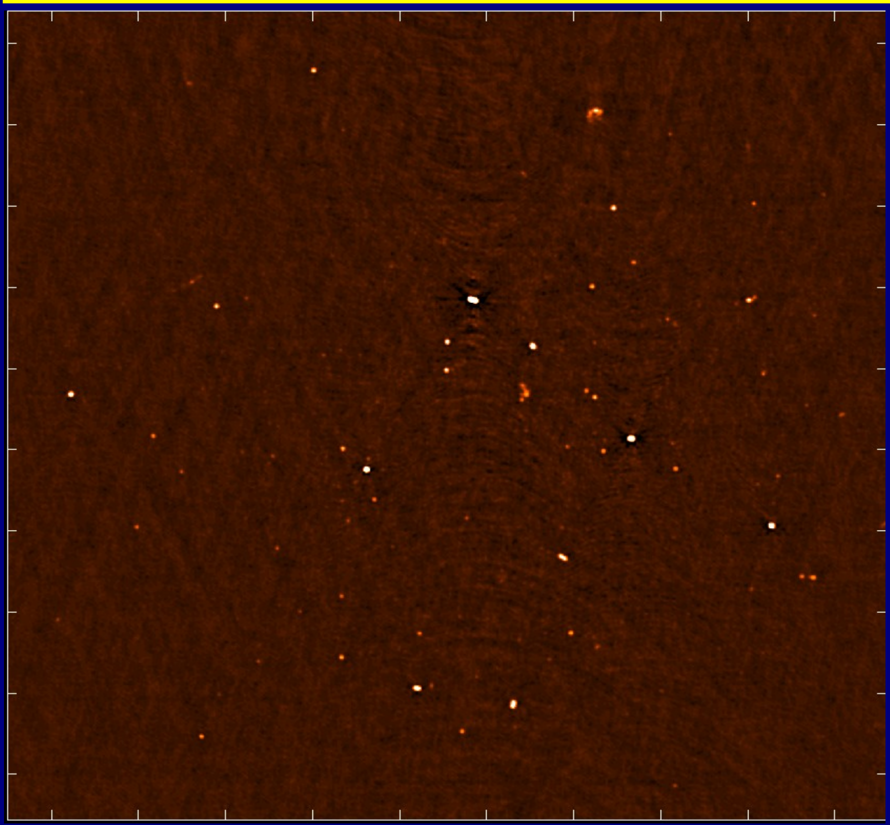


- 1.4 GHz/VLA, 30 µJy/b @ 4”

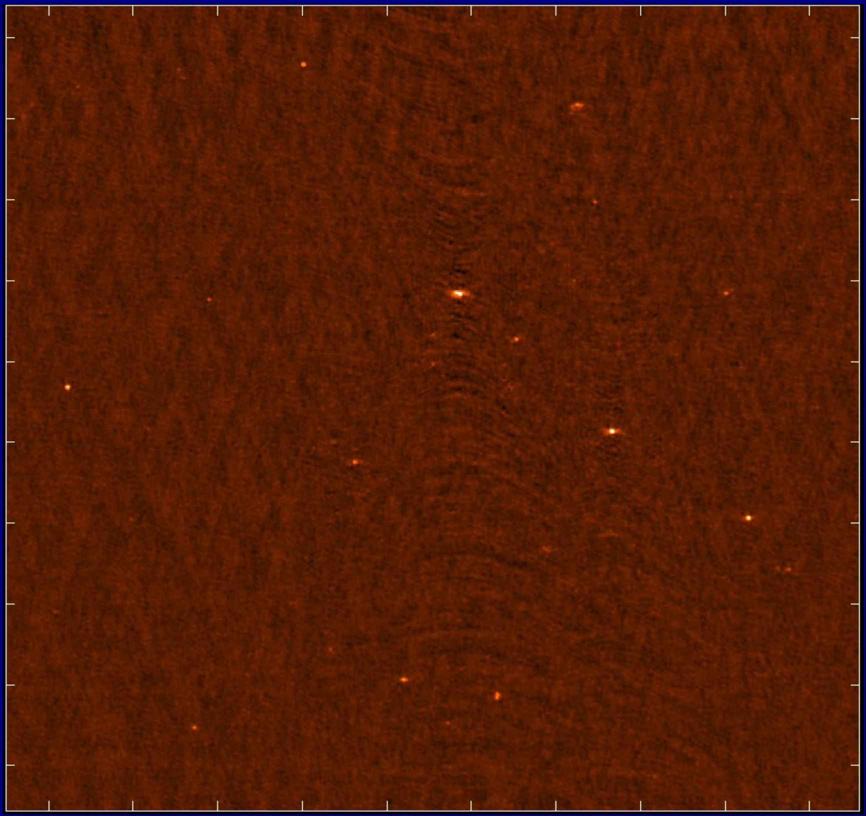
(Data from: Fomolant et al.)



