Pointing Self Calibration

SKA1-Mid Calibration Consultation Workshop,
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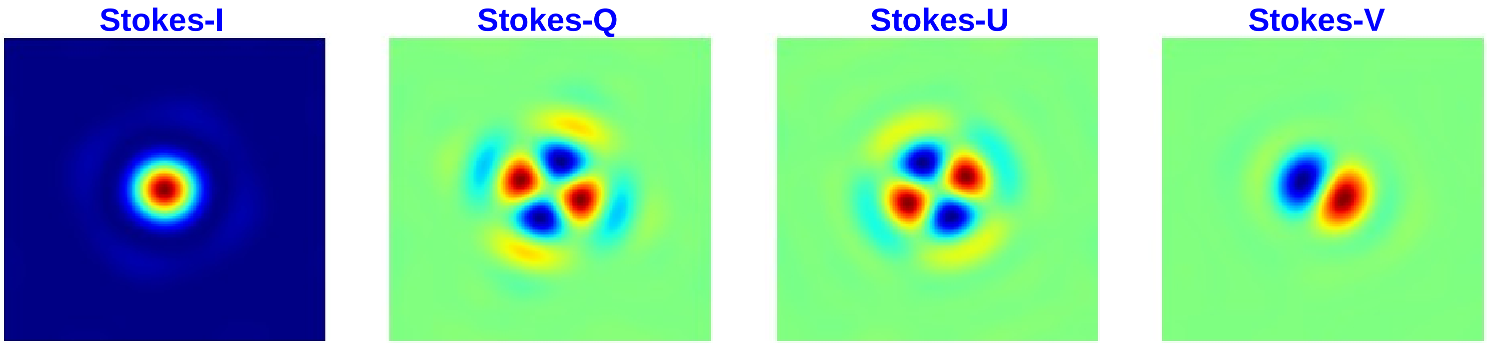
S. Bhatnagar
NRAO

Motivation

- High Dynamic Range imaging
  - Thermal noise-limited imaging with the EVLA at “low” bands implies >1M:1 DR
  - Requires corrections for PB effects: Rotation, Frequency dependence & off-axis polarization, Pointing jitter
  - Pointing corrections at short time scales: reference pointing done at high frequencies at ~30min time scales

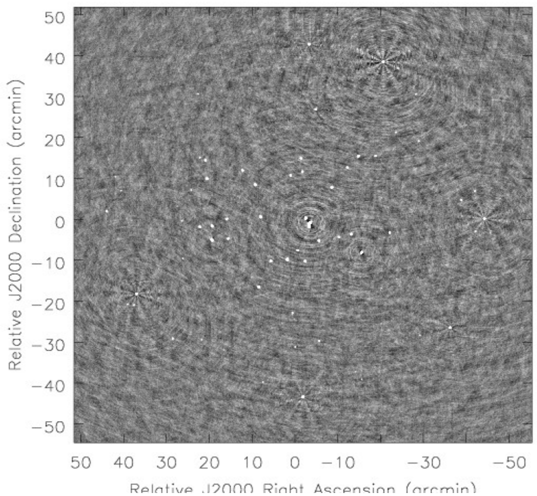
- Wide-field full-polarization imaging capability

