Recent progress in EVLA-specific algorithms

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Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array
NRAO

Imaging issues

- Full beam, full bandwidth, full Stokes noise limited imaging

- Algorithmic R&D Requirements:
  - PB corrections:
    - Rotation, Freq. & Poln. dependence, W-term (L-band)
  - Multi-frequency Synthesis at 2:1 BWR
    - PB scaling with frequency, Spectral Index variations
    - Scale and frequency sensitive deconvolution
  - Direction dependent corrections
    - Time varying PB, pointing offsets, polarization

Calibration issues

- Band pass calibration
  - Solution per freq. Channel (limited by SNR)
  - Polynomial/spline solutions (also ALMA req.)
  - Multiple Spectral Windows
- Direction dependent instrumental calibration
  - Time varying PB, pointing offsets, ionospheric (L-band)/atmospheric (all bands)
- Polarization calibration
  - Freq. Dependant leakage
  - Beam polarization correction
- RFI flagging/removal
  - Strong: Auto-, Semi-auto flagging
  - Weak: Research problem

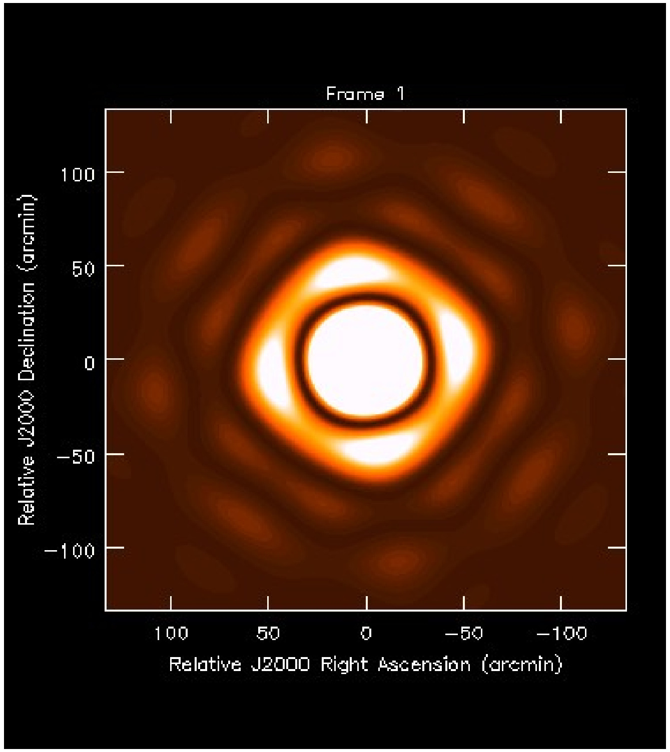
Imaging limits: Due to PB

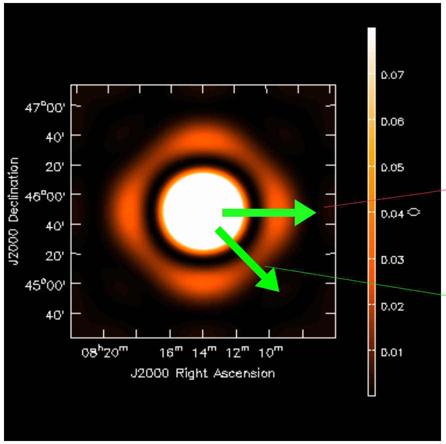
- Limits due to asymmetric PB
  - In-beam max. error @ 10% point: ~10000:1
  - Errors due to sources in the first side-lobe: 3x-5x higher
  - Less of a problem for non-mosaicking observation at higher frequencies (>C-band)
    - But similar problems for mosaicking at higher frequencies

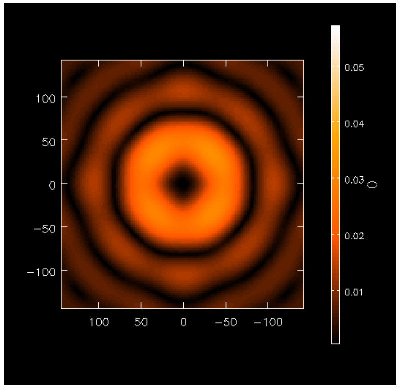
- Limits due to antenna pointing errors
  - In-beam and first side-lobe errors: ~10000:1
  - Similar limits for mosaicking at higher frequencies

