Primary beam calibration

SKA Pathfinders Radio Continuum Surveys (SPARCS)

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Plan for talk

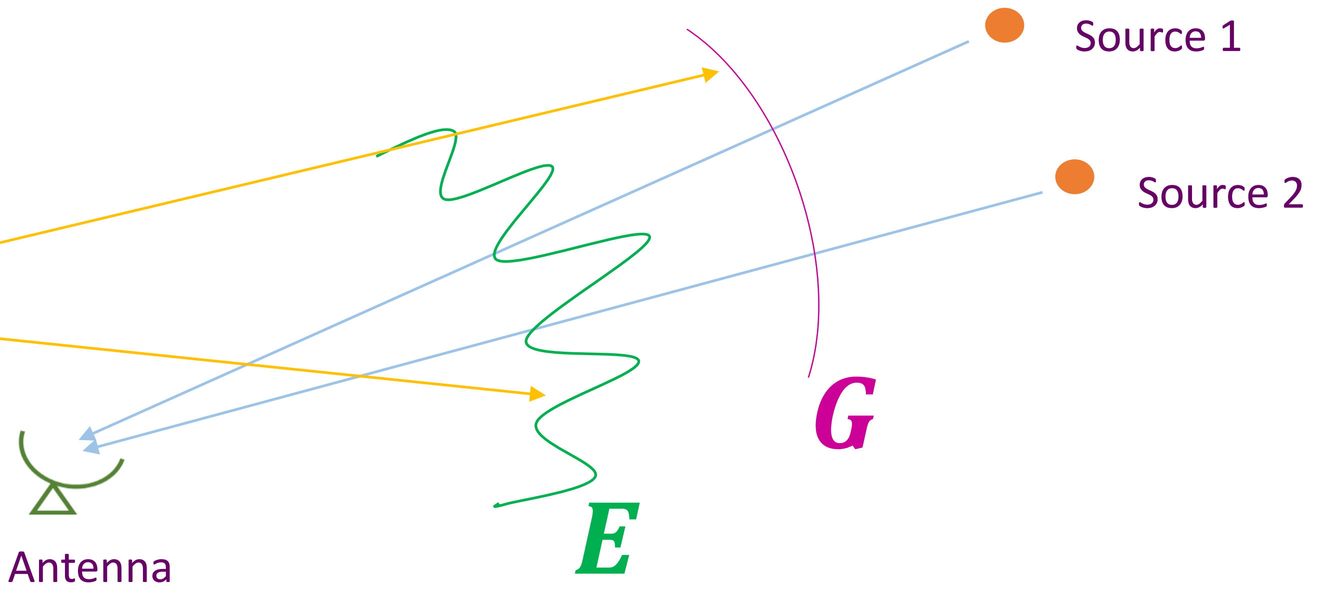
- Direction-dependent effects
  - Primary beam
- Pipeline for calibration of wide-band JVLA data at L-band (1-2 GHz), and subsequent wide-field imaging
  - Primary beam modeling
  - Multi-Term Multi-Frequency Synthesis (MT-MFS) algorithm

    → Used to correct for effect of primary beam during calibration
- Differential gains

  → Used to correct for residual direction dependent effects after primary beam has been corrected for
- Results and images
- Conclusion

Direction-independent and direction-dependent effects

- Propagation effects along the signal path from the source to an antenna can be of two kinds:
    - Direction-independent effects
    - Direction-dependent effects



