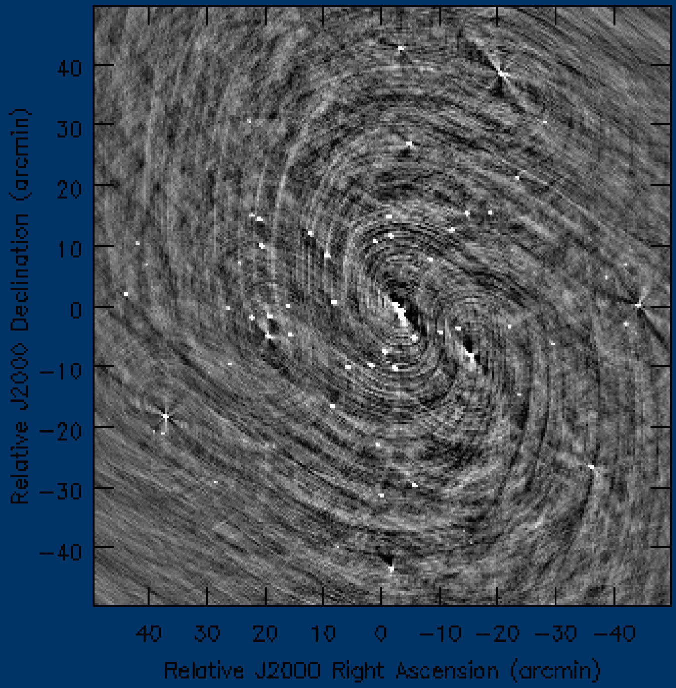
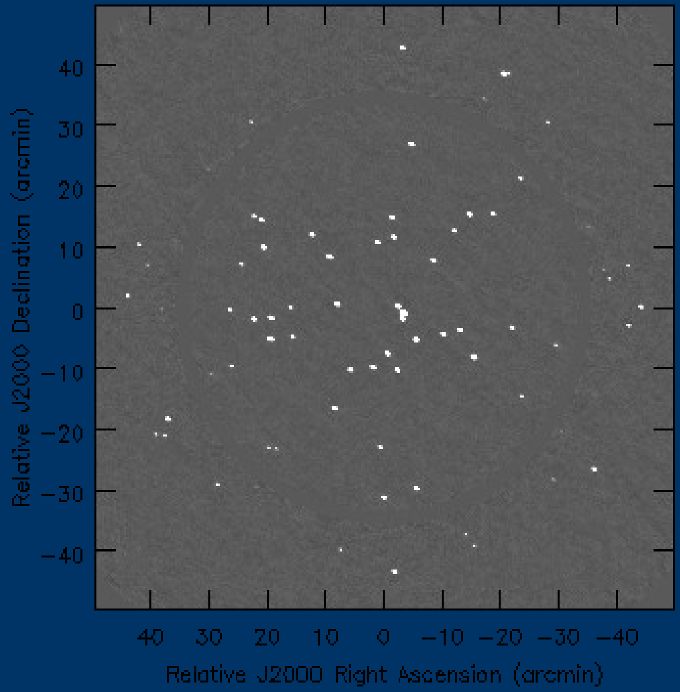
Direction-dependent effects



RMS ~15μ Jy/beam



RMS ~1μ Jy/beam

S. Bhatnagar
NRAO, Socorro

Direction dependent effects

- Instrumental
  - Primary Beam Effects
    - Time and frequency dependent
    - Polarization response
  - Pointing Errors
  - Non co-planar baselines (w-term)
  - FPA calibration/stability

- Sky
  - Stronger and more complex at low frequencies
    - Deconvolution errors, pixelation errors
  - Spectral index variations across the sky

- Ionospheric/atmospheric

Measurement Equation

- Generic Measurement Equation

$$V_{ij}^{Obs}(\nu) = J_{ij}(\nu, t) W_{ij} \int J_{ij}^{S}(s, \nu, t) \; I(s, \nu) \; e^{\iota s.b_{ij}} \; ds$$

Data — Corruptions — Sky — Geometry

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

  $J_{ij}^S = J_i^S \otimes J_j^{S*}$ Direction dependent corruptions

- Sky: Frequency dependence: $I(s, \nu) = I(s, \nu_0) \left(\frac{\nu}{\nu_0}\right)^{\alpha(s, \nu)}$
- Sky: Complex structure
  - Representation in a more appropriate basis
- Geometrical: W-term $e^{\iota s.b_{ij}} = e^{\iota[ul + vm + w(\sqrt{1 - l^2 - m^2} - 1)]}$

- The combined LHS determines “time constant” over which averaging helps

Challenges

- Unknowns
  - J_{ij}, J^s_{ij}: Electronics, Primary Beams, antenna pointing, Ionosphere
    - Heterogeneous arrays (difference PB per baseline)
  - I^M: Extended emission, spectral index variations
- Need efficient algorithms:
  - To solve parametrized ME (Curse of Dimensionality)
  - For *known* direction dependent corrections
  - Better parametrization of the sky (I^M)
    - Including frequency dependence
  - Solver for the *unknown* DD effects (PB, ionosphere)
- Computing
  - Parallel computing & I/O
  - Software development costs

Algorithmic challenges

- Higher sensitivity ==> mode data + correction of more error terms
  - Imaging and calibration gets coupled
  - DD corrections can be as expensive as imaging

- *More sophisticated parametrization required for the next generation telescopes*
  - *DD correction: PB(t, Freq, Pol.), atmosphere/ionosphere*
  - *Sky: Decompose the structure in scale sensitive basis*
  - *Sky: Parametrized for frequency and poln. Dependencies*

- *Physically motivated parametrization*
  - *Algorithmic performance-measure: SNR per DoF*

Recent advances

- $J_i^s(t) \neq J_j^s(t)$ (Pointing offsets, PB variations, etc.)
  - Corrections in the visibility plane
    - Scale sensitive deconvolution
      - Asp-Clean (2004), MS-Clean (2003)
    - Pointing SelfCal (2004)
    - Correction for J_{ij}^s during image deconvolution
      - W-Projection (2004)
      - AW-Projection (2005)
      - MS-MFS (2006-07)
  - Direct evaluation of the integral

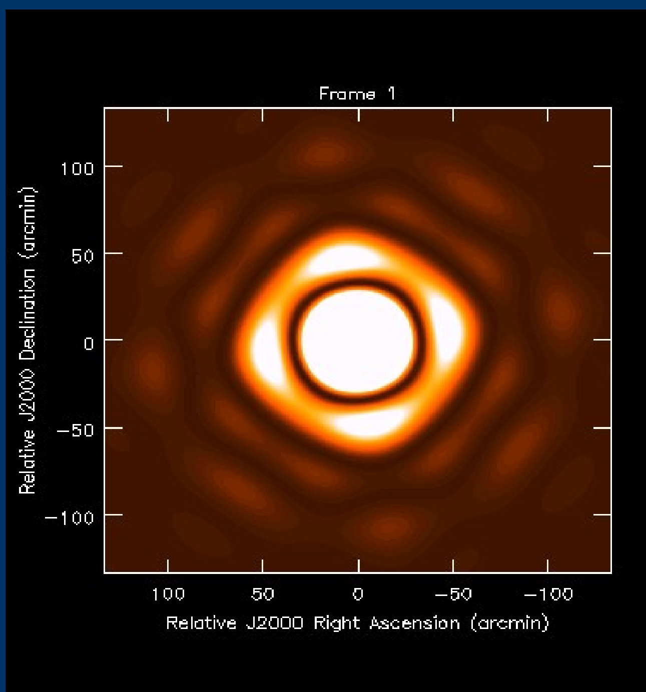
$$V_{ij}^{Obs}(\nu) = J_{ij}(\nu, t) \int J_{ij}^S(\mathbf{s}, \nu, t) \sum_k I(x_k, y_k)\; e^{\iota \mathbf{s}.\mathbf{b}_{ij}}\; d\,\mathbf{s}$$