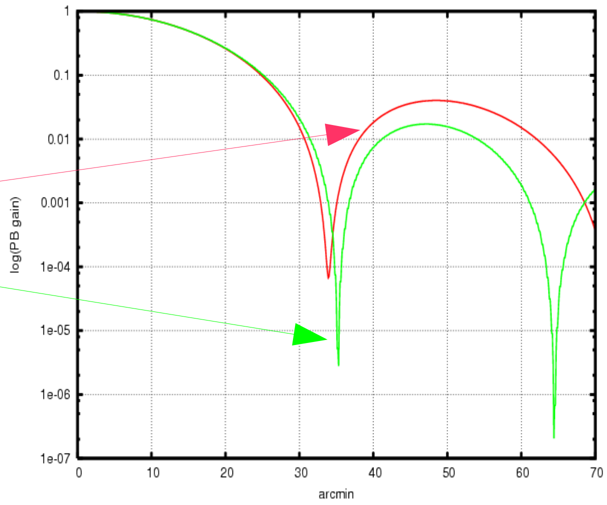
Imaging limits: Due to PB

- Time varying PB gain









Sources of time variability

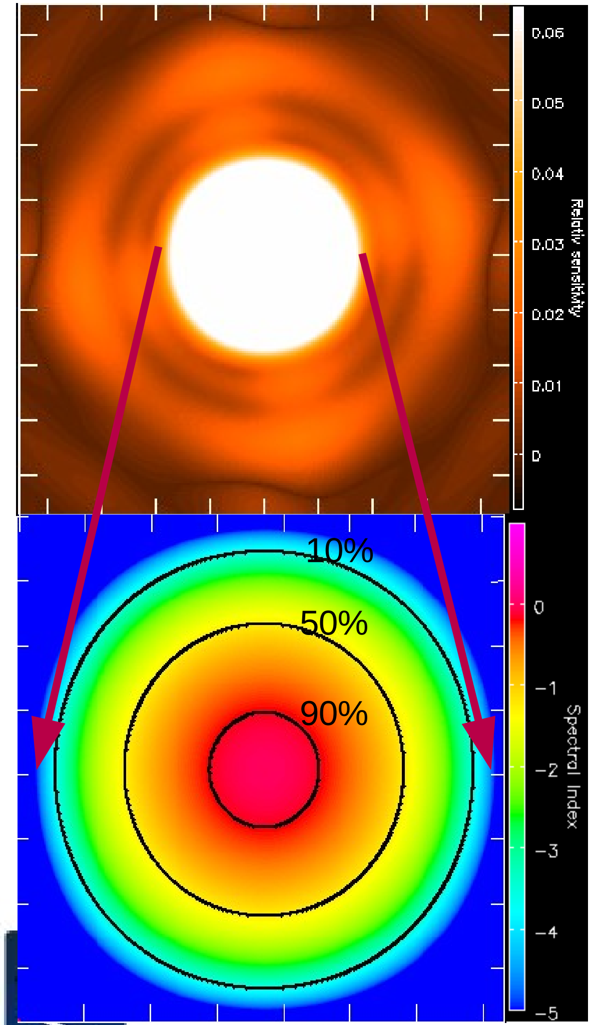
- PB rotationally asymmetric
- PB rotation with PA
- PB scaling with frequency
- Antenna pointing errors

Imaging limits: Due to bandwidth

- Frequency dependence
  - Instrumental: PB scales by 2X is strongest error term
  - Sky: Varying across the band – needs to be solved for during imaging (MFS)

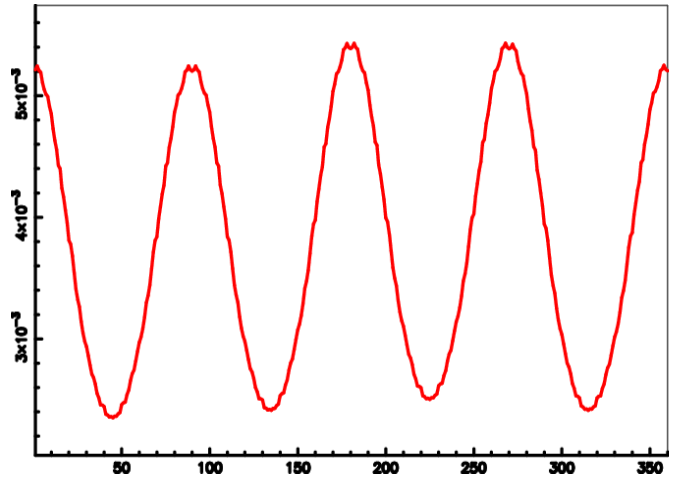
- Limits due to sky spectral index variations:
  - A source with Sp. Index ~1 can limit the imaging dynamic range to ~$10^{3\text{-}4}$

Wide-band static PB

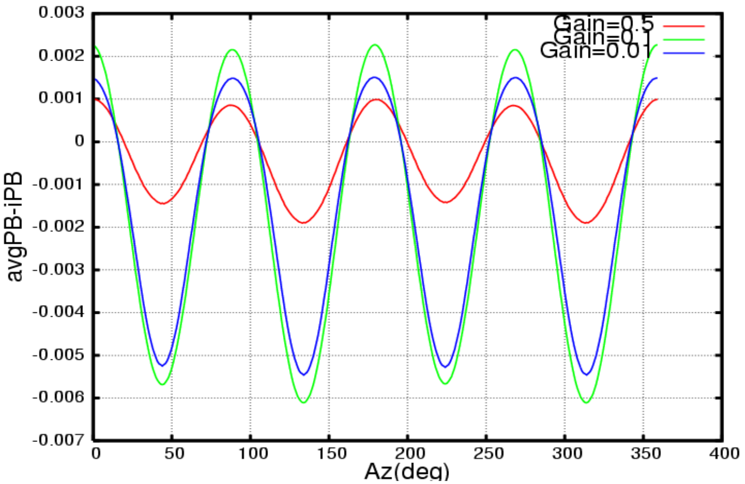


Wide-band power pattern (3 Channels spanning 1 GHz of bandwidth)