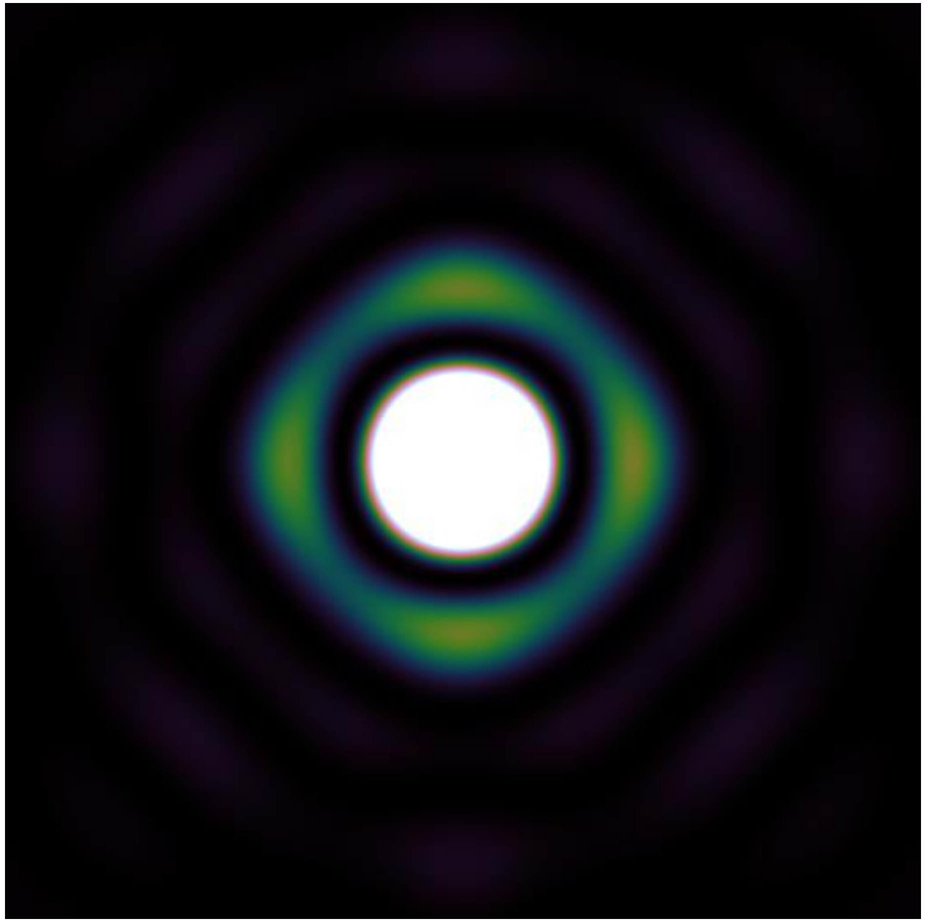
$$\boldsymbol{J} = \boldsymbol{G}\,\boldsymbol{E}$$

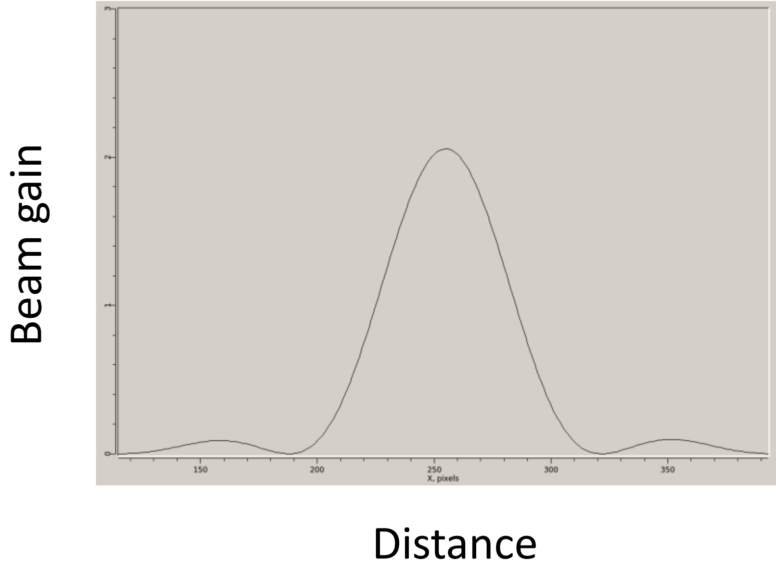
Final Jones matrix Direction-independent effects Direction-dependent effects

Direction dependent effects: Primary beam

- The primary beam of the antenna is the most important direction-dependent effect.
- Becomes important in calibration of wide-band data, and subsequent wide-field imaging.
- The primary beam pattern has a multiplicative effect in the image plane, convolutional effect in the visibility plane.
- In this work, we incorporate the primary beam of the JVLA in the calibration process.