- Peeling (since ?)/ VLA Squint correction (2008)

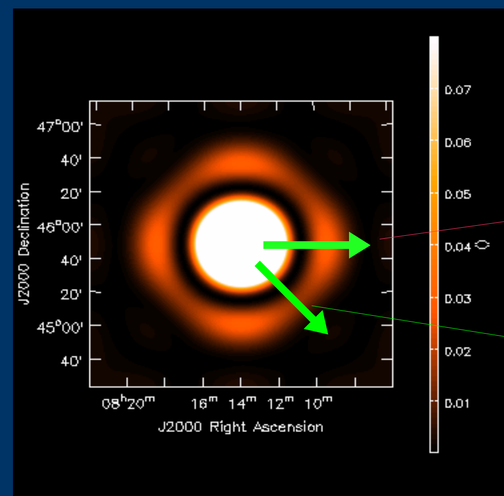
Primary beam effects

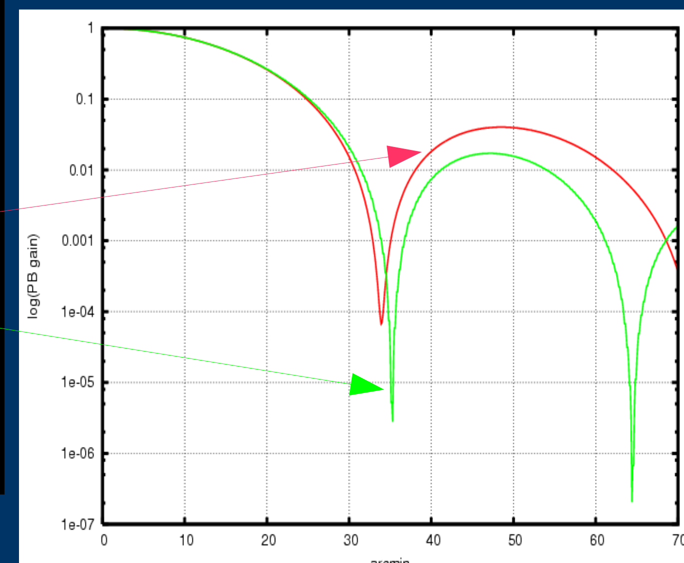
- EVLA full-beam, full-band, full-pol imaging

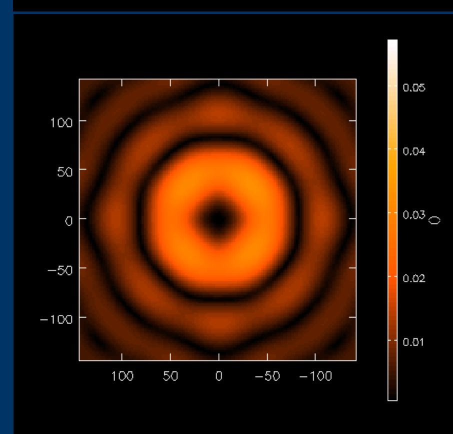
PB rotation, pointing errors



PB variation across the band
EVLA: Sources move from main-lobe to side-lobes







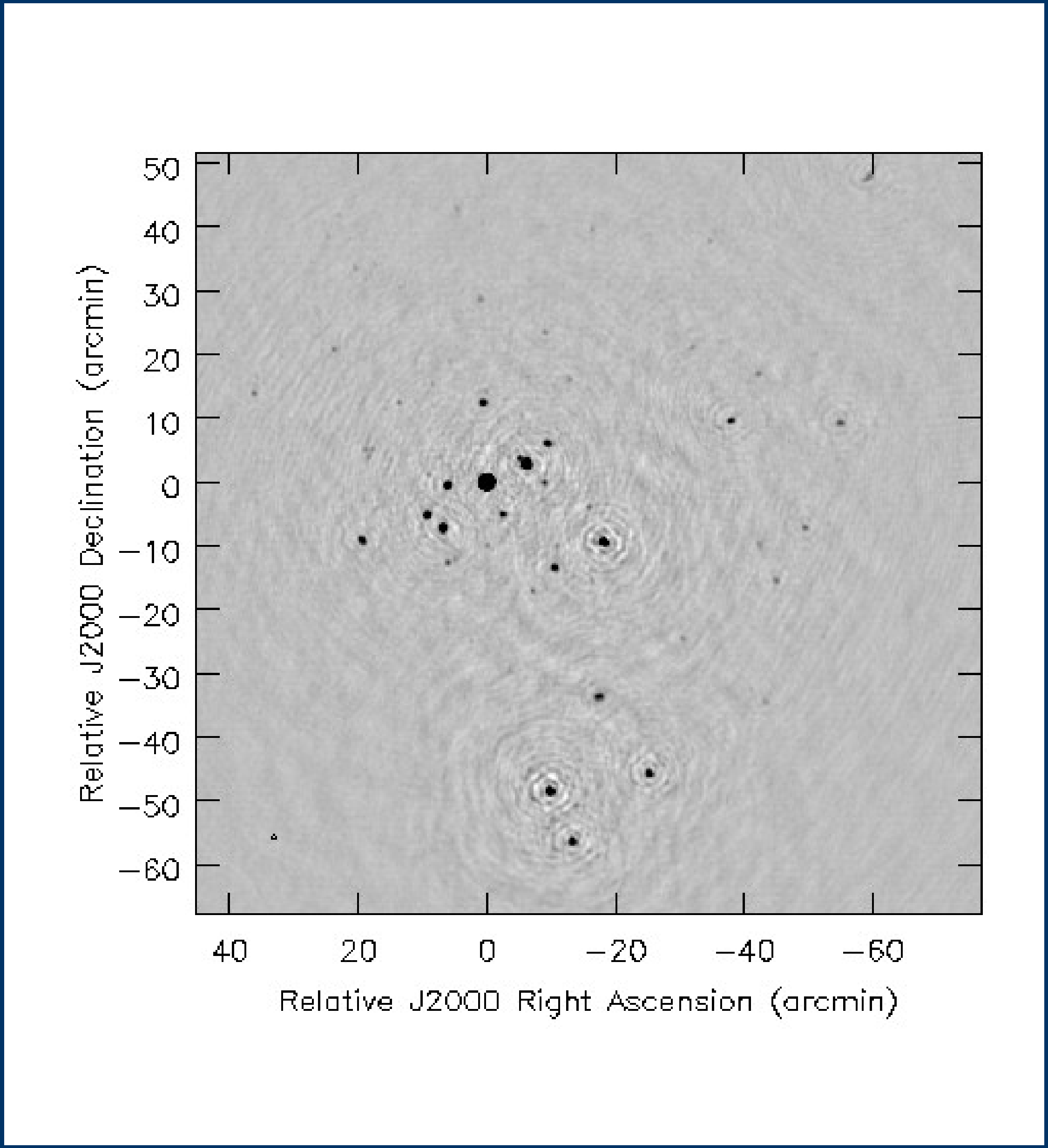
Cross hand power pattern

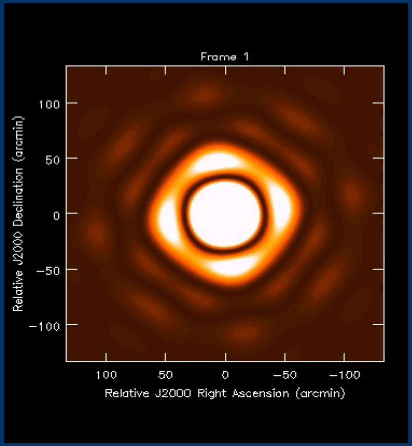
PB gain varies as a function time, frequency and direction in the sky