Avg. PB Spectral Index (1-2GHz)



Gain change at first side lobe due to rotation



Gain change in the main-lobe due to rotation

Algorithmic dependencies

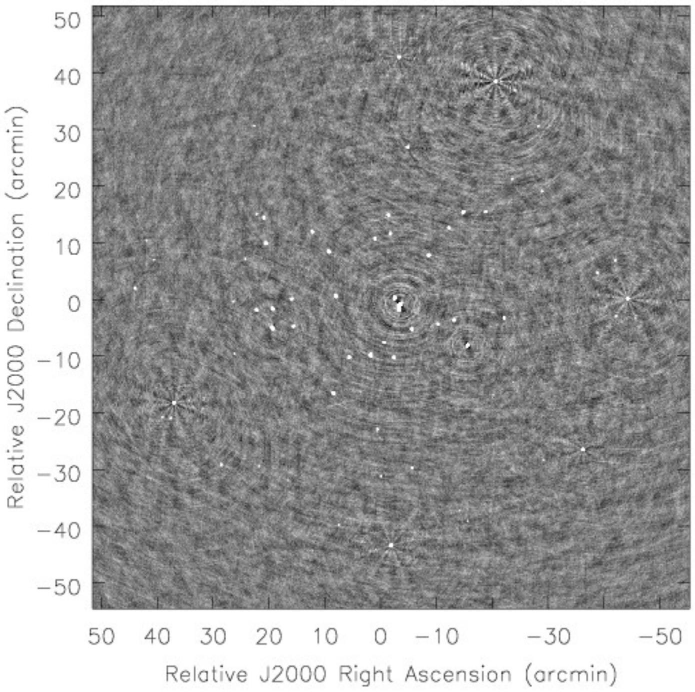
- Wide-band, “narrow field” imaging
  - Dominant error: Sky spectral index variation
    - Post deconvolution PB corrections: Assume static PB
- Wide-band, wide-field imaging
  - Dominant error: PB scaling
    - Require time varying PB correction during deconvolution
    - Pointing error correction
- Wide-band, full-beam, full-pol. Imaging
  - Dominant error: PB scaling and PB polarization
- High DR imaging / mosaicking (ALMA)
  - Requires all the above + Scale- and freq-sensitive modeling (multi-scale methods)

Progress (follow-up from last year)

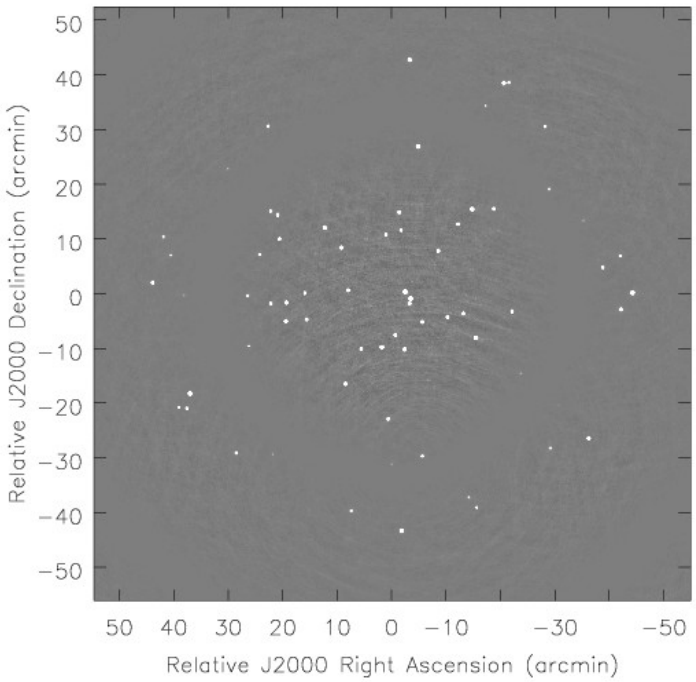
- Wide field imaging
  - W-Projection algorithm: [Published/in use]
    - 3-10X faster (Cornwell, Golap, Bhatnagar, IEEE, 2008)
    - Better handles complex fields
    - Easier to integrated with other algorithms
  - PB corrections
    - Basic algorithm: AW-Projection algorithm: [Bhatnagar et al./ Testing]
    - All-Stokes PB correction [Initial investigations]
    - PB freq. Scaling [In progress]
  - PB-measurements [In progress]
  - Pointing SelfCal: [Sci. Testing]
    [Bhatnagar et al., EVLA Memo 84]
- Wide-band imaging [Basic algorithm Sci. Testing]
  - U. Rau's thesis: [in prep]