Sky Frequency dependence



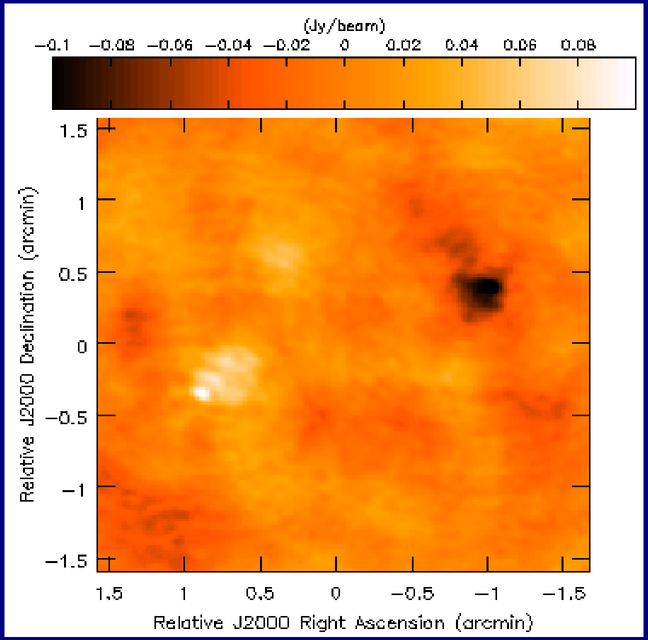
1.365GHz



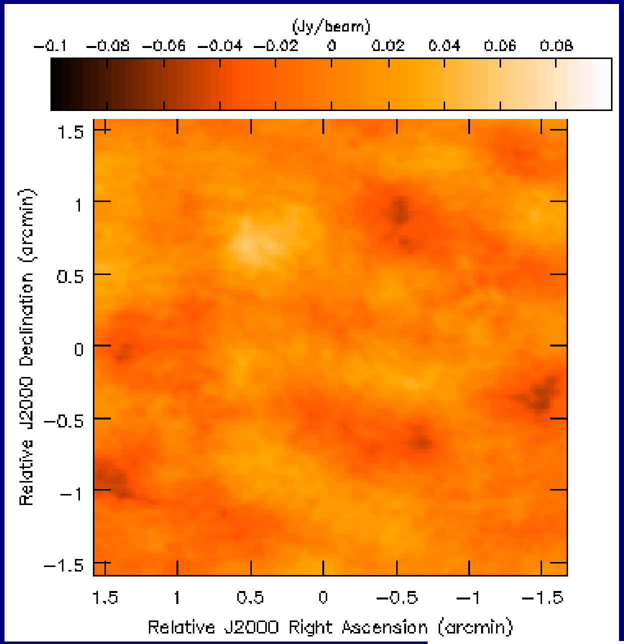
I(1.365GHz)-I(1.435GHz)