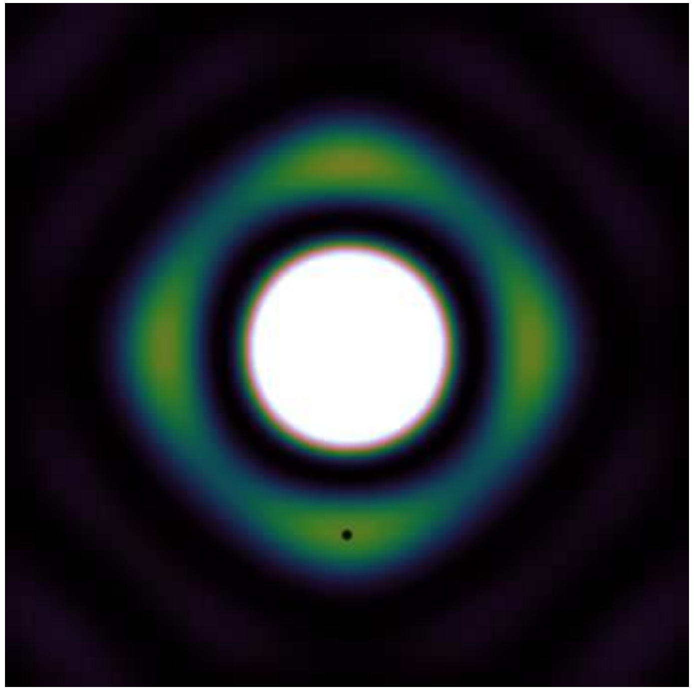
Primary beam of a JVLA antenna

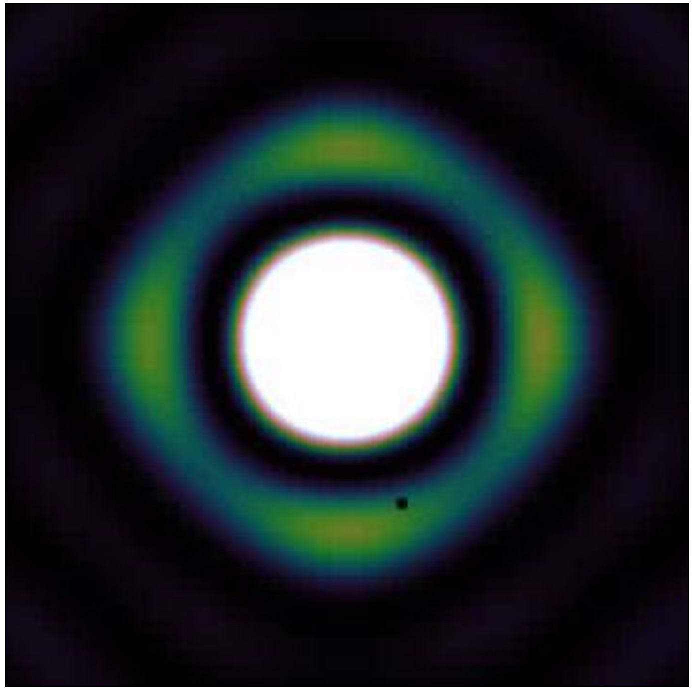




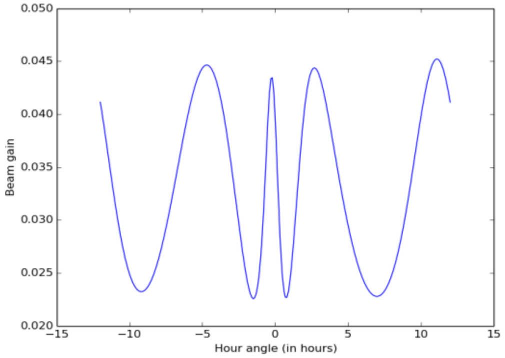
Horizontal cross-section of the beam through the center