Correction for pointing errors and PB rotation: Narrow band

Before correction

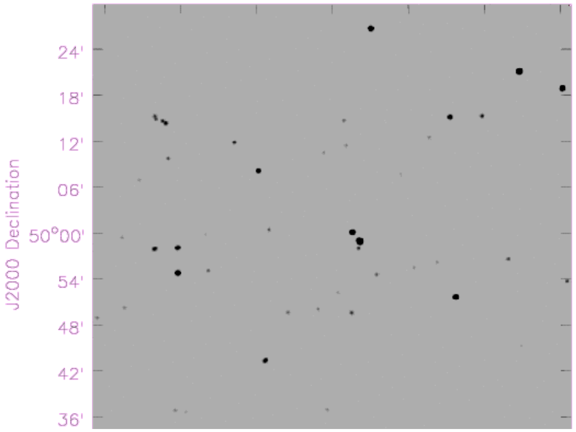


After correction



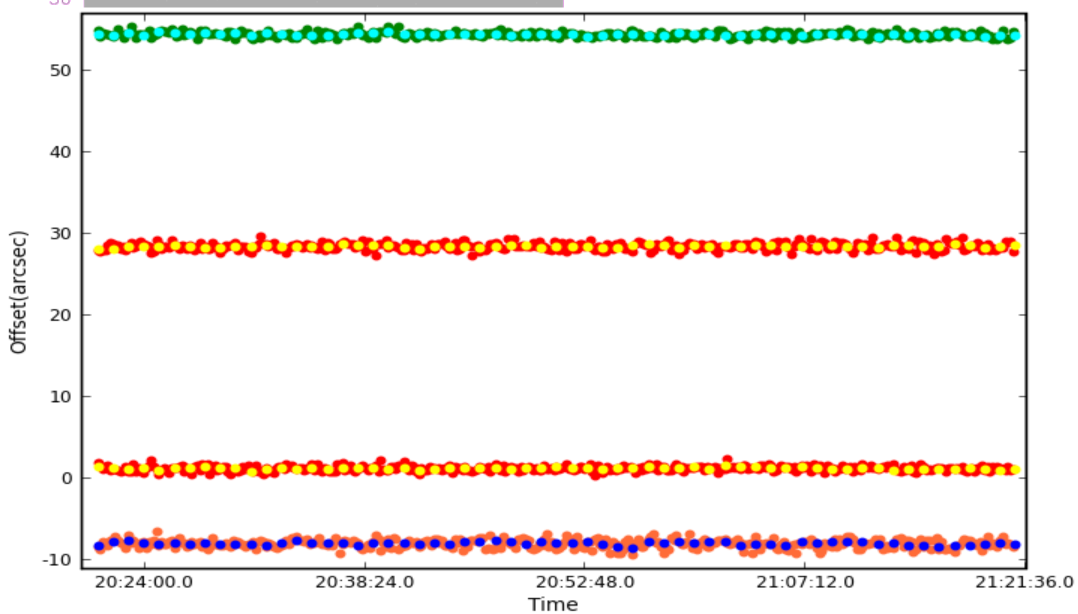
(Bhatnagar et al., EVLA Memo 100 (2006), A&A (2008))

Pointing SelfCal



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

(Bhatnagar et al., EVLA Memo 84)

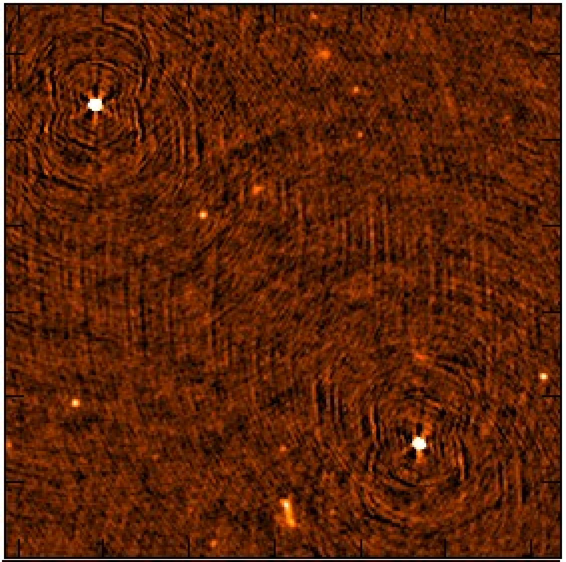


•Typical antenna pointing offsets for VLA as a function of time

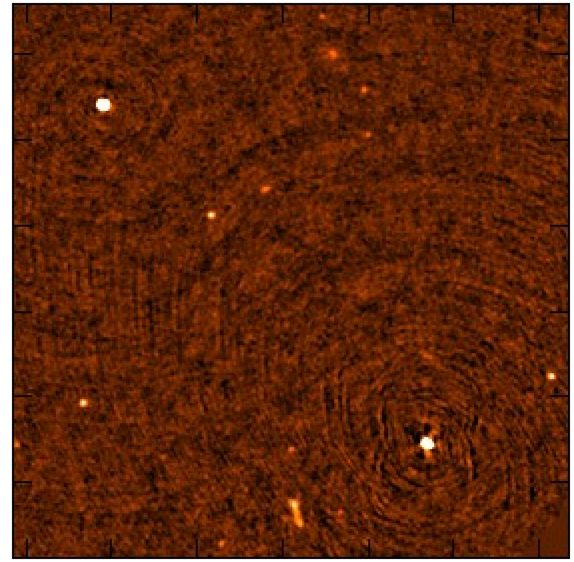
•Over-plotted data: Solutions at longer integration time