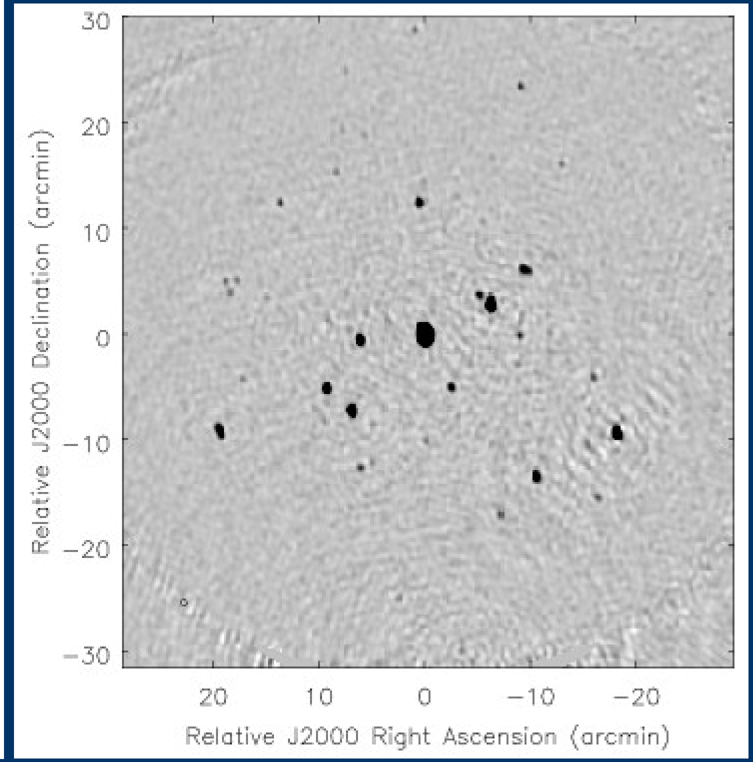
PB correction

- AW-Projection algorithm
  (Bhatnagar et al. A&A,487, 419, 2008)
  - Time and poln. Parametrization of the PB
  - No assumption about the sky emission
  - Scales well with imaging complexity
  - Straightforward to integrate with algorithms to correct for other errors (MFS, W-Projection, MS/Asp-Clean)
  - Requires a model for the Aperture Illumination