Primary beam rotation and scaling



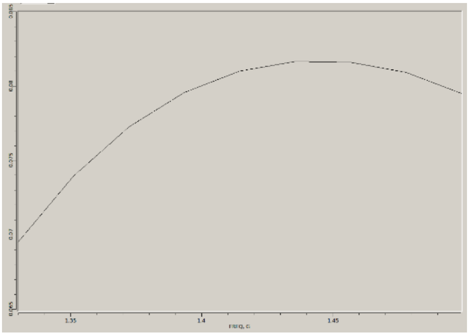


Beam gain



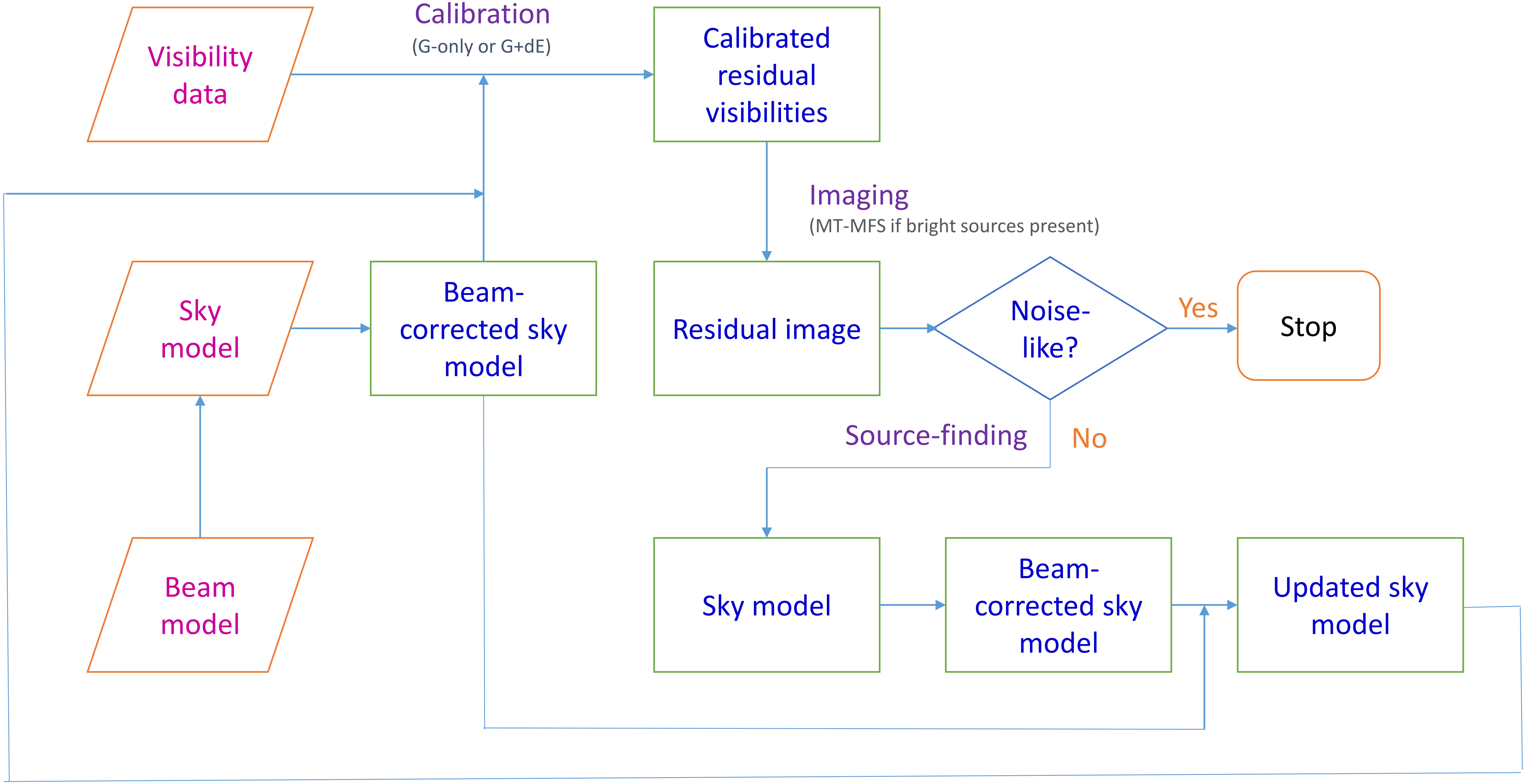
Hour angle

Beam gain



Frequency

Calibration pipeline



Beam model

- Used cassbeam (Brisken, 2003), which calculates beam patterns for a Cassegrain antenna using geometrical ray tracing.

- Beam patterns produced in the form of 8 multi-frequency fits files - real and imaginary parts of {LL, LR, RL, RR} beam patterns.