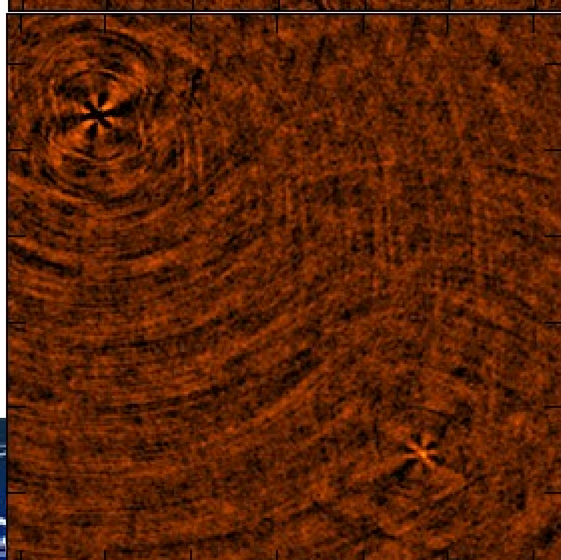
•Noise per baseline as expected from EVLA

L-band imaging: Stokes-I & -V



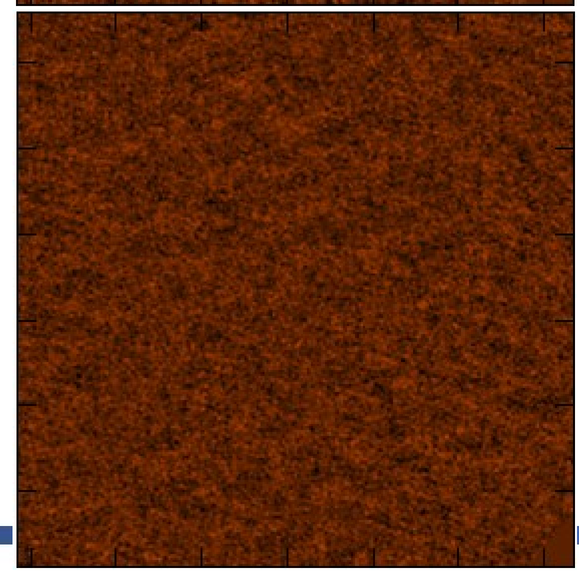
Stokes-I





Stokes-V

(10x improvement)



Wide-band imaging: Rau's thesis

- Narrow field (EVLA Memo 101; Rau)
  - Traditional MFS/bandwidth synthesis/Chan. Averaging inadequate for EVLA 2:1 BWR
  - Post deconvolution PB correction
  - Hybrid approach: DR ~10^4:1 (Rau et al.,EVLA Memo 101)
    - And requires more computing!
- MS-MFS (REF: in prep)
- MS-MFS + PB-correction
  - Combining MS-MFS with AW-Projection
  - Initial integration + testing in progress (with real data)