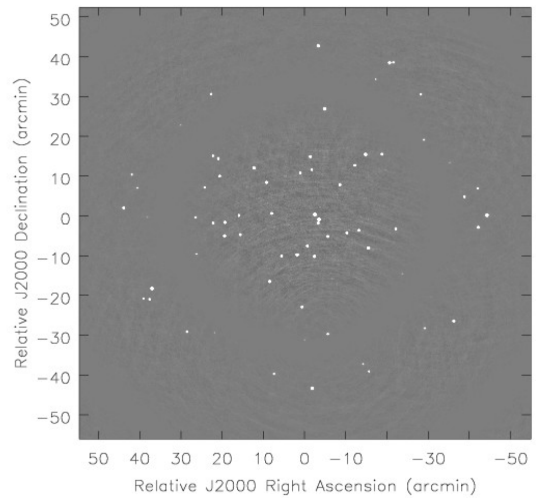
- Poln. Leakage



Simulations

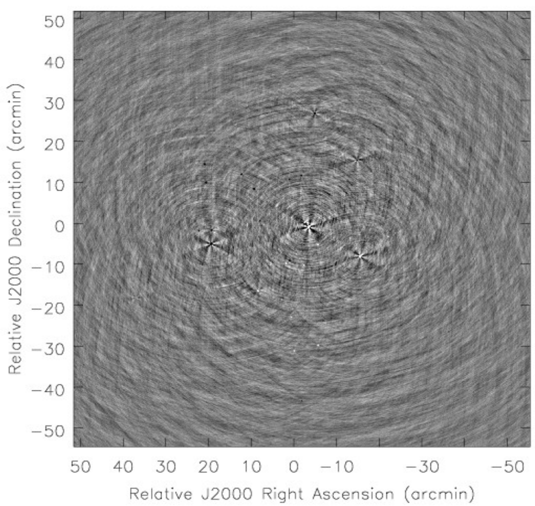
Stokes-I

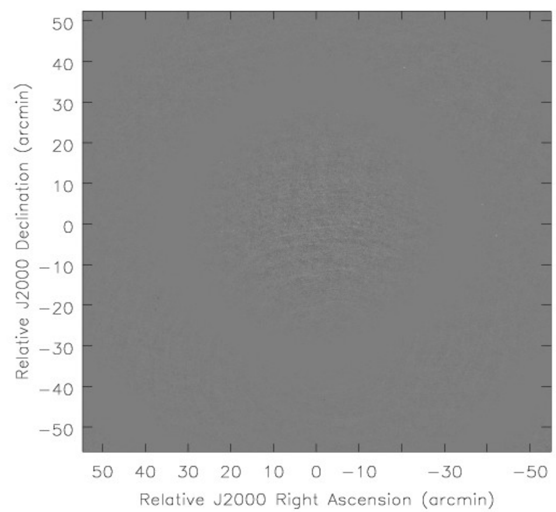


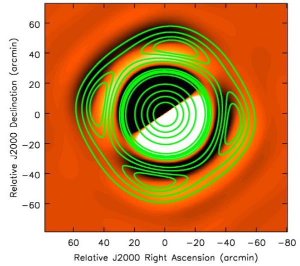


Flux range:
2—200 mJy

Stokes-V



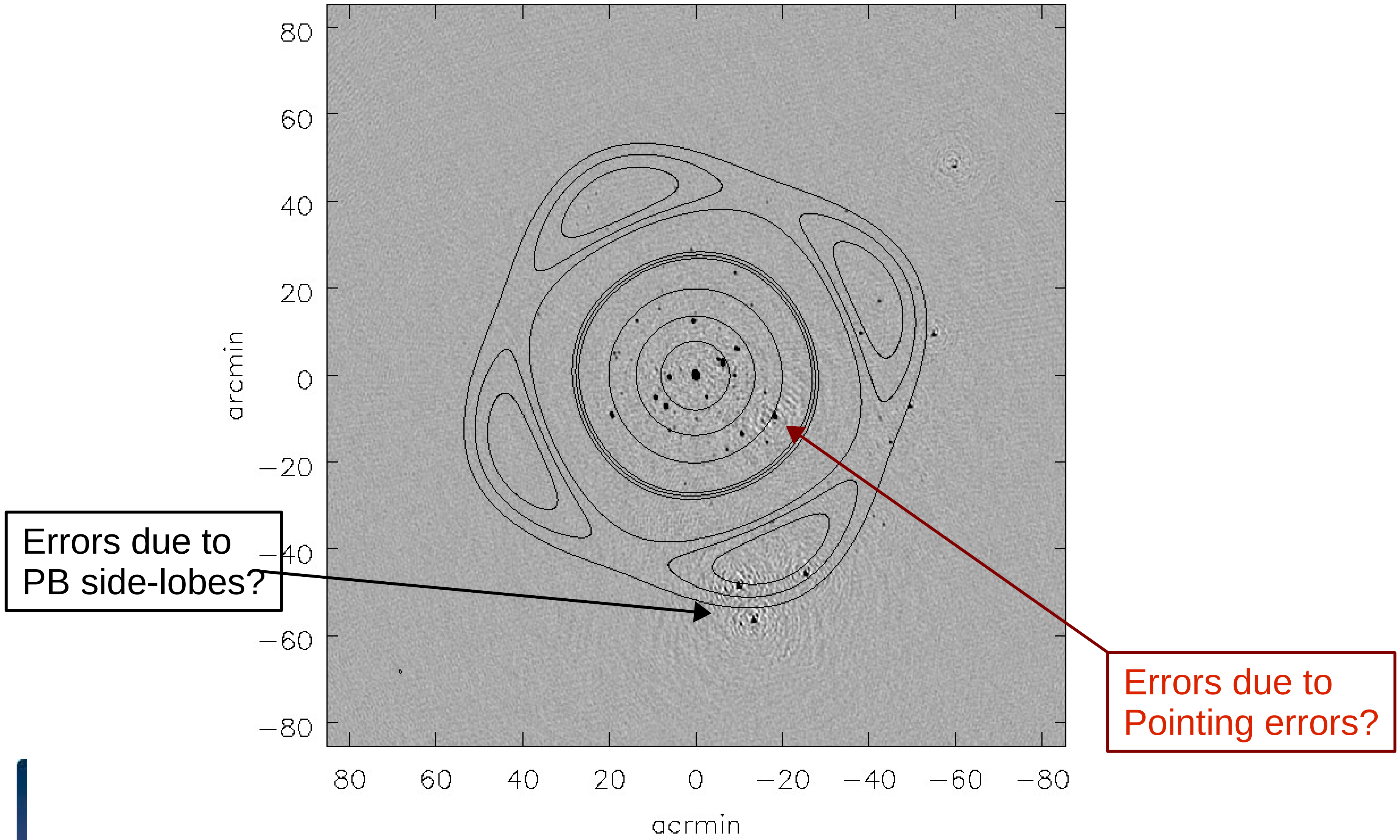




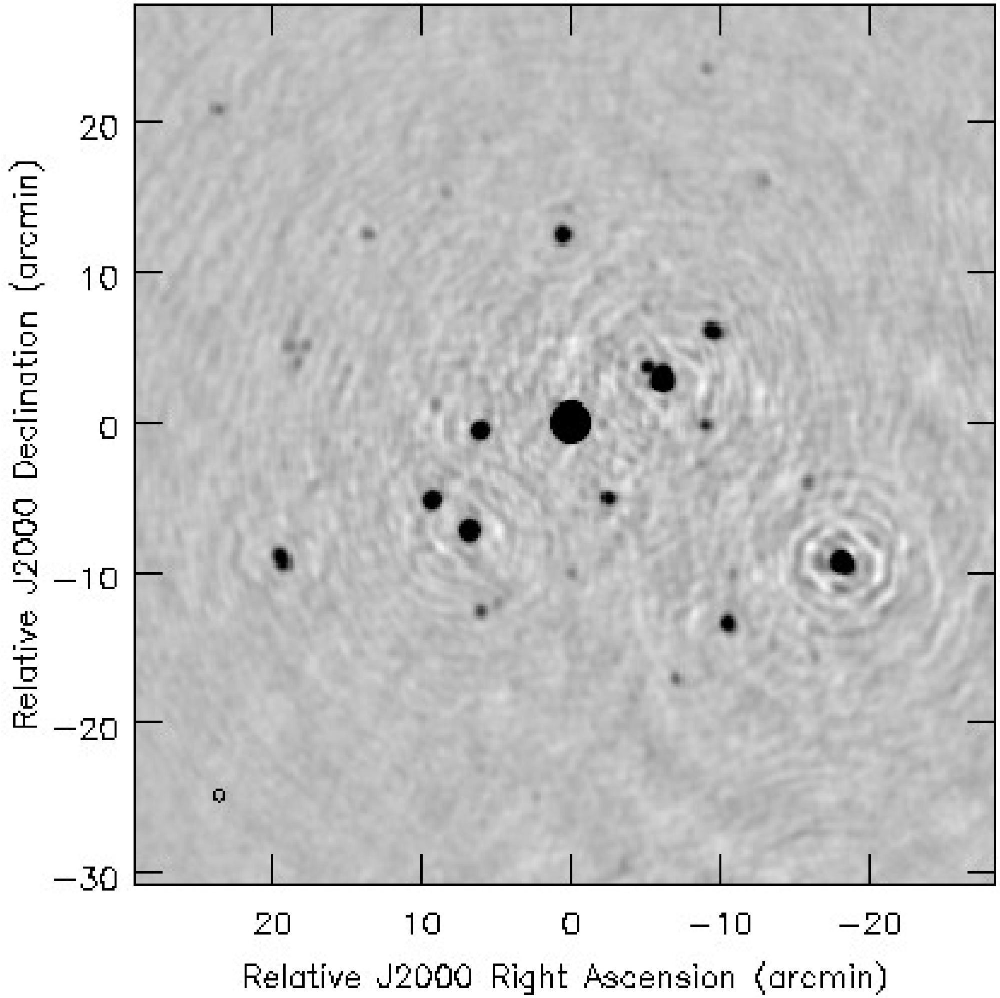
RMS ~15µJy/beam

RMS ~1µJy/beam

3C147: Wide-field residual errors

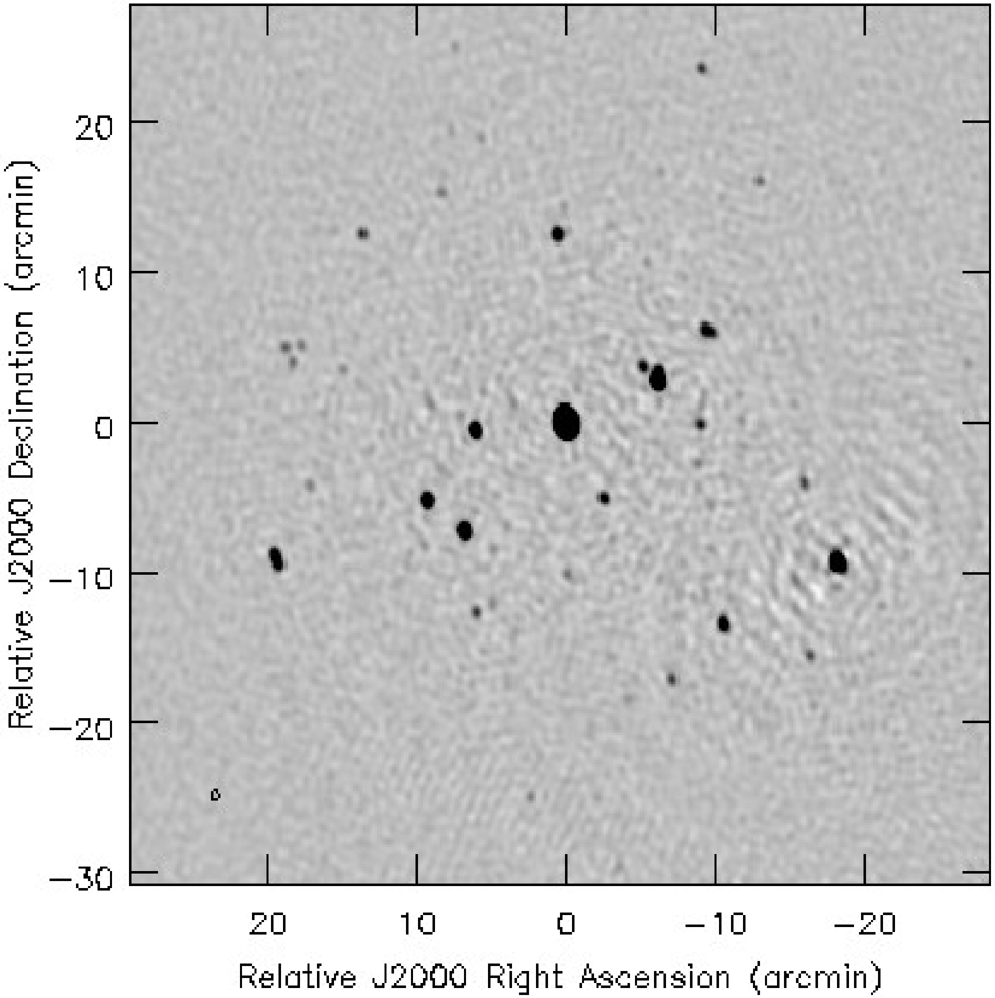


EVLA L-Band Stokes-I: Before correction



- 3C147 field at L-Band
- Pre-OSRO Mode
  WIDAR0!
- Only 12 antennas used
- Bandwidth: 128 MHz
- ~7 hr. integration