- Direction & Frequency Dependent errors
  - Sky spectral index? PB effects? Pointing? Pixelation errors?
- Errors not coherent across frequency
  - Will affect spectral line signals (EoR)

Extended Emission (Algorithm in CASA)

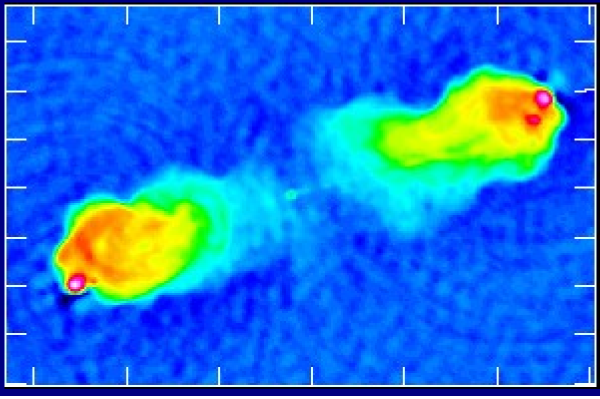


No PB correction

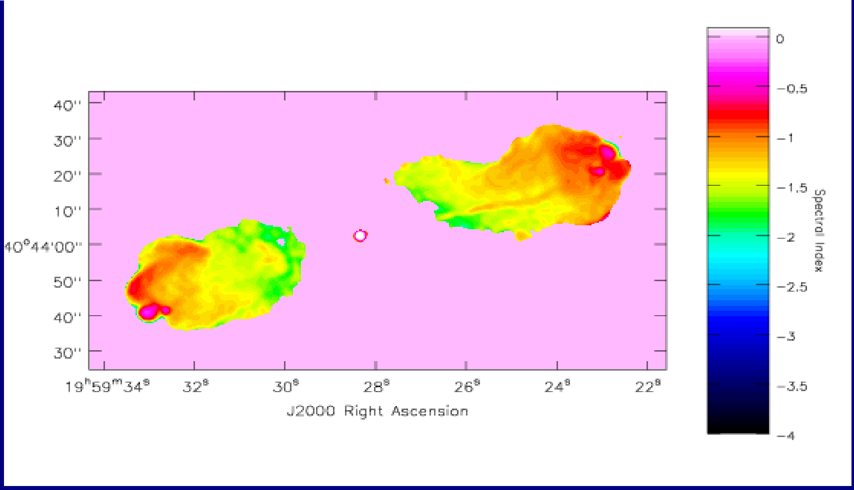


PB correction

(Bhatnagar et al, A&A, June 2008)