Multi-Term Multi-Frequency Synthesis (MT-MFS)

(Rau & Cornwell, 2011)

- Image at a given frequency expressed as a Taylor series expansion in (shifted and normalized) frequency:

Order of expansion

$$I_\nu = \sum_{n=0}^{N} I_n \left(\frac{\nu - \nu_0}{\nu_0} \right)^n$$

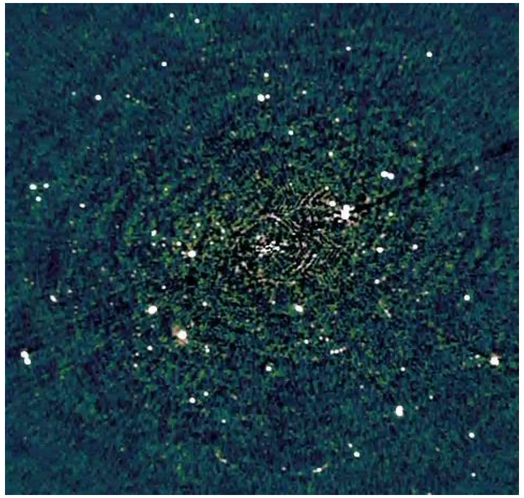
Image at frequency ν

n^{th} coefficient image

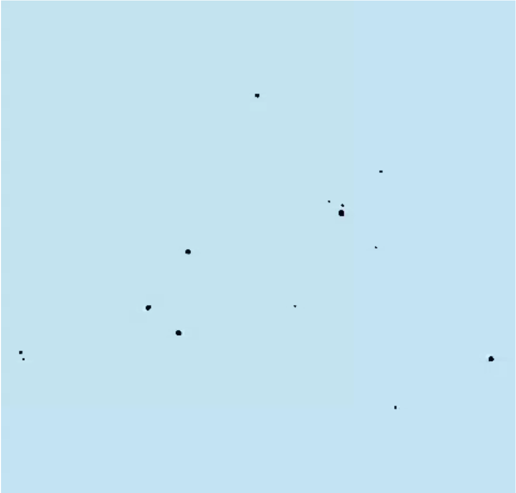
Reference frequency

MT-MFS output

- We perform an MT-MFS expansion till order 1 (2 terms):



Total intensity map
I_{ν_0}

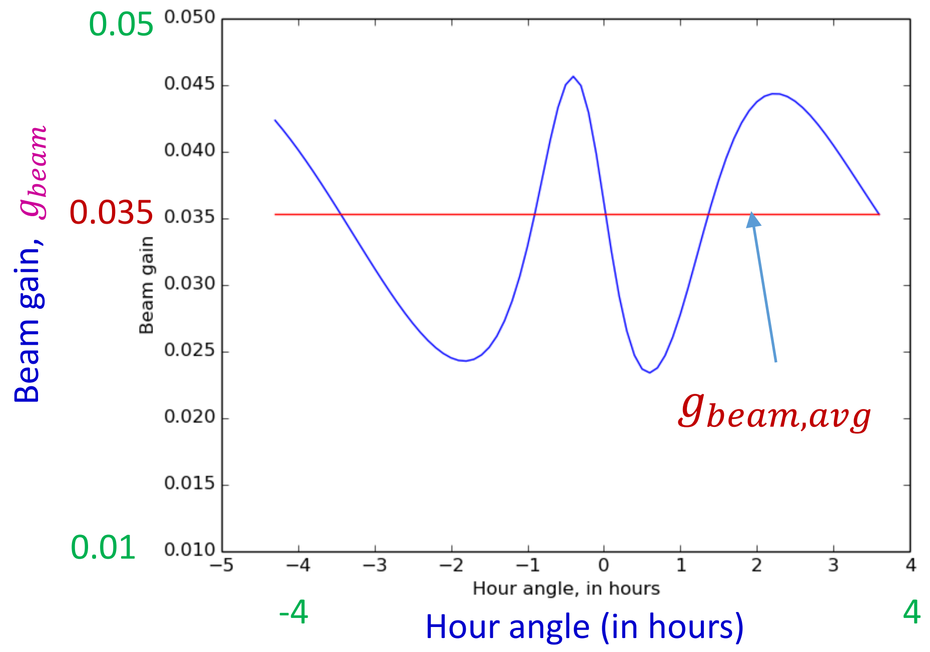


Spectral index map
I_{α}

- Source-finding performed on total intensity map I_{ν_0} (using PyBDSM); sources written to sky model.
- Spectral indices for these sources, if available in the spectral index map I_{α}, added to the sky model.

This sky model contains *apparent* intensities and *apparent* spectral indices for the sources.
→ Effect of beam on intensities and spectral indices not yet accounted for.