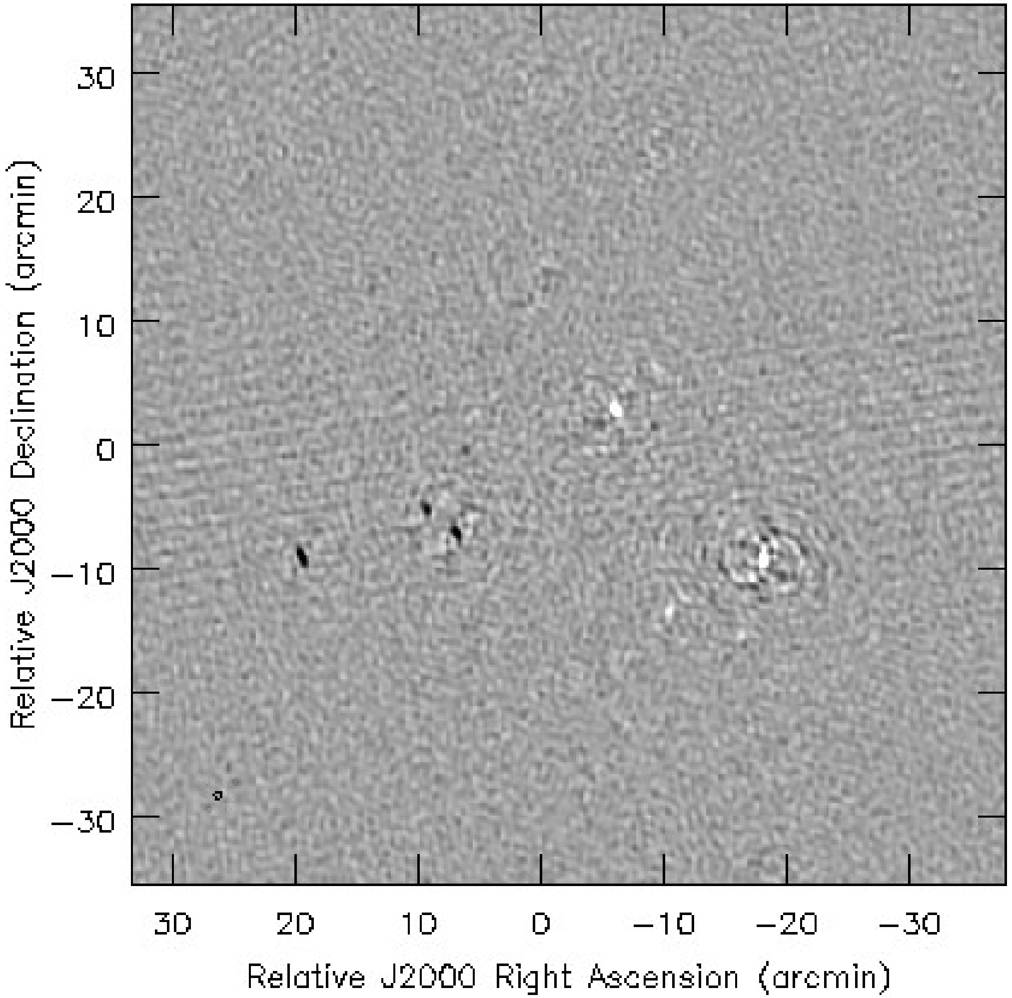
EVLA L-Band Stokes-I: After correction



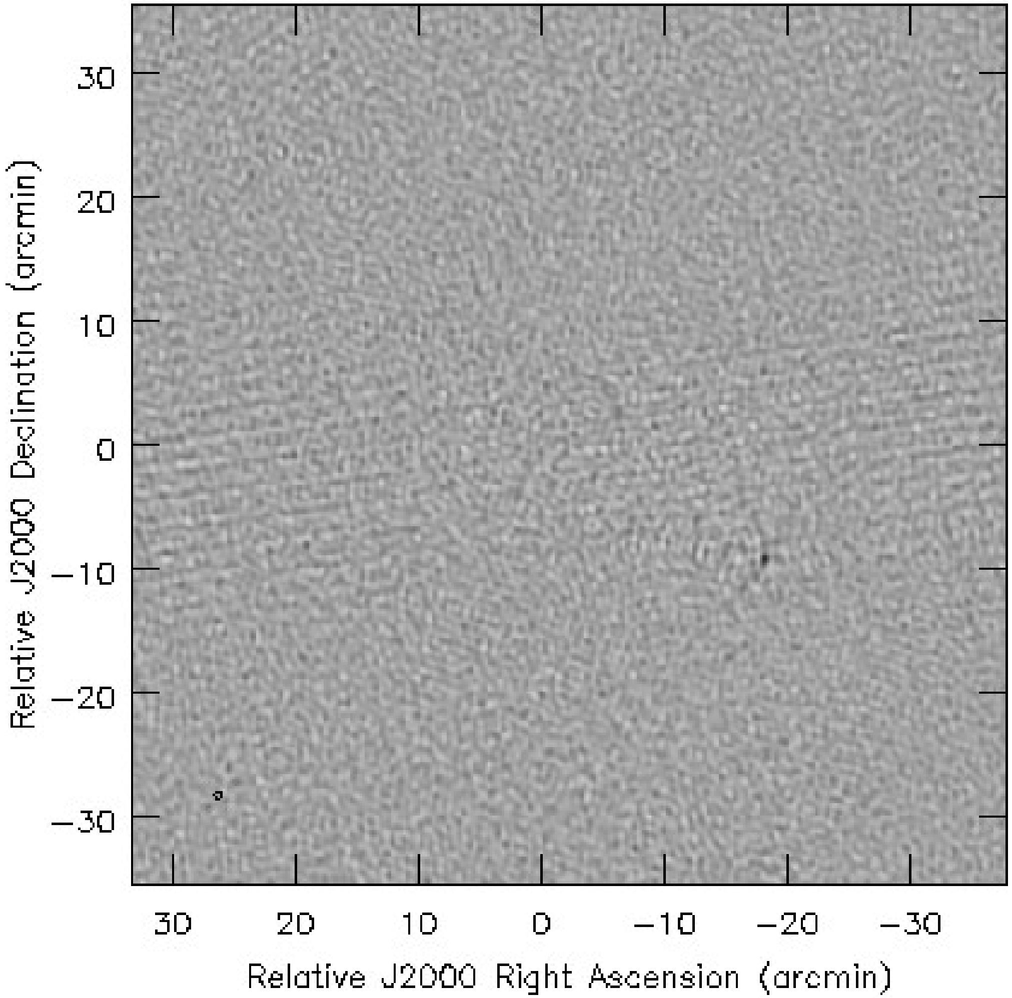
- 3C147 field at L-Band with the EVLA
- Only 12 antennas used
- Bandwidth: 128 MHz
- ~7 hr. integration

- Dynamic range: ~1M:1

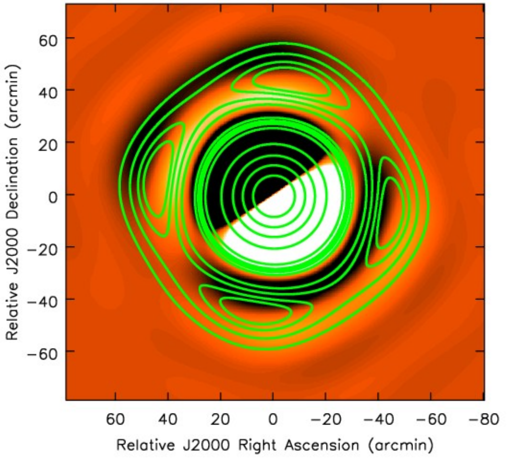
EVLA L-Band Stokes-V: Before correction



EVLA L-Band Stokes-V: After correction



Use physical model for the Stokes-V pattern:



Contours: Stokes-I power pattern
Colour: Stokes-V power pattern

Parametrized Measurement Equation

- Measurement Equation

$$General: \quad V_{ij}^{Obs} = \left(E_i \otimes E_j^T \right) * V_{ij}^o$$

$$For\ DI\ gain: \quad V_{ij}^{Obs} = \left(g_i \cdot g_j^* \right) \cdot V_{ij}^o$$

- Parameters remain separable as antenna-based in the data-domain (min. DoFs)
- Functions are more compact