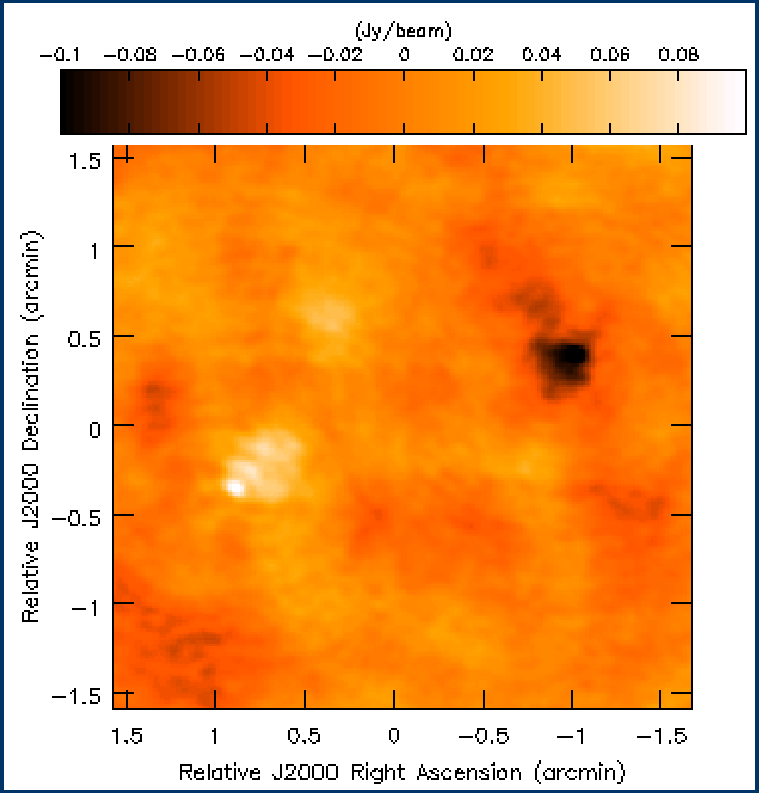
An example: EVLA @ 1.4 GHz

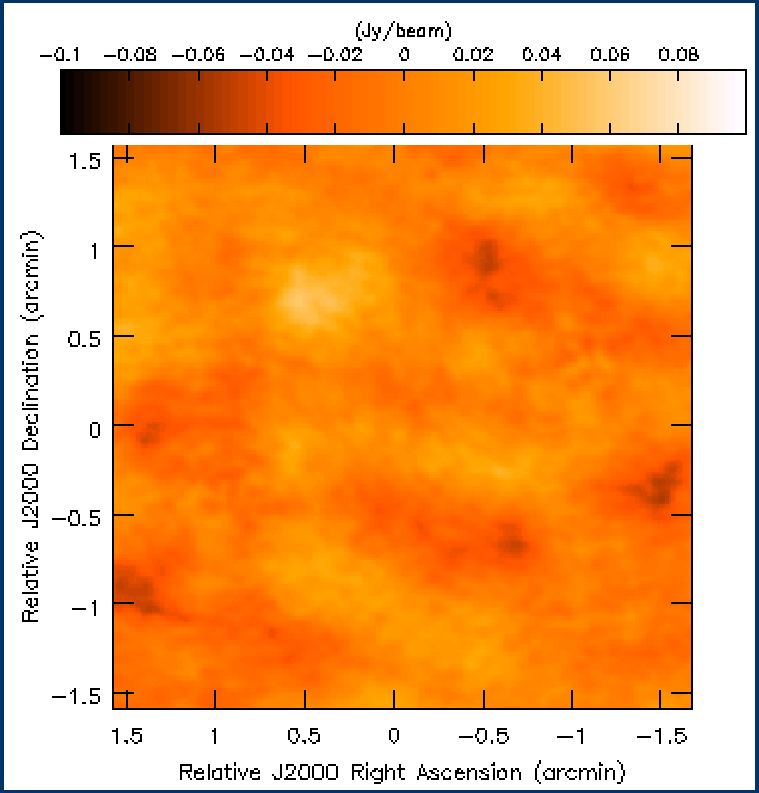




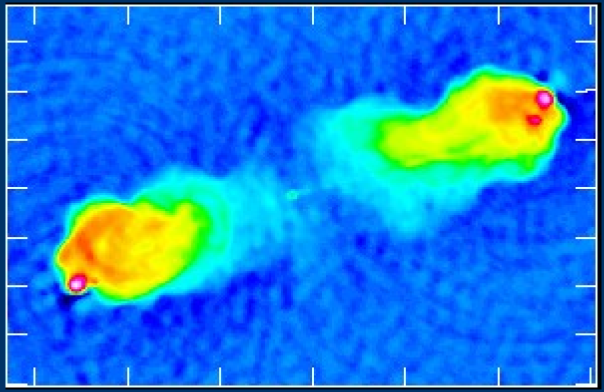


Example: Extended emission

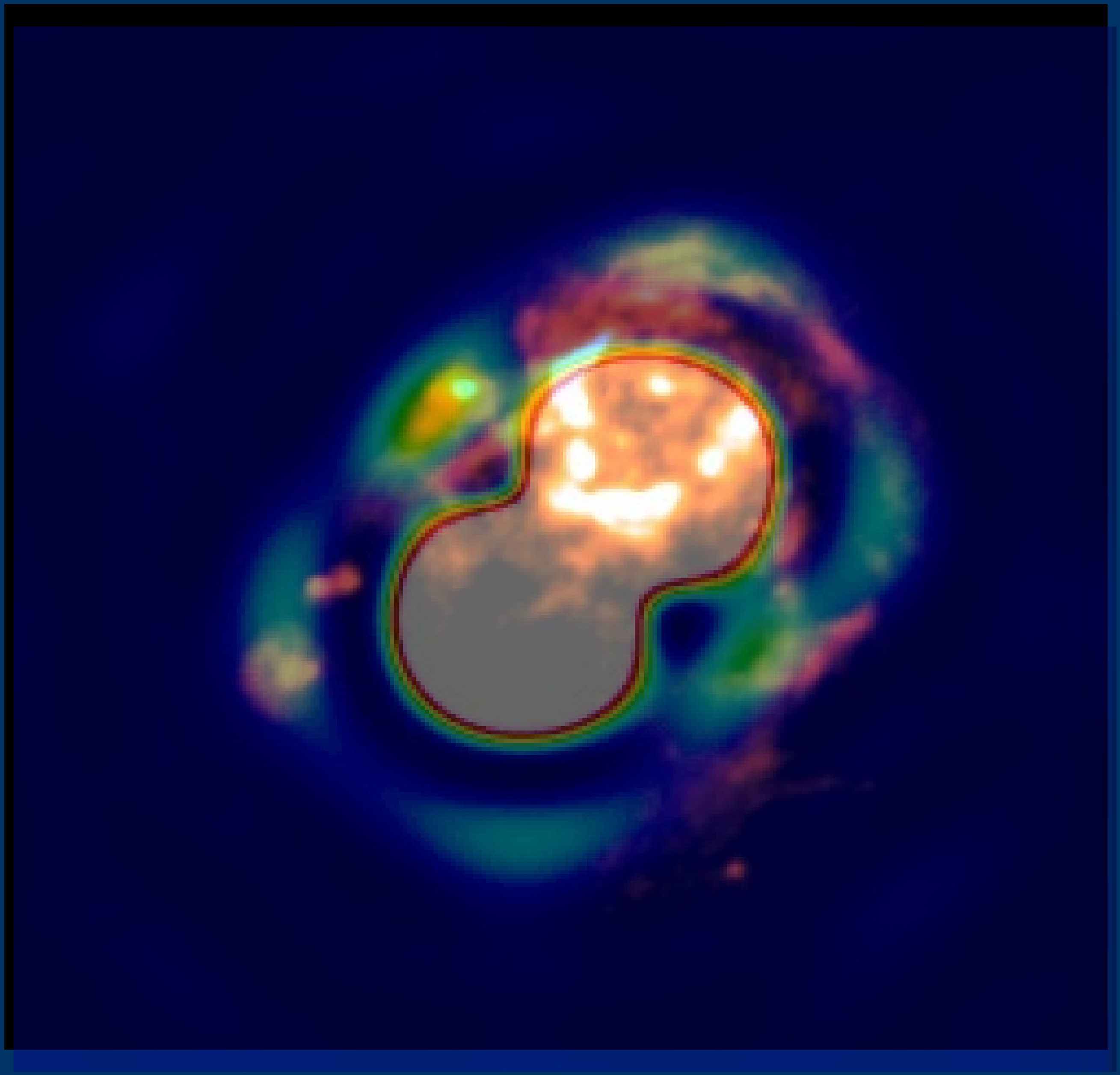


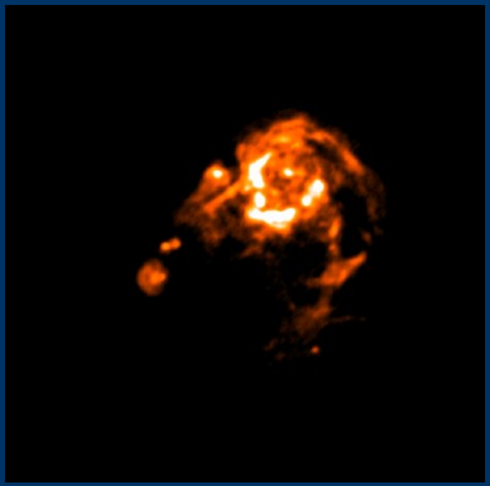


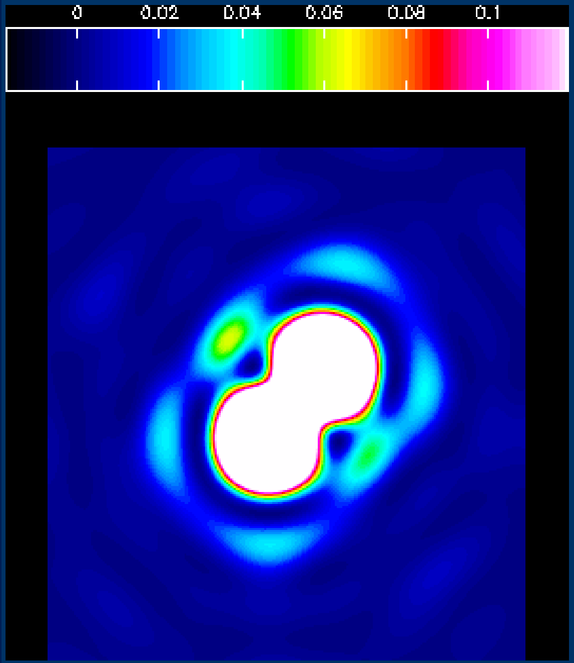
- Stokes-V imaging of extended emission
  - Algorithms designed for point sources will not work
  - Need more sophisticated modeling of the extended emission