Extending MFS: Basics algorithm

True Images

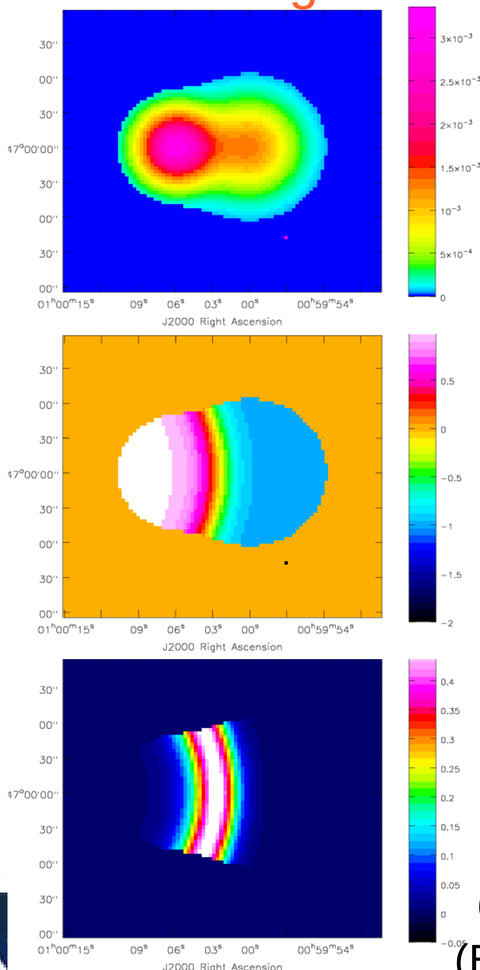


Image at reference frequency

Average Spectral Index

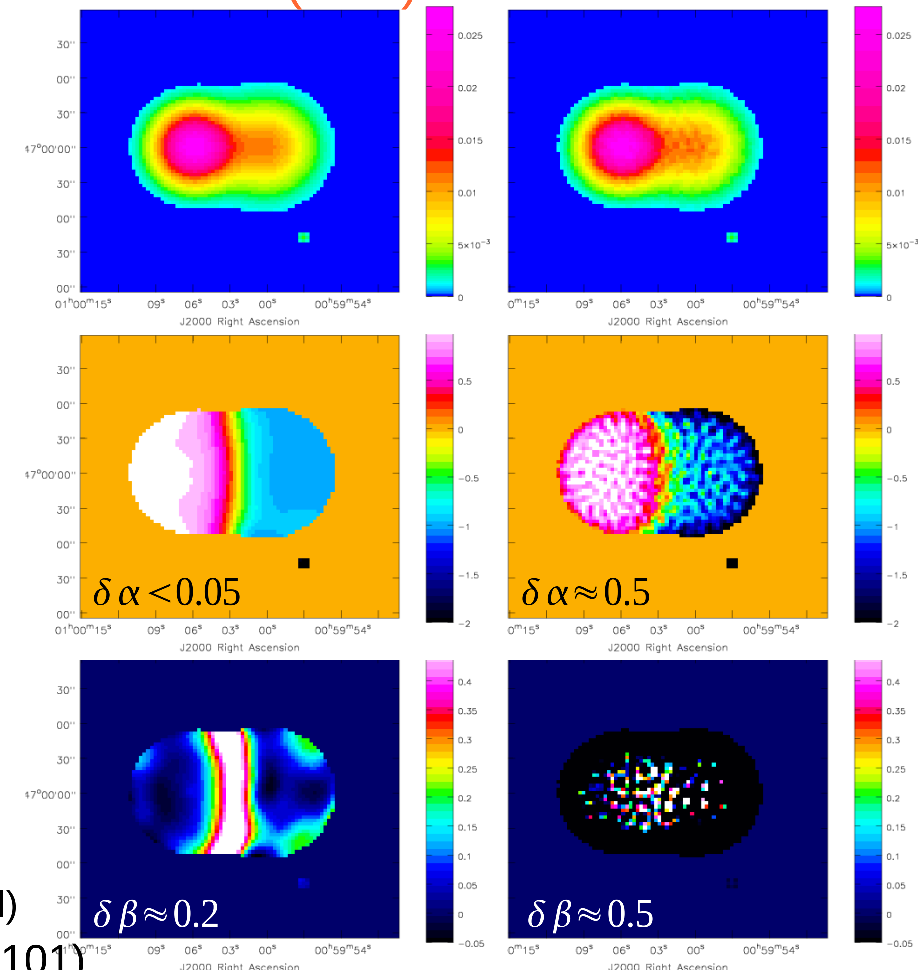
Gradient in Spectral Index

(Rau, Cornwell)

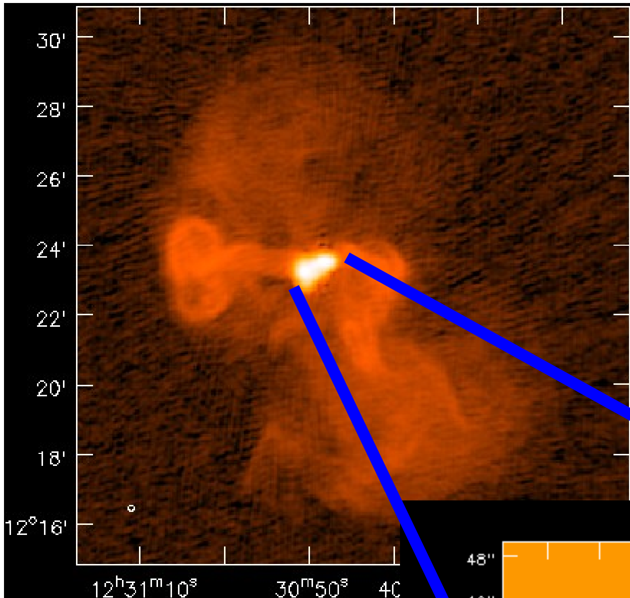
(EVLA Memo 101)

MS-MFS (new)