- Generalization of the standard SelfCal

$$Minimize: V_{ij}^O - E_{ij} * V_{ij}^M \quad w.r.t. \quad E_i$$

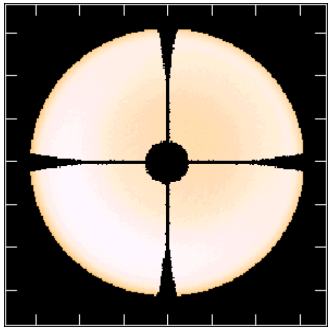
$$\left[\frac{\partial E_{ij}(p_i^k, p_j^k)}{\partial E_i} \frac{\partial E_i}{\partial p_i^k} \right] * V_{ij}^M = 0$$

- p_i^k antenna pointing errors

What is needed?

$$\left[\frac{\partial E_{ij}(p_i^k, p_j^k)}{\partial E_i}\frac{\partial E_i}{\partial p_i^k}\right] * V_{ij}^M = 0$$

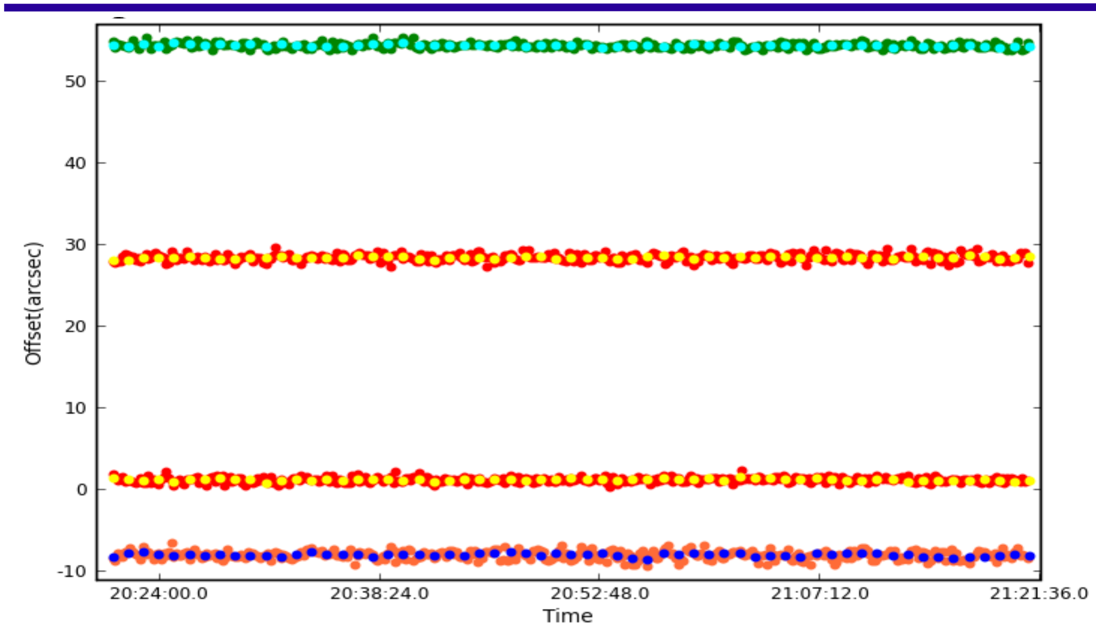
- E_i : parametrized model for the antenna aperture illumination pattern (AIP)



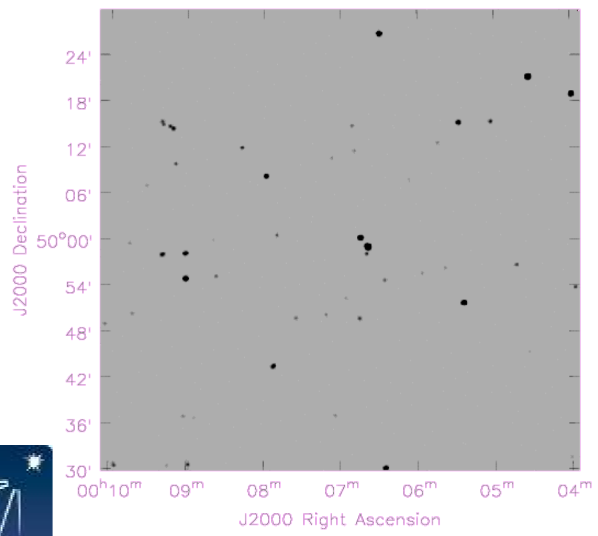
One element of the DD-Jones ("DI Jones Matrix" per pixel)

- $V_{ij}^M = FT(I^M)$: Nominal model of the wide-field sky emission
  - Existing GSM
  - Derived via the Imaging-Calibration loop
- Efficient algorithm to apply pointing offsets during imaging
  - Full-Mueller A-Projection algorithm

Pointing SelfCal algorithm: Simulations



- Typical antenna pointing offsets for VLA as a function of time (timescale 60s)
- Over-plotted data: Solutions with integration time of ~600s
- Noise per baseline as expected from VLA



Sources from NVSS.
Flux range ~2-200 mJy

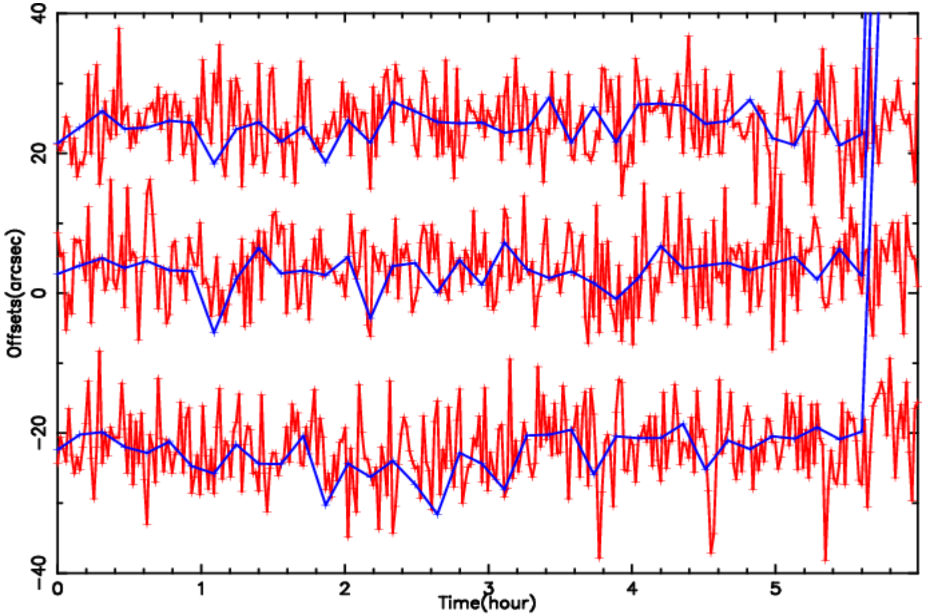
Noise Budget:

$$\sigma(p) = \left[\frac{2 k_b T_{sys}}{\eta_a A N_{ant} \sqrt{\nu_{corr} \tau_{corr} N_{SolSamp}}} \right] \frac{1}{S}$$

$$\textit{where } S = \int \frac{\partial E_i(s,p)}{\partial s} E_j^*(s,p) I^M(s) e^{2\pi\iota s.b_{ij}} ds$$

[Bhatnagar et al., EVLA Memo 84, 2004]

Pointing SelfCal algorithm: Simulations



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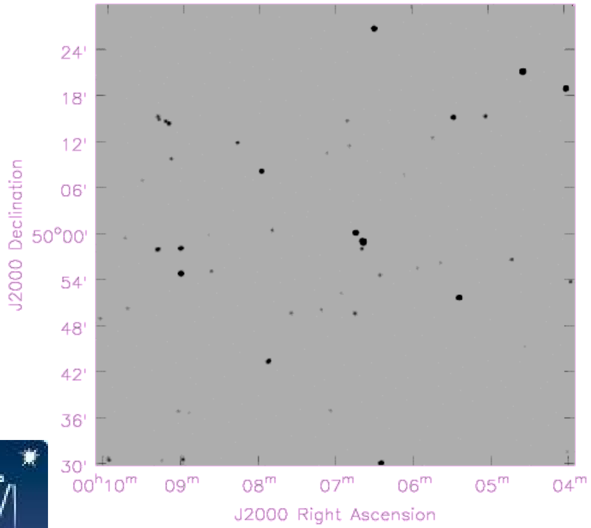