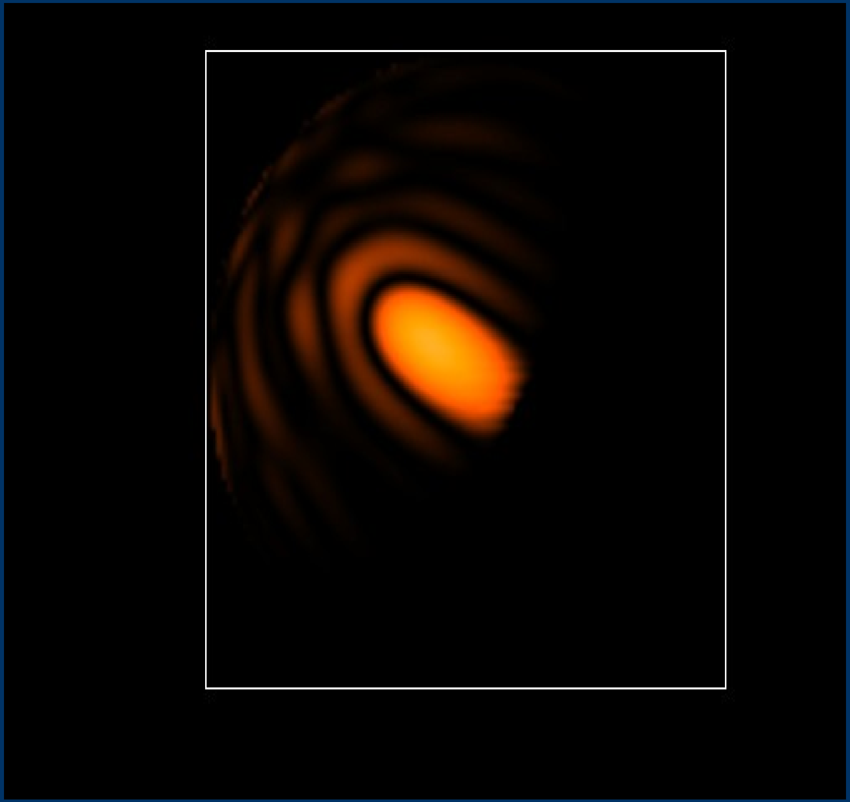
Example: PB effects in mosaicking



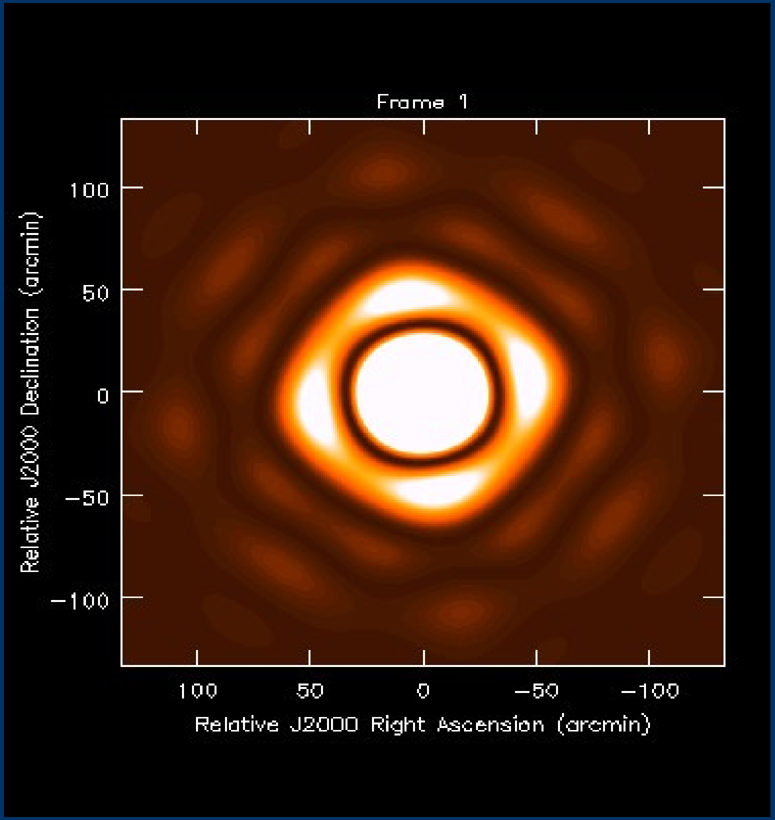




Antenna: AA vs Dishes



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



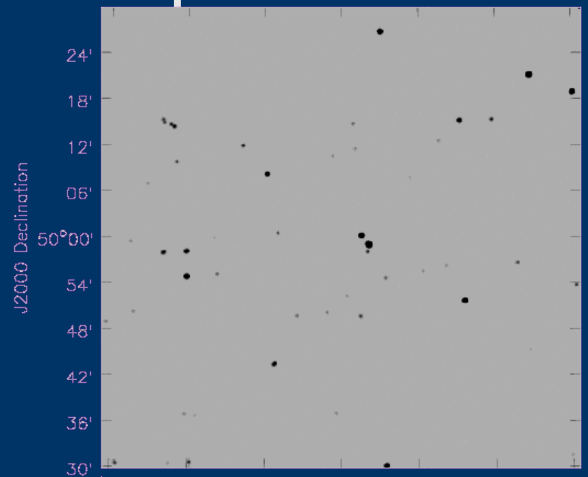
EVLA antenna PB rotation with Parallactic Angle

Full beam imaging limits

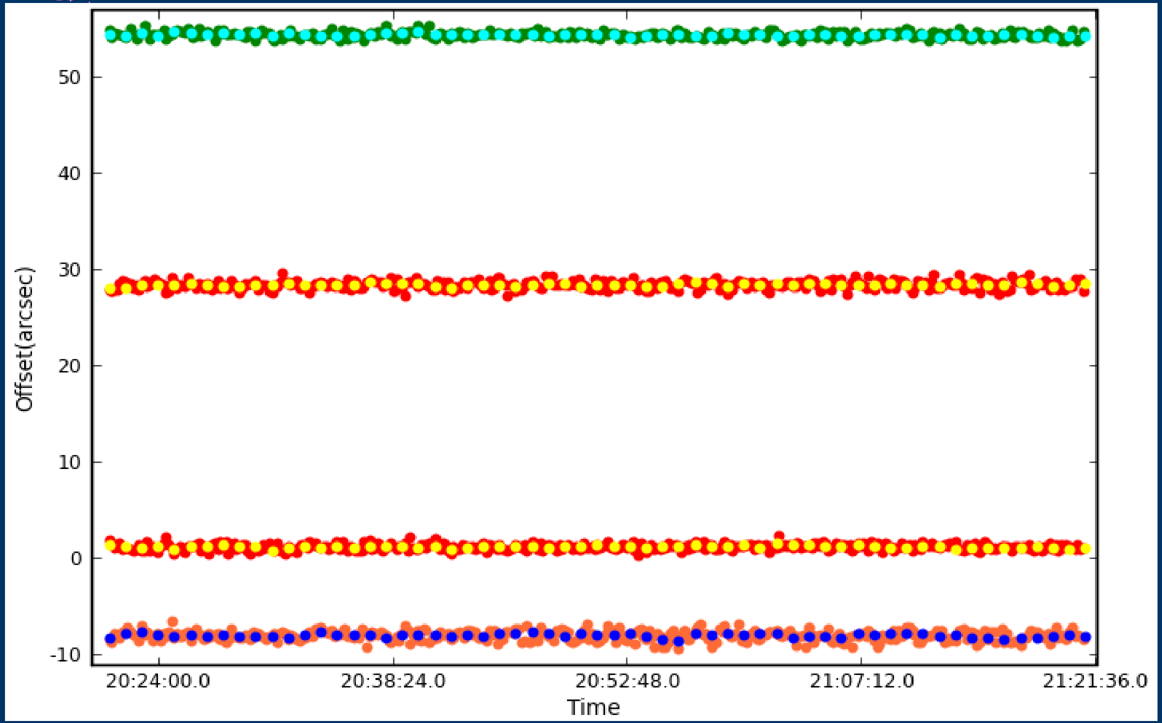
- Limits due to rotation of asymmetric PB
  - Error in PB model max. @ ~10% point
  - Max. in-beam error signal @ 50% point
  - DR of few x 10^4: 1
  - Errors higher in the first sidelobe
- Limits due to antenna pointing errors
  - In-beam max. error signal at 50% point
  - DR of a few x 10^4:1
  - Limits for mosaicking would be worse
    - Significant flux at half-power and side-lobes for many pointings