Traditional-MFS

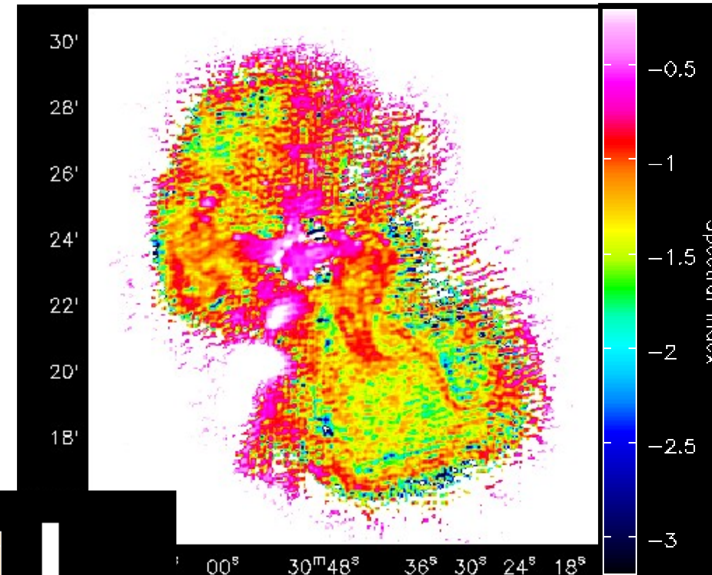


Application to M87: Fresh results



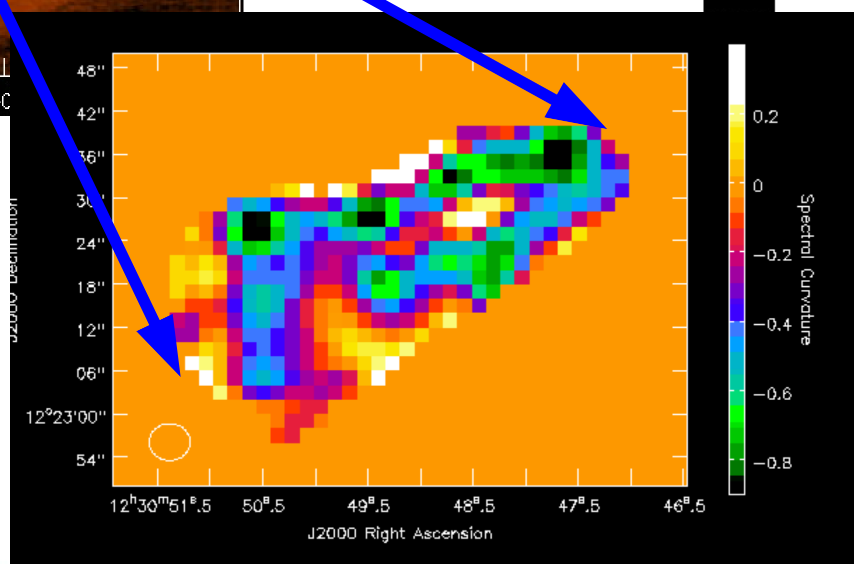
Stokes-I

(Rau, Owen)



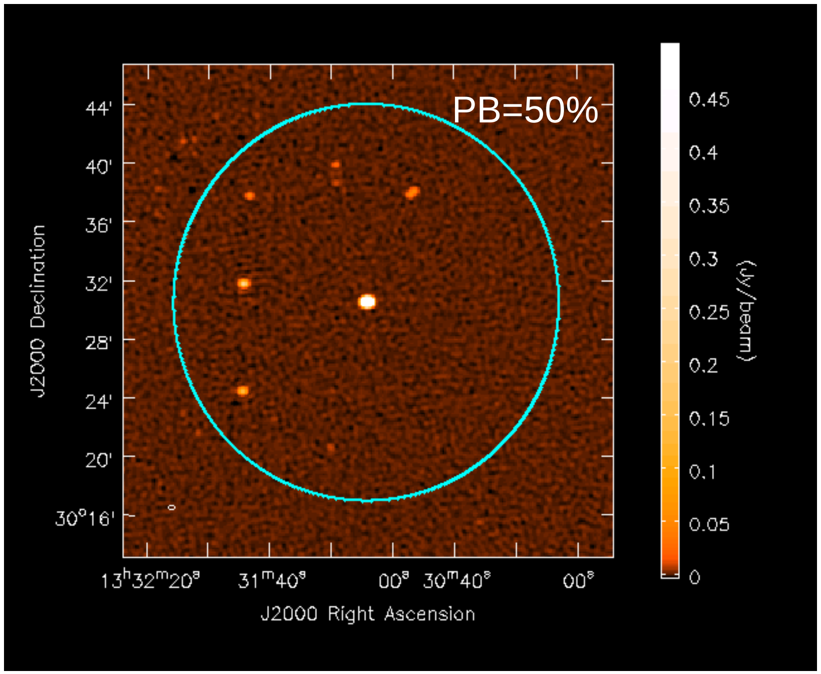
Sp. Ndx.