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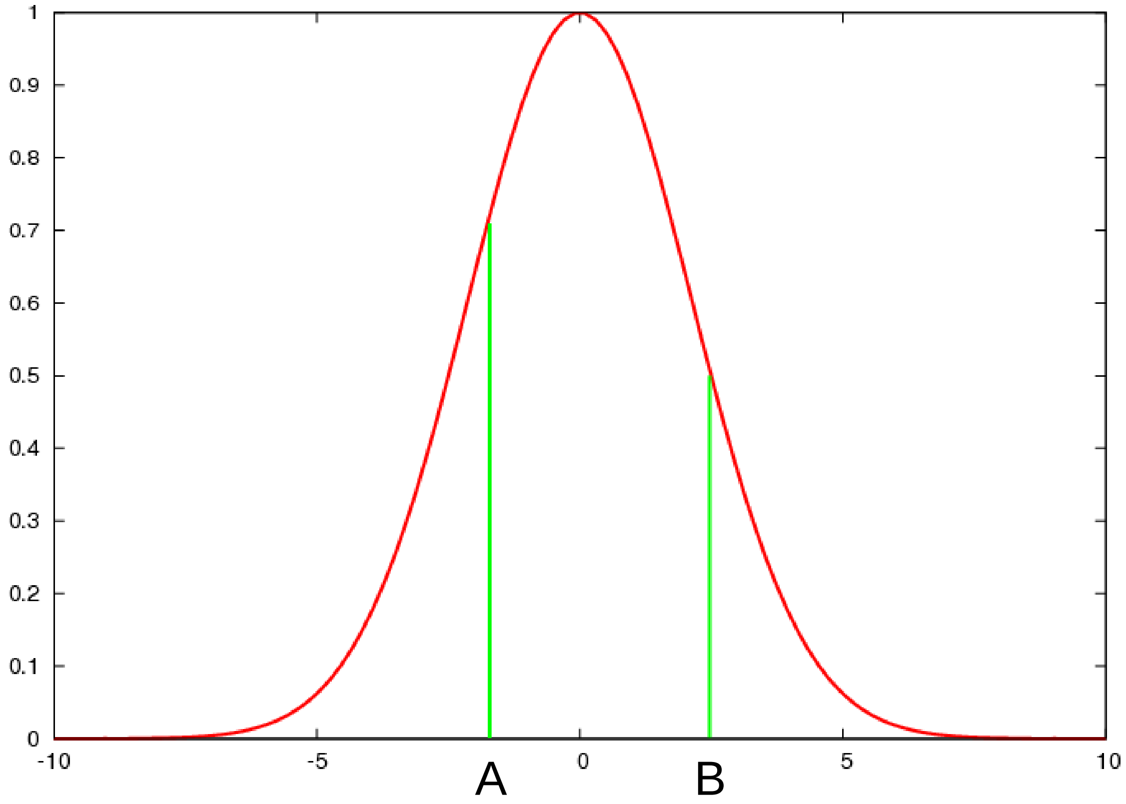
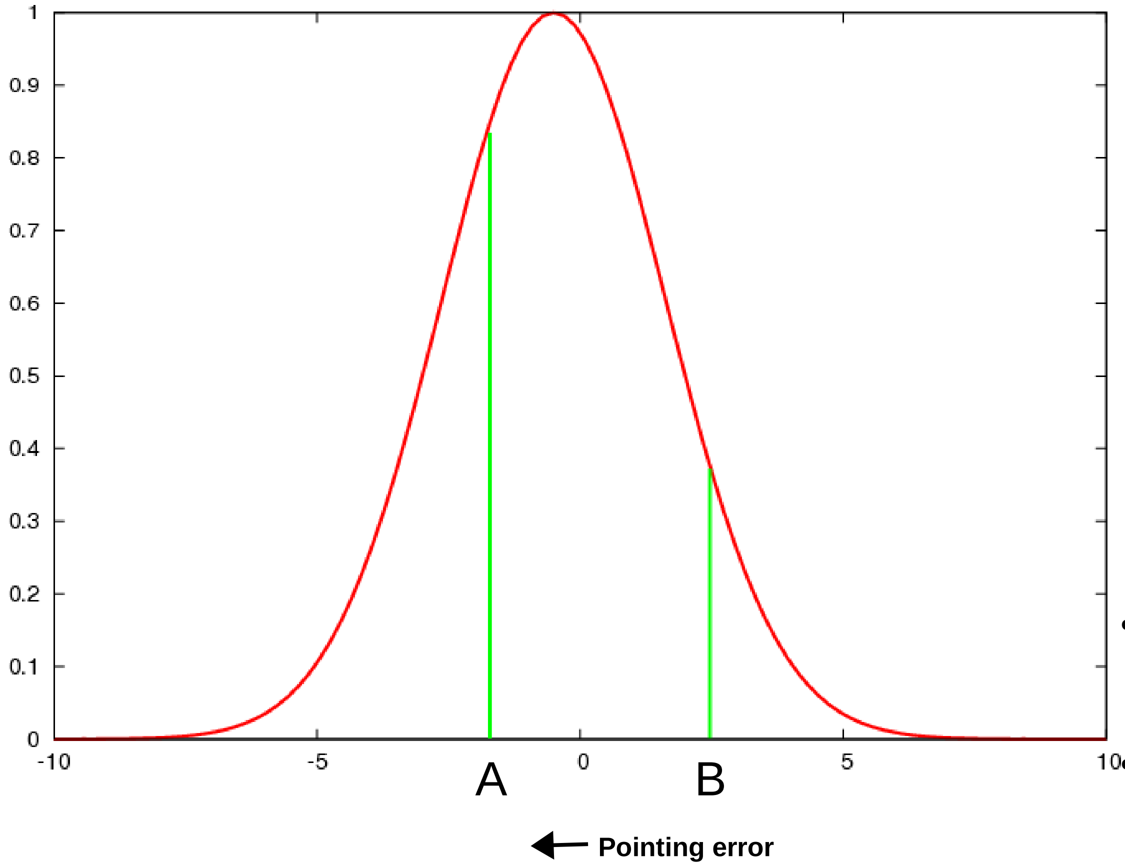
[Bhatnagar et al., EVLA Memo 84, 2004]

Effect of antenna pointing errors



- Effect of antenna pointing error is a direction dependent effect
- Makes the effective PSF look varying with time and direction
- Breaks assumptions made in deconvolution algorithms

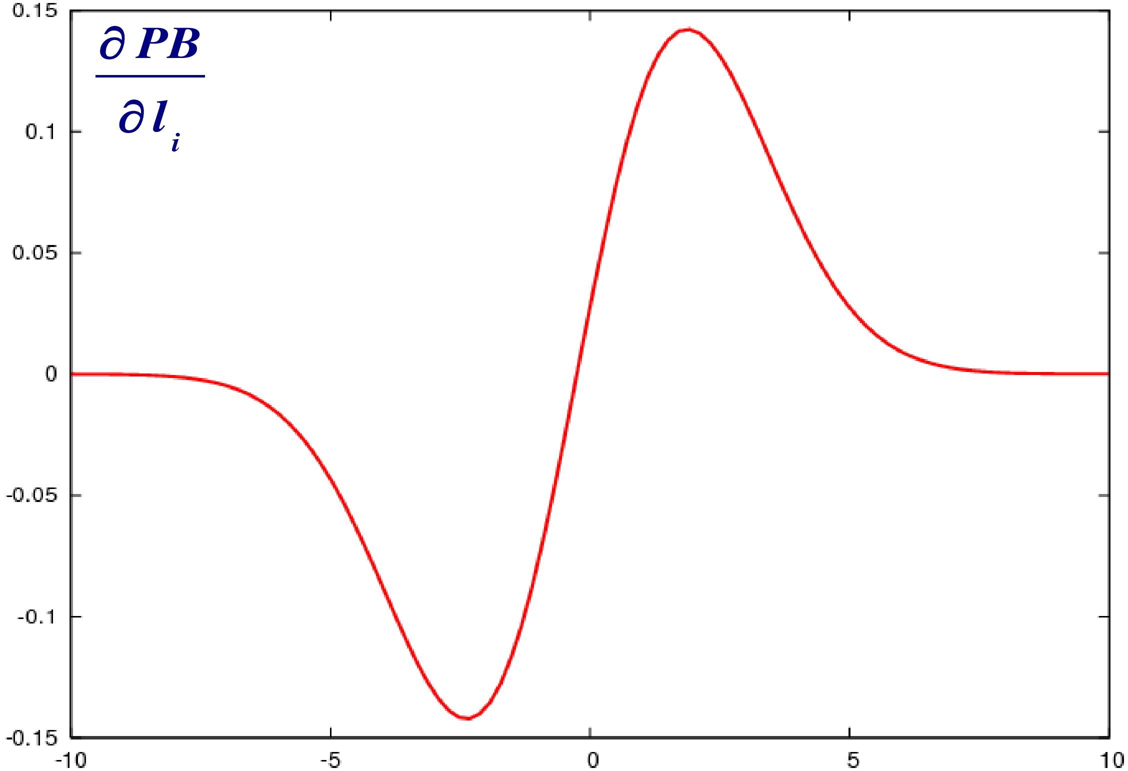
Effect of antenna pointing errors



- Effect of antenna pointing error is a direction dependent effect
- Makes the effective PSF look varying with time and direction
- Breaks assumptions made in deconvolution algorithms