Pointing SelfCal: Solver

- PB parametrized for pointing errors



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

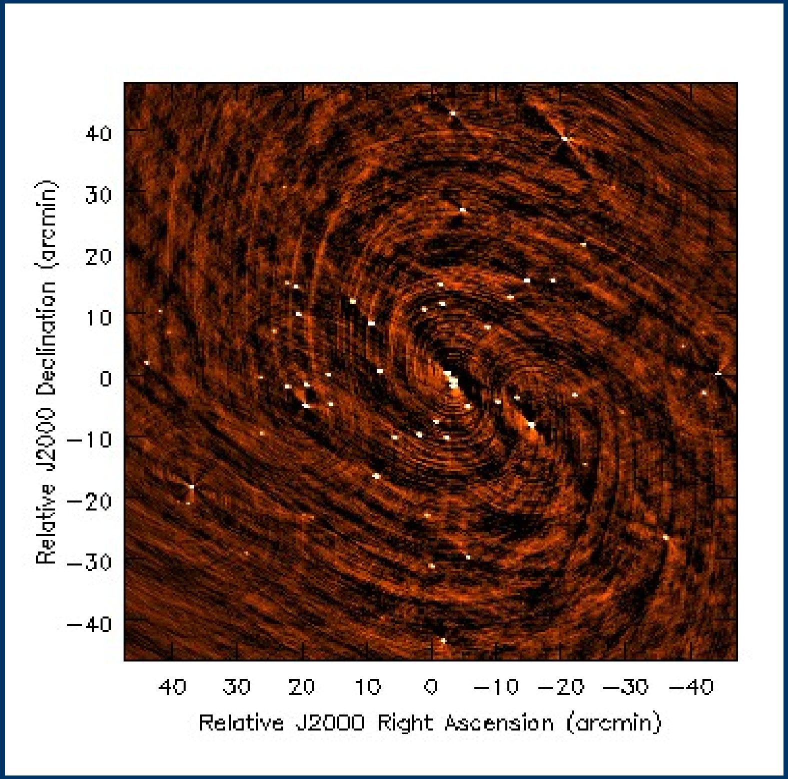


Typical antenna pointing offsets for VLA as a function of time

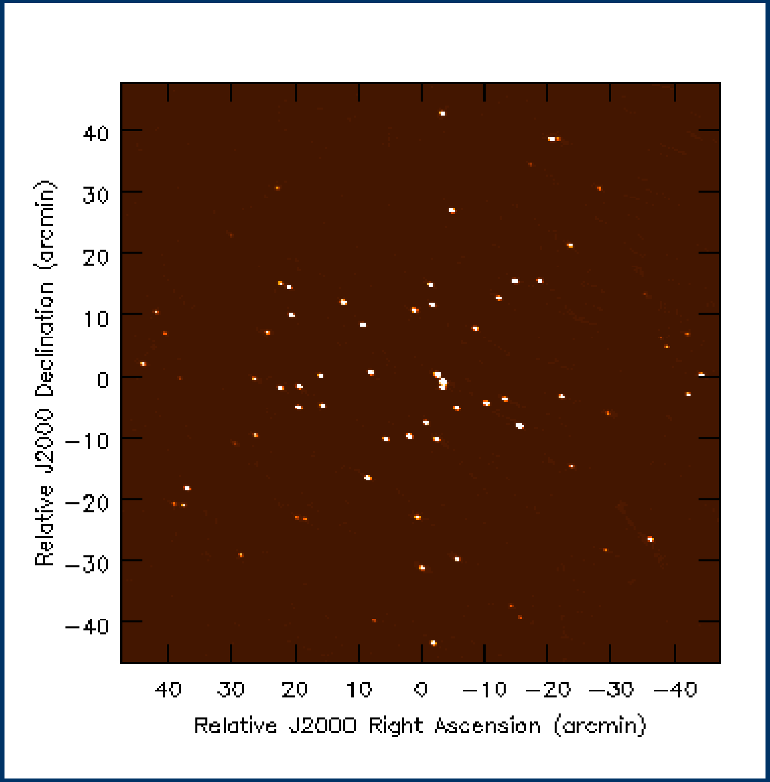
Over-plotted data: Solutions at longer integration time

Noise per baseline as expected from EVLA

Pointing SelfCal: Correction



- No pointing correction:
- RMS ~ 15µJy/b



- After pointing correction:
- RMS ~ 1µJy/b

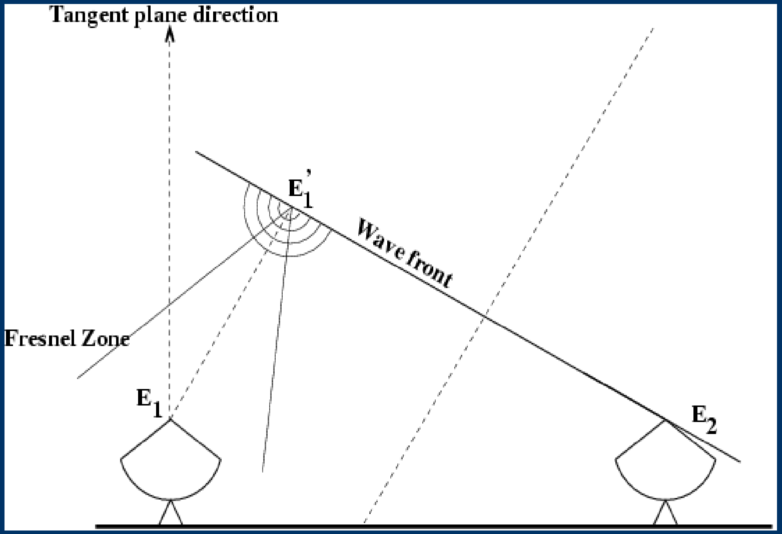
(Bhatnagar, Cornwell & Kolap, EVLA Memo #84/paper in prep.)