(No PB correction)



Sp. Ndx. variation

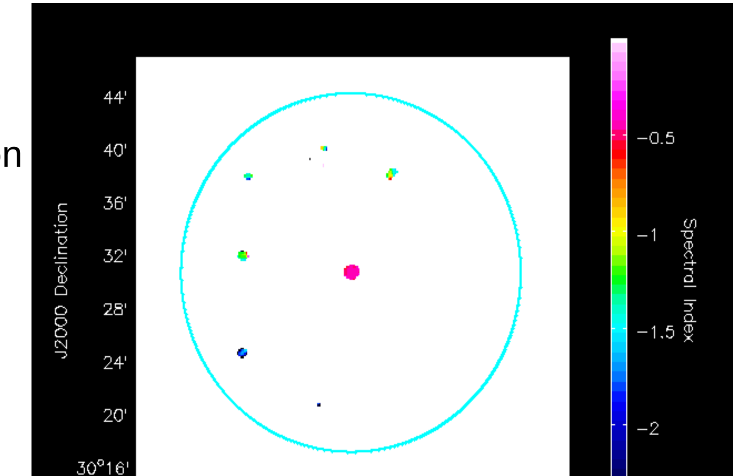
Wideband PB correction



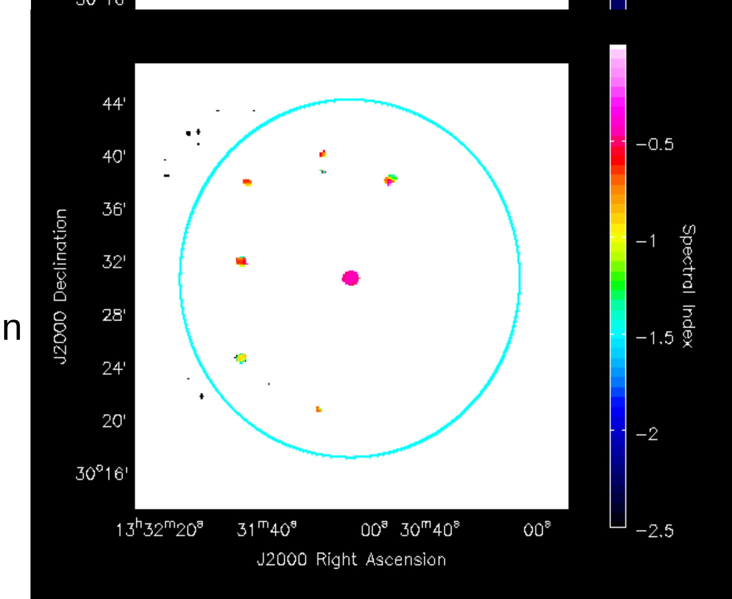
3C286 Stokes-I

(Rau, Bhatnagar)

Before PB correction



After PB correction



Computing challenges

- Significant increase in computing for wide-band and wide-field imaging
  - Larger convolution kernels
  - MFS and MS-MFS loads: Equivalent of $N_{taylor} * N_{scales}$ imaging load. Typical $N_{taylor} = 3$, $N_{scales} = 5$
- Direction dependent terms
  - Correction and calibration as expensive as imaging
- I/O load
  - Near future data volume: 100-200 GB / 8hr by mid-2010
  - 20-50 passes through the data (flagging + calibration + imaging)

CASA Terabyte Initiative

- Develop pipelines for end-to-end processing
  - Primary calibration, flagging, Imaging, SelfCal
- Test Cluster parameters (Paid for by ALMA & EVLA)
  - 16 nodes
  - Each node: 8GB RAM, 200GB disk, 8 cores
  - Total cost: ~$70K

- Current effort:
  - Data volume: 100 GB
  - Integration time=1s; Total length: 2hr
  - No. of channels: 1024 across 32 Sub-bands
- Future tests with 500 GB and 1 TB data sizes

Computing & I/O load: Single node

- Data: 100 GB, 512 Channels, 4K x 4K x 512 Stokes-I imaging
- 4 CPU, 16 GB RAM computer
- I/O : Compute = 3:2
- Conclusions:
  - Simple processing is I/O dominated
  - Image deconvolution is the most expensive step
    - Most expensive part of imaging is the Major Cycle
  - Exploit data parallelism as the first goal
- Total effective I/O ~1 TB (iterations)

Parallelization: Initial results

- Spectral line imaging: (8GB RAM per node)
  - Strong scaling with number of nodes & cube size
  - Dominated by data I/O and handling of image cubes in the memory
  - 1024 x 1024 x 1024 imaging
    - 1-Node run-time : 50hr
    - 16-node run : 1.5 hr
- Continuum imaging: (No PB-correction or MFS)
  - Requires inter-node I/o
  - Dominated by data i/o
  - 1024 x 1024 imaging:
    - 1-node run-time : 9hr
    - 16-node run-time : 70min (can be reduced upto 50%)

Plan: Parallelization & Algorithms

- Initial goal for parallelization
  - Pipelines to exploit data parallelization
  - Get cluster h/w requirements
  - Collaboration with UVa
- New developments: Algorithms research
  - Imaging
    - Integration of various DD terms (W-term, PB-corrections, Sp.Ndx….)
    - Wide(er) field
    - Full polarization
    - Better scale-sensitive (multi-scale) deconvolution
  - Calibration
    - DD calibration
- New developments: Computing
  - OpenMP to exploit multi-CPU/core computers
  - Robust pipelines for e2e processing

Computing challenges (backup slide)

- Residual computation (Major Cycle)
  - Most expensive part of post processing
  - I/O limited
  - Required in iterative calibration and imaging

- Component modeling (Minor cycle)
  - Required in MS and MS-MFS
  - Computation limited

- Direction dependent calibration
  - As expensive as imaging