- Faceting approach:
  - Solve for gains for A and B separately
  - Interpolate in between
- Pointing SelfCal
  - Solve for the shape of the function which best-fits the gain variations

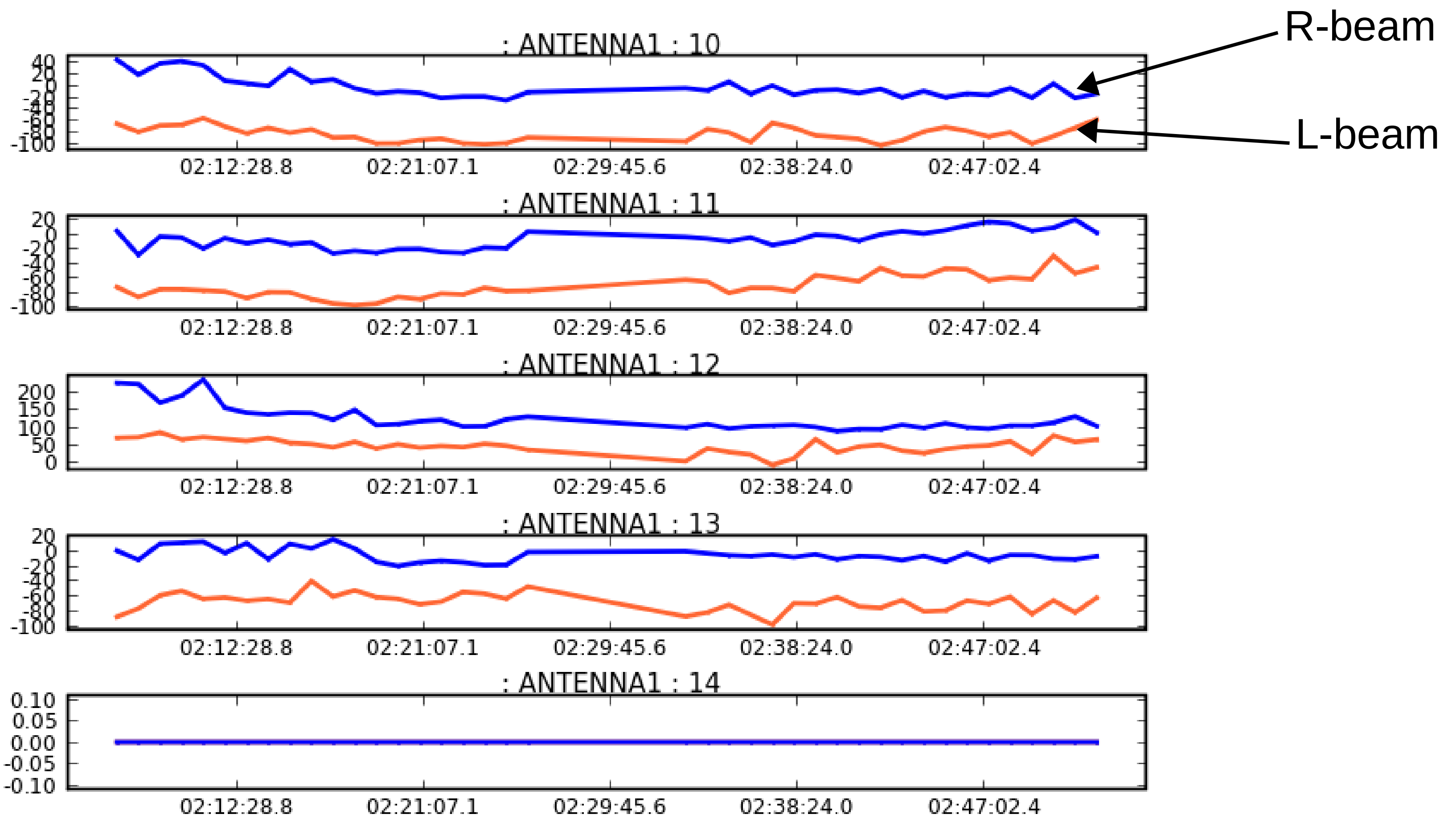
Error pattern: Derivatives



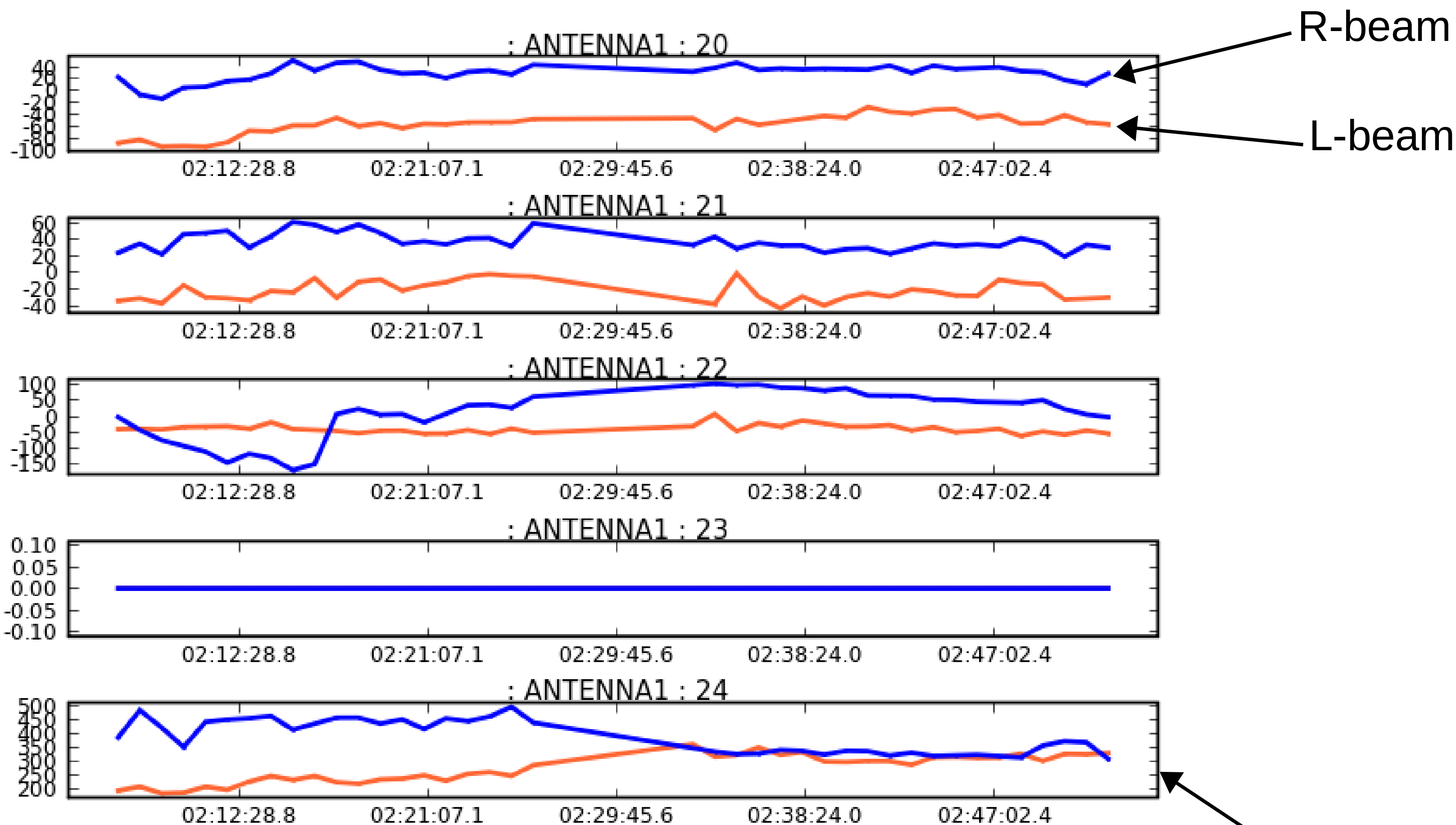
$$\text{Image plane error} \sim PSF * \left(I(s) \frac{\partial PB(s)}{\partial l_i} \right)$$