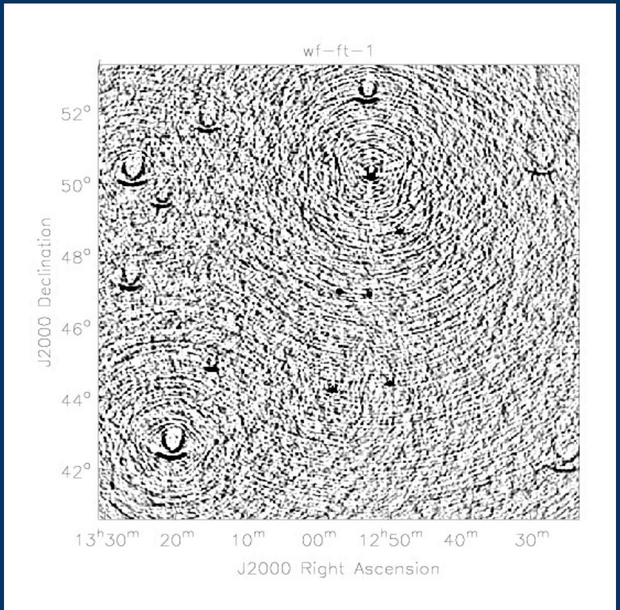
Non-coplanar Baselines

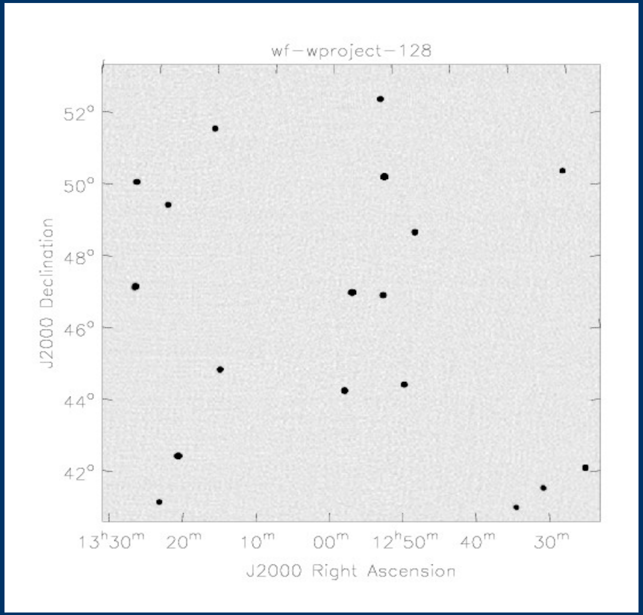
- $V(u,v,w) = G(u,v,w) * V(u,v,w=0)$

  $where\ \overline{G}(l,m,w) = e^{2\pi\iota\left[w\left(\sqrt{1-l^2-m^2}\right)\right]}$

- $E_1 = E'_1(u,v,w)$ propagated using Fresnel diffraction
- Away from the phase center, sources are distorted

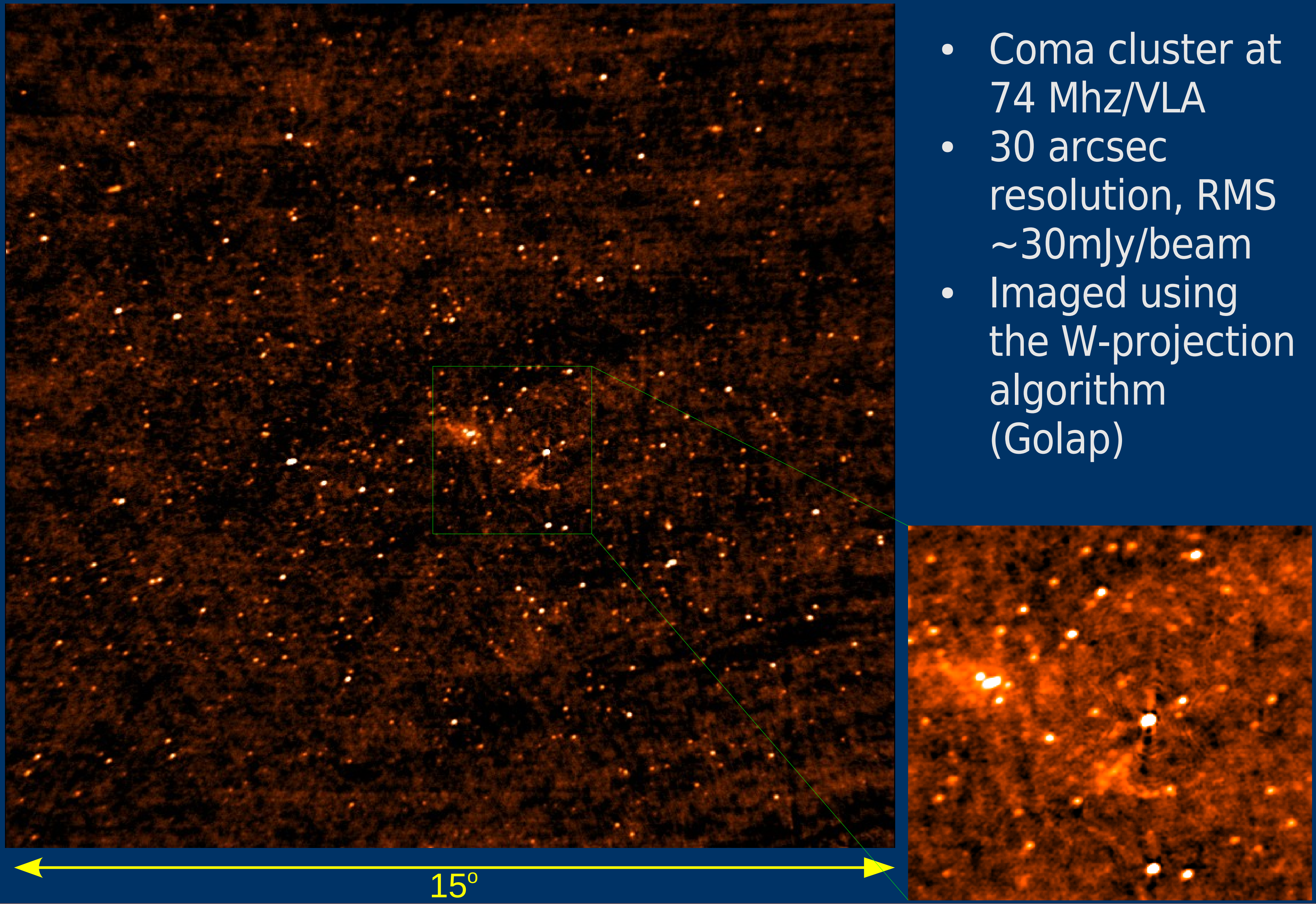






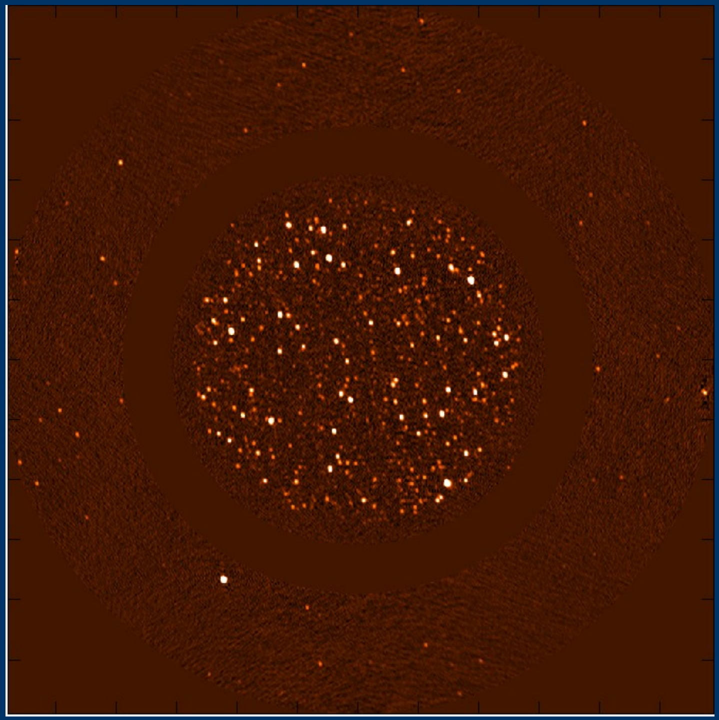
(Cornwell, Kolap & Bhatnagar, EVLA Memo (2004), IEEE Special Issue on RA, (2008))