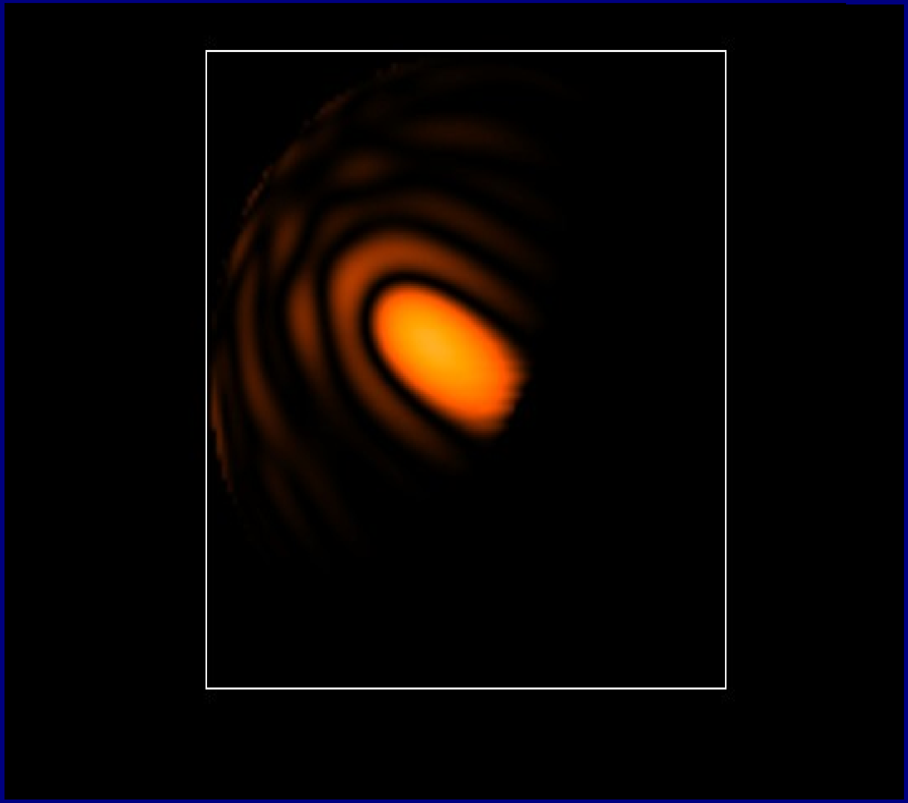


- Stokes-V imaging of extended emission
  - **Algorithms designed for point sources will not work**
  - **Need more sophisticated modeling of the extended emission**

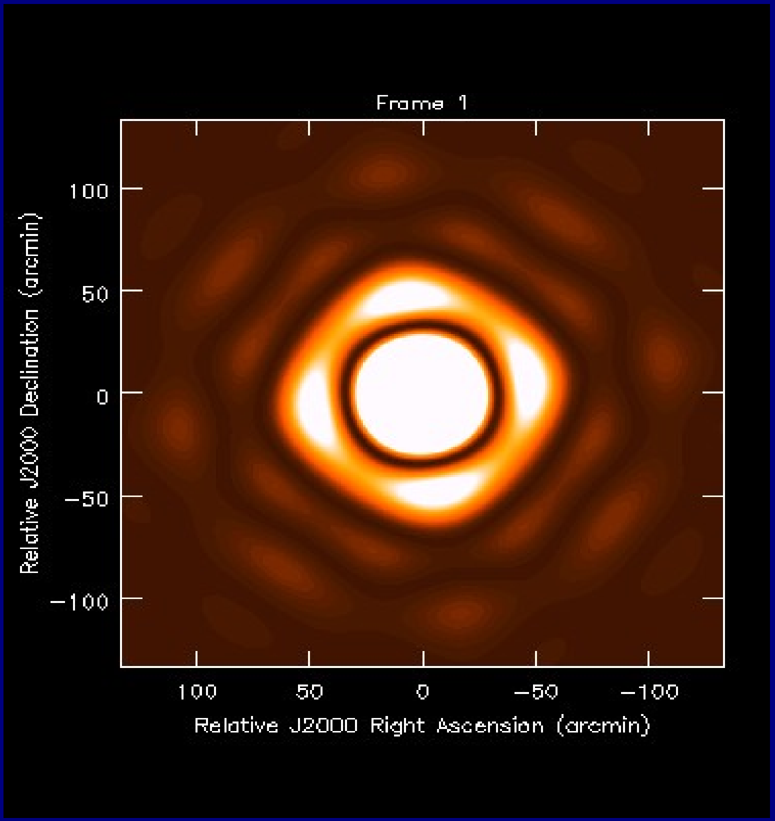


Sp. Index Image (Carilli et al.)