- Peak error signal around the half-power point
  - Points of largest derivative
- Significant for fields with emission distributed throughout the Primary Beam
  - Single pointing or mosaicking at low frequencies
  - Mosaicking at high frequencies
- Realistic Primary Beam patterns are wide-spread in image plane
  - Compact in FT domain
- Think of sinc(x) vs Pill-box functions

Time dependent solutions

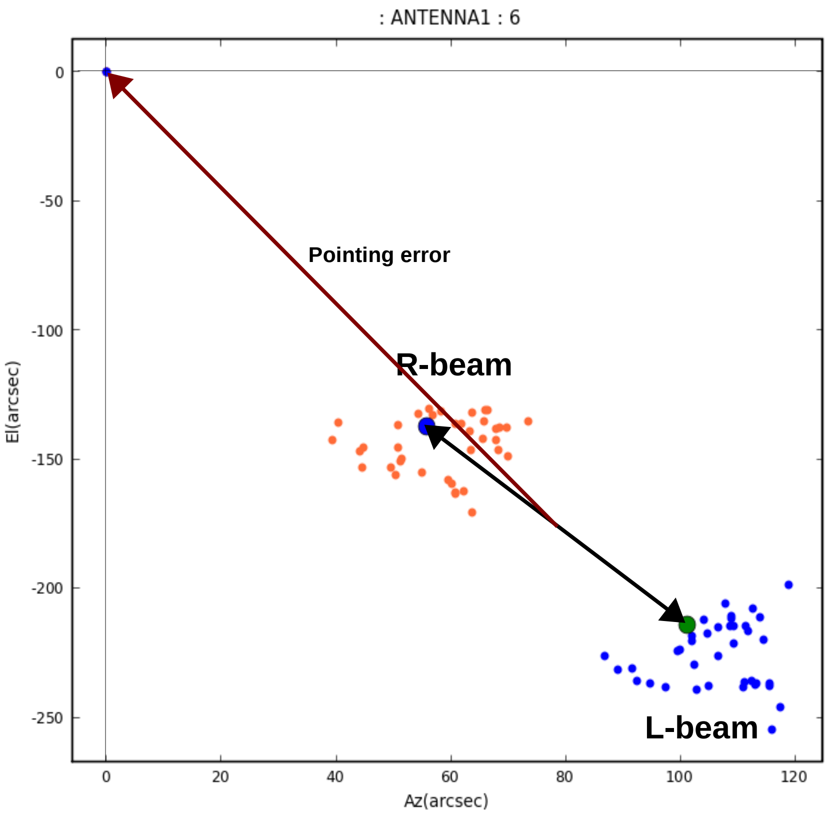


DD SelfCal: EVLA Data



The one with ~7 arcmin pointing error

DD SelfCal: EVLA Data



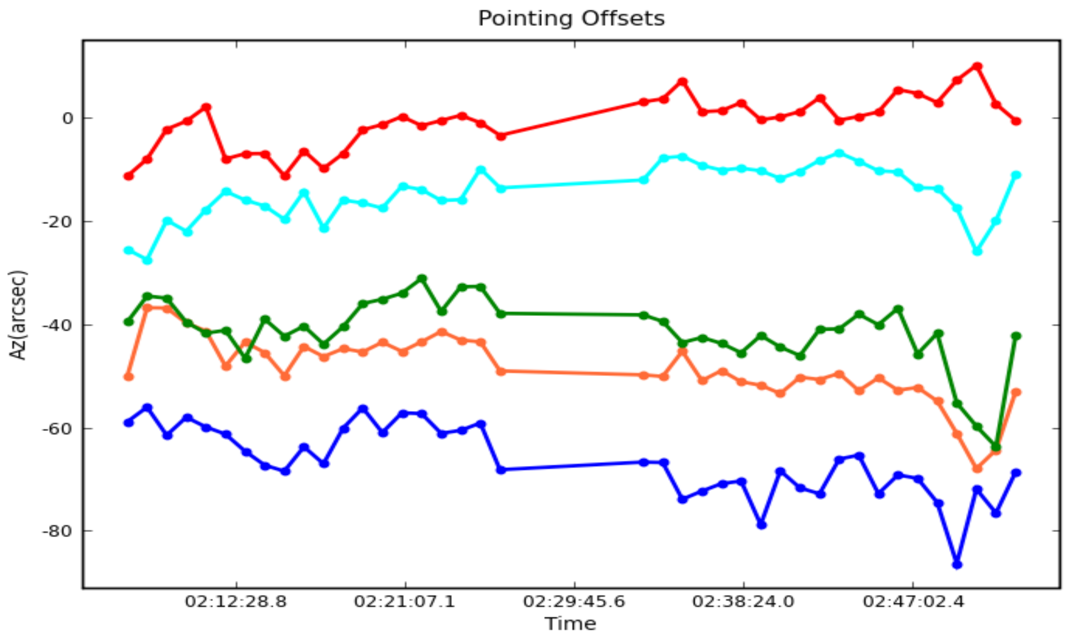
- El-Az mount antennas
- Polarization squint due to off-axis feeds
  - The R- and L-beam patterns have a pointing error of +/- ~0.06$\frac{\lambda}{D}$

- DoF used: 2 per antenna
- SNR available for more DoF to model the PB shape

- EVLA polarization squint solved as pointing error (optical pointing error).
- Squint would be symmetric about the origin in El-Az plane in the absence of antenna servo pointing errors.
- Pointing errors for various antennas detected in the range 1-7 arcmin.
- Pointing errors confirmed independently via the EVLA online system.

[paper in preparation]

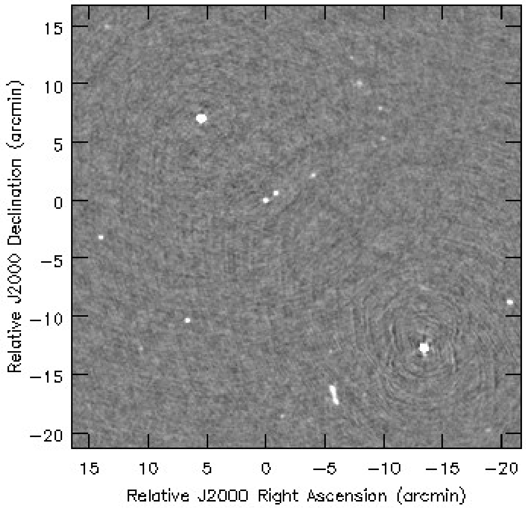
DD SelfCal: EVLA Data



- Typical solved pointing errors for a few antennas
- Solution interval: 2min

- Using ~300 MHz of bandwidth.

- Data from TALG0002



IC2233 field in the 1-2 GHz band with the EVLA

Noise Budget:

$$\sigma(p) = \left[\frac{2 k_b T_{sys}}{\eta_a A N_{ant} \sqrt{\nu_{corr} \tau_{corr} N_{SolSamp}}} \right] \frac{1}{S}$$

$$where\ S = \int \frac{\partial E_i(s,p)}{\partial s} E_j^*(s,p) I^M(s) e^{2\pi\iota s.b_{ij}} ds$$

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General comments

- Fundamentally an antenna based effect
  - Difficult to decouple/interpret in the image plane (needs more DoFs)
- Fundamentally a data-domain effect
  - Not an “sky-plane effect”
  - Unlike, e.g., effects of sky spectral index variations (a DD error)
- SNR available to the solver corresponds to the total apparent flux in the FoV
- Solution intervals of min-timescale at L-band looks possible
- Solving for multiple parameters describing the AIP may be possible
  – `Simulations necessary`
- Series expansion of AIP (work in progress)