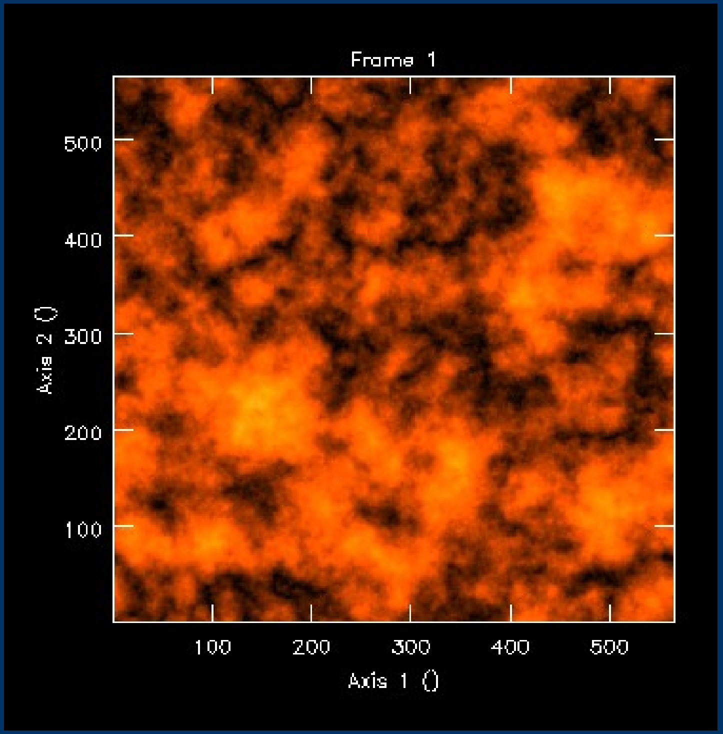
Example: VLA @ 74 MHz



- Coma cluster at 74 Mhz/VLA
- 30 arcsec resolution, RMS ~30mJy/beam
- Imaged using the W-projection algorithm (Golap)

Ionospheric calibration

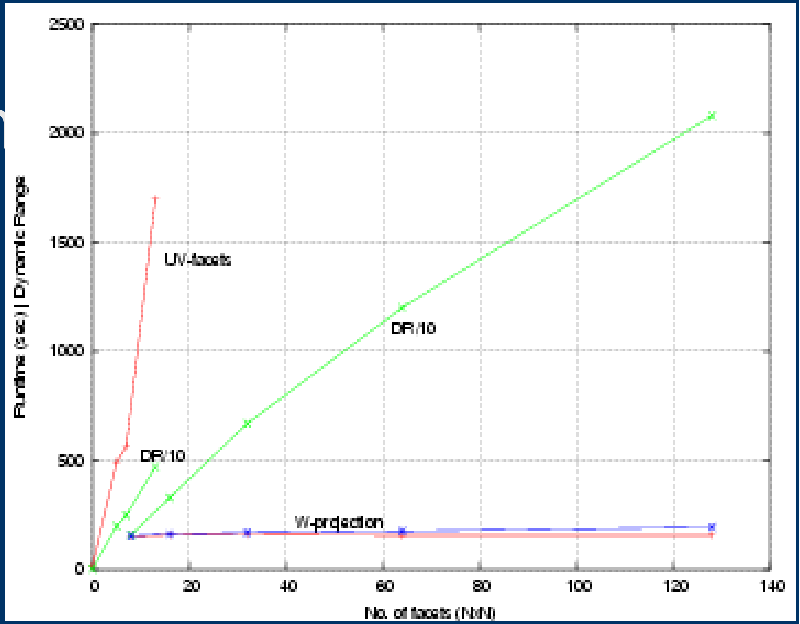




- Challenges:
  - W-term an issue for B_{max} > 2-3Km & DR > 10^4
  - Ionospheric calibration: Even field based calibration fails for B_{max} > 3Km

Computing

- Imaging scaling laws
  - Non co-planar baseline correction
    - W-Projection: $(N^2_{wproj} + N^2_{GCF})\, N_{vis}$
    - Faceting: $N^2_{facets}\ N^2_{GCF}\ N_{vis}$
  - AW-Projection: $N^2_{GCF} * N_{vis}$
  - Peeling: $N_{comp} * N_{vis} * ?$



- Scaling laws for DD solvers
  - FFT-based transforms: $N^2_{GCF} * N_{vis} * N_{iter} * N_{params}$
  - DFT-based transforms: $N_{comp} * N_{vis} * ? * N_{iter} * N_{params}$
  - N_{vis}: $10^{8\text{-}10}$, N^2_{GCF}: 50-100 , N_{comp}: $10^{4\text{-}5}$

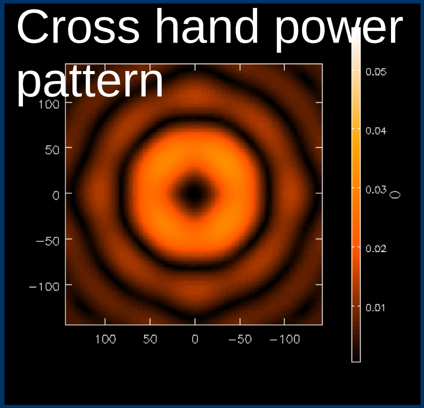
Near future data sizes

- Data I/O : Computing ~ 3:2 (at least)
- Expected average data rates about 10x larger
- Manual processing (data flagging, calibration and imaging) not an option
  - Need robust and efficient algorithms
  - Need robust heuristics
  - Need pipe line processing
  - Need all of this to run in a parallel computing environment

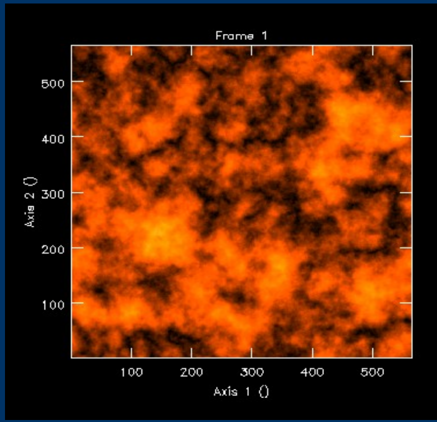
- Interoperability
  - Possible now via FITS
  - Data sizes is the problem!
  - Lower level software exchange is better
    - Sociological rather than technological problem!

Dominant DD Effects for SKA

- Station Power Pattern
  - AA vs. Dishes: Can we model the power patterns as a function of time, frequency and polarization?
  - Dishes: 2-axis vs 3-axis – Is the "software 3rd axis" sufficient?



- Sky Spectral Index variations
  - $S(\nu) \propto \left(\frac{\nu}{\nu_o}\right)^{\alpha(\nu)}$
  - Must work with PB-correction
- Sky and Beam polarization
- Ionosphere
  - Limits of existing techniques



- Deconvolution of complex emission