Antenna: Dipole arrays vs. Solid Steel



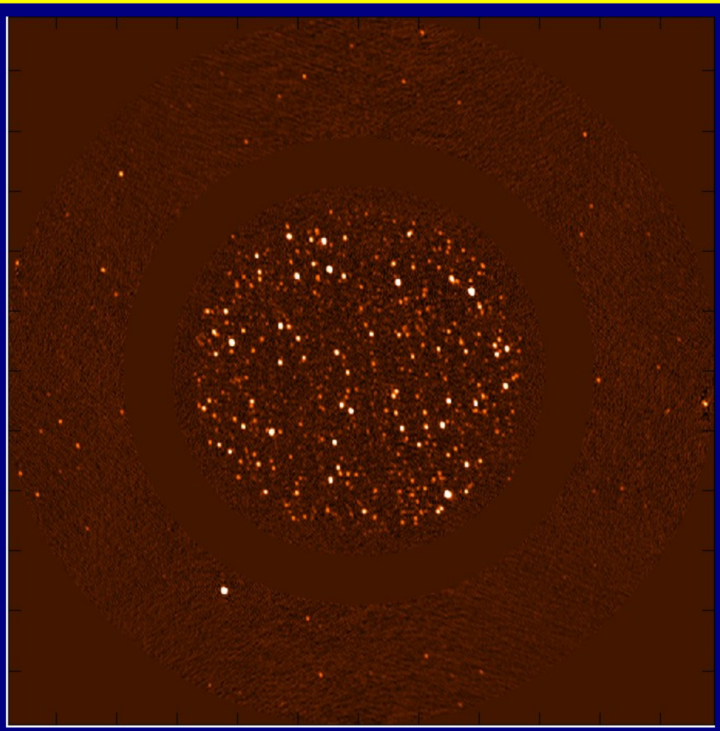
Simulation of LWA station beam @50MHz
(Masaya Kuniyoshi, UNM/AOC)