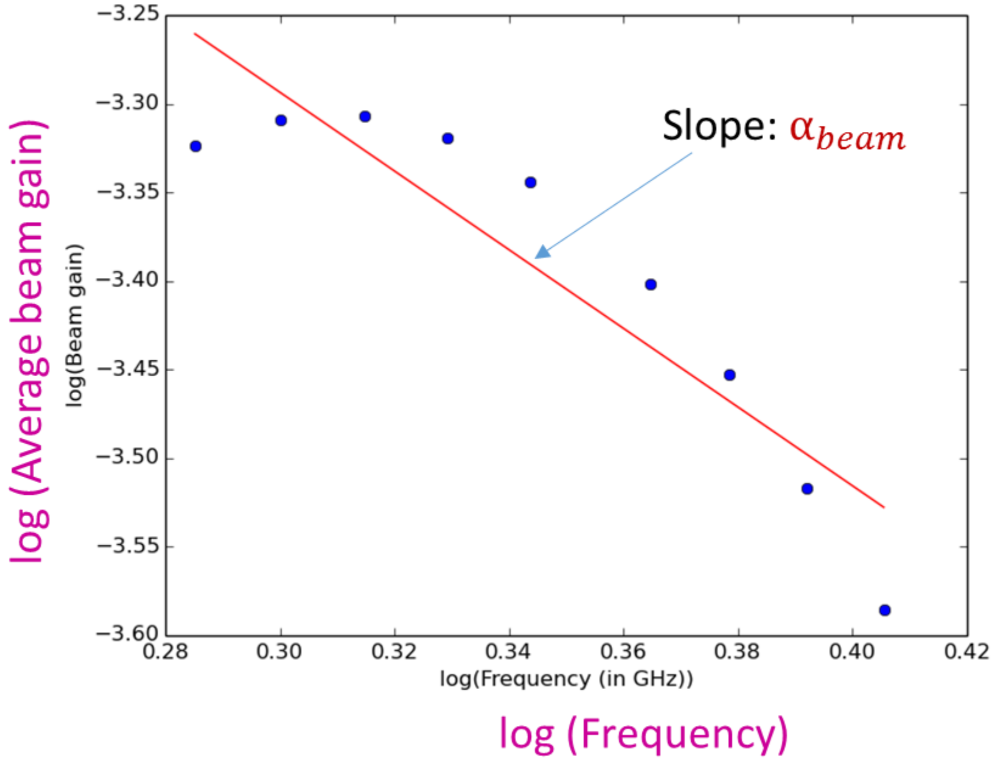
Apparent intensity to *intrinsic* intensity



- Apparent intensity from source-finding step: $I_{apparent}$
- Average beam gain: $g_{beam,average}$
- Intrinsic intensity:

$$I_{intrinsic} = \frac{I_{apparent}}{g_{beam,average}}$$

Apparent spectral index to *intrinsic* spectral index



- Apparent spectral index from MT-MFS: $\alpha_{apparent}$
- Beam spectral index: α_{beam}

- Intrinsic spectral index:

$$\alpha_{intrinsic} = \alpha_{apparent} - \alpha_{beam}$$

Summary of beam-correction procedure

- Correct intensities and spectral indices for sources in sky model by removing the contribution from the beam:

- Intrinsic intensity:

$$I_{intrinsic} = \frac{I_{apparent}}{g_{beam,average}}$$

- Intrinsic spectral index:

$$\alpha_{intrinsic} = \alpha_{apparent} - \alpha_{beam}$$

Residual direction-dependent effects after correcting for primary beam

- The primary beam is the major cause of direction-dependent effects, but even after using a simulated beam model to account for the primary beam, residual direction-dependent effects remain.

- These residual direction-dependent effects can be due to inaccuracies in the beam model, pointing errors, imperfect mounts, variation in the beam pattern between antennas in the array, mechanical deformation of antennas due to gravity, wind, etc.

- Differential gain solutions are computed (in the direction of a few bright sources) and applied after regular calibration in order to correct for leftover, uncalibrated effects.

Differential gains

- Differential gain solutions encompass the unknown and unmodeled direction-dependent effects in the signal path.
- The Jones matrix in the direction of source s is then given by:

$$\boldsymbol{J}^{(s)} = \boldsymbol{G}\,\boldsymbol{E}^{(s)}\,\Delta\boldsymbol{E}^{(s)}$$

Final Jones matrix in the direction of source *s*

Direction-independent effects

Known and modeled direction-dependent effects