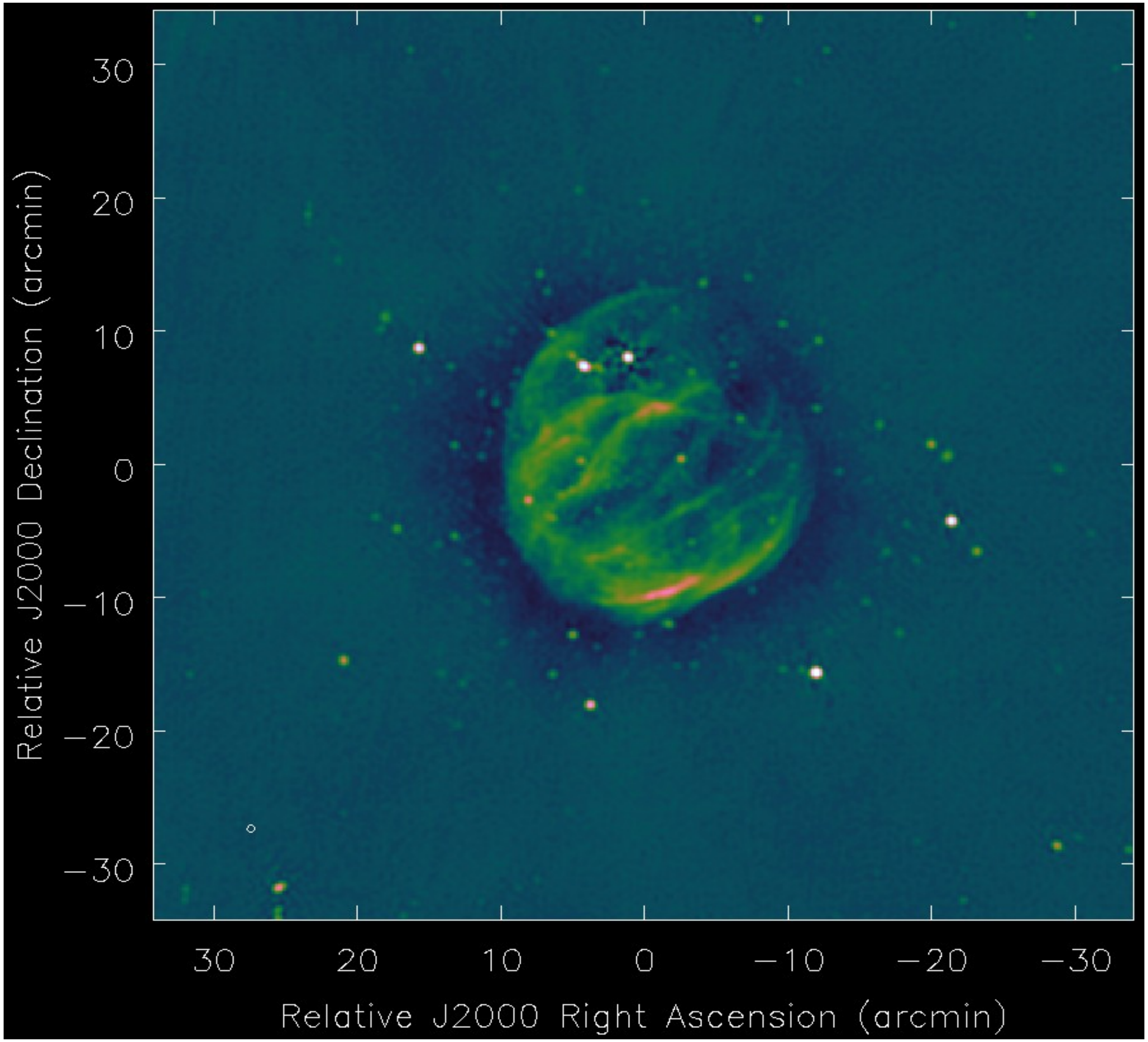
Noise Budget:

$$\sigma(p) = \left[\frac{2 k_b T_{sys}}{\eta_a A N_{ant} \sqrt{\nu_{corr} \tau_{corr} N_{SolSamp}}} \right] \frac{1}{S}$$

$$\textit{where } S = \int \frac{\partial E_i(s,p)}{\partial s} E_j^*(s,p) I^M(s) e^{2\pi\iota s.b_{ij}} ds$$

$$A(u) = \underbrace{A_o(u)}_{\text{A-Projection}} [1 + a_o \underbrace{Z_o(u)}_{\text{Pointing (solver+correction)}} + \ldots]$$

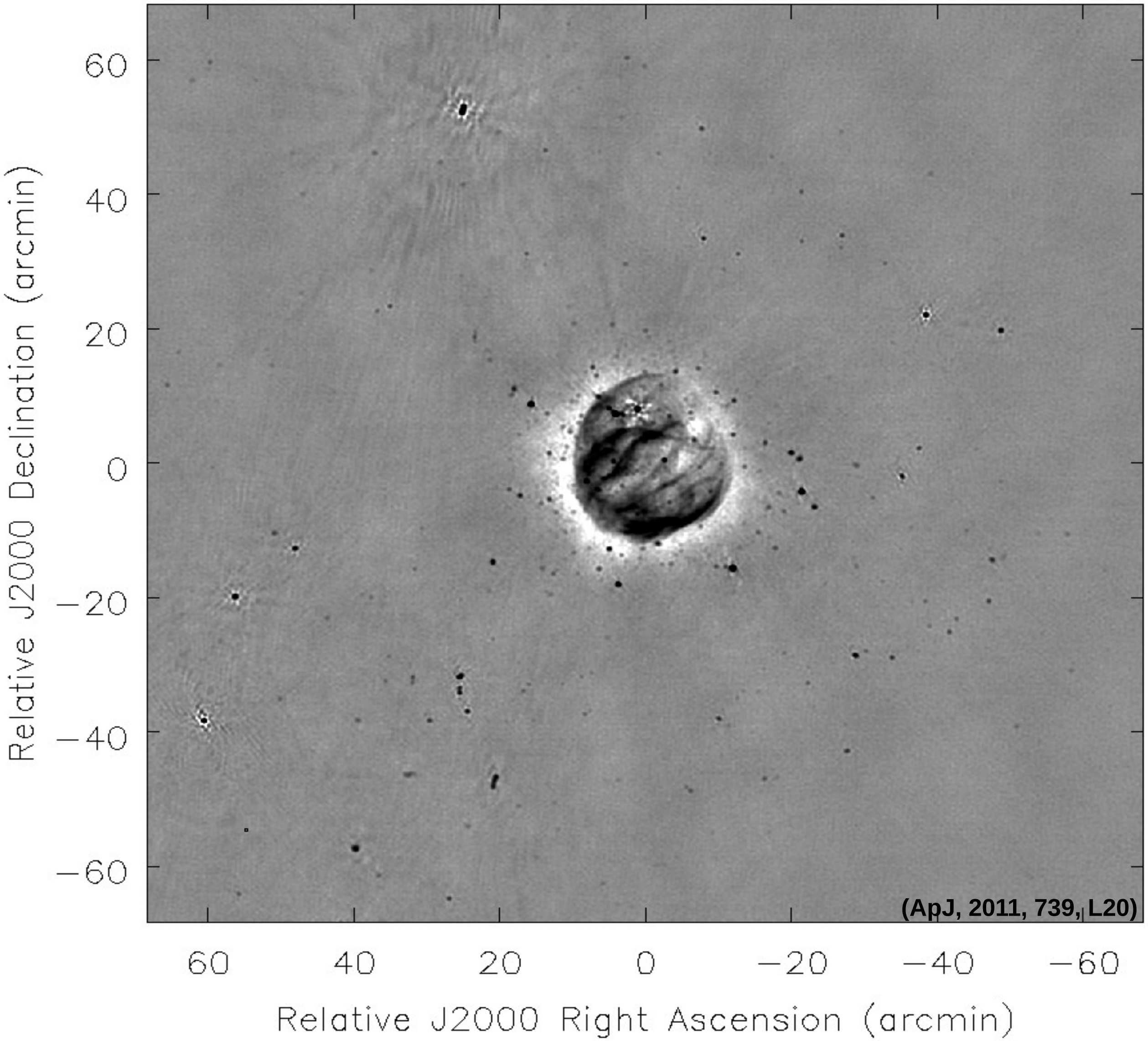
Wide band imaging with the EVLA



- Emissions fills the PB
- Extended emission with superimposed compact sources

- Partitioning approach design-out such fields!

Wide band imaging with the EVLA



- 1.2 -- 1.8GHz (4x128 MHz)
- RMS ~25 microJy/beam

- Scientific goals
  - Spectral Index mapping
  - RM mapping