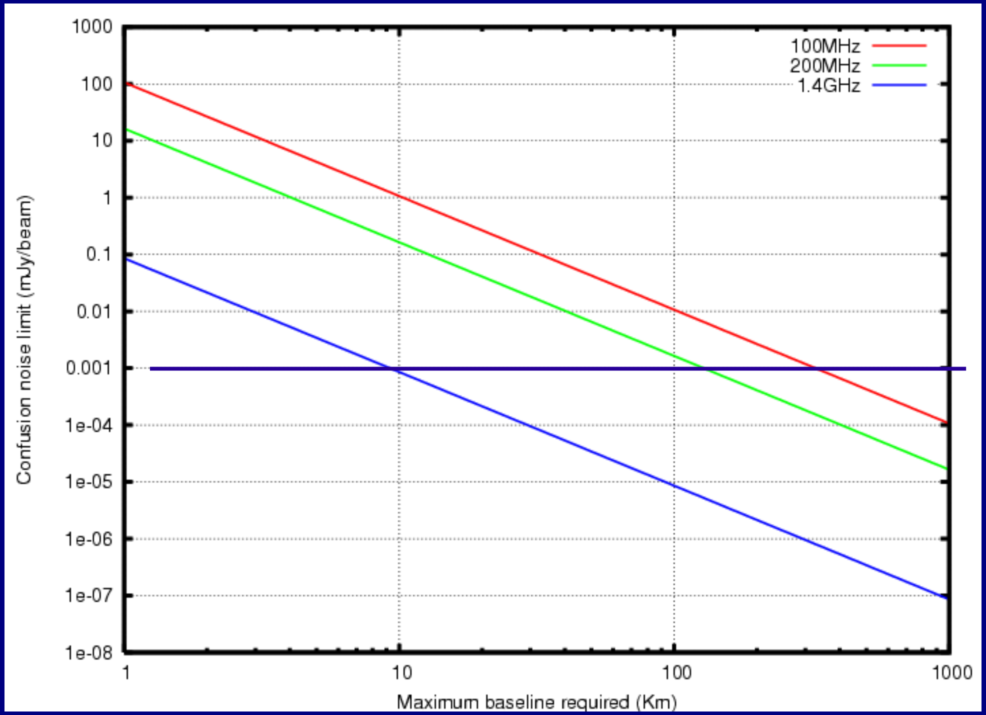


EVLA antenna PB rotation with Parallactic Angle

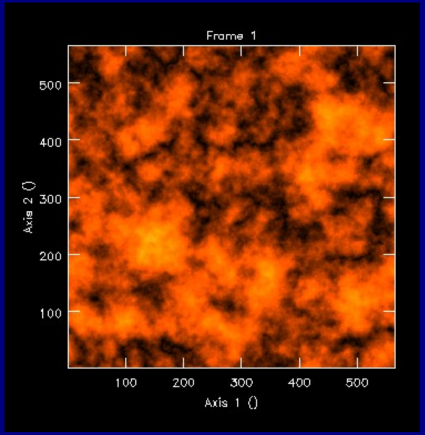
Simulations using the CASA software

Confusion limit vs. resolution





- $\sigma_{confusion} \propto (\nu^{-2.7}/B^2_{max})$
- B_{max} ~100 Km at 200MHz for $\sigma_{confusion}$ ~ 1μJy/beam
- Challenges:
  - W-term an issue for B_{max} > 2-3Km & DR > 10^4
  - Ionospheric calibration: Even field based calibration fails for B_{max} > 3Km



PB errors: Full beam imaging limits

- Limits due to rotation of asymmetric PB
  - In-beam max. error @~10% point
  - DR of few x10^4:1
  - Errors larger in the first sidelobe

- Limits due to antenna pointing errors
  - In-beam max. error at half-power points
  - DR of few x10^{3-4}:1
  - Limits for mosaicking would be worse
    - Significant flux at half-power and side-lobes for many pointing

Computing & I/O costs

- $$DataSize = \frac{N_a * (N_a - 1)}{2} \; \frac{T}{\delta T} \left[N_{ch} \;\; N_p \left[2 * SoF + \frac{SoWt}{N_p} \right] + 4 \;\; SoF \right]$$
  - For EVLA: 0.5-1.0 TB + 0.5GB

- $$FlOp \;\; per \;\; gridding = \frac{N_a * (N_a - 1)}{2} \; \frac{T}{\delta T} \left[N_{ch} \;\; N_p \;\; N_{IP} \right] \left[N_{op} \, S^2 \right]$$
  - One gridding (Major Cycle) will take 1.5-2hrs.
    - Computing efficiency: 10-20% of the rated GFLOPs
  - @100 MB/s, single read of 1 TB data will take ~3hrs.

- Total full data accesses: 10-20

Computing & I/O costs

- Computing scales linearly with N_{ch} , N_p and S^2
  - Convolution support size larger for DD correction (e.g. PB)
- DD calibration
  - Required for what has been promised!
  - N_{iter} N_{par} x [Gridding operations + 2 x full data reads]
- PB-correction+Multi-frequency Synthesis:

$$I(\nu) = I(\nu_o)\left(\frac{\nu}{\nu_o}\right)^{\alpha}$$

  - Taylor expantion: N_{terms} depends on the required DR
  - N_{iter} N_{terms} x 2 Gridding Operations + full data read

Computing & I/O costs

- Higher sensitivity ==> more data + correction of more error terms
  - Needs more sophisticated parameterization
  - Significant increase in computing and I/O loads
- Imaging:
  - Correction for PB variations, Pointing errors, ionosphere
  - Better modeling of extended emission
- Calibration: solve for direction dependent effects
  - As expensive as imaging
  - PB shape, pointing, ionosphere
- Processing cost dominated by forward and backward transforms (gridding)
  - I/O time comparable to computing time

Computing & Algorithms

- Hard to get away from FFT based forward and inverse transforms
  - Only “peeling” approach not feasible
    - Requires 10K-100K components DFT for a 1 TB data base!

- Better understanding of error propagation can lead to efficient algorithms
  - All algorithms (Calibration & Image Deconvolution) are function minimization algorithms (Steepest Descent in fact!)
  - But need to invest and believe in R&D!

- Compute for the allowed dynamic range
  - Computation more accurate than the allowed DR is a waste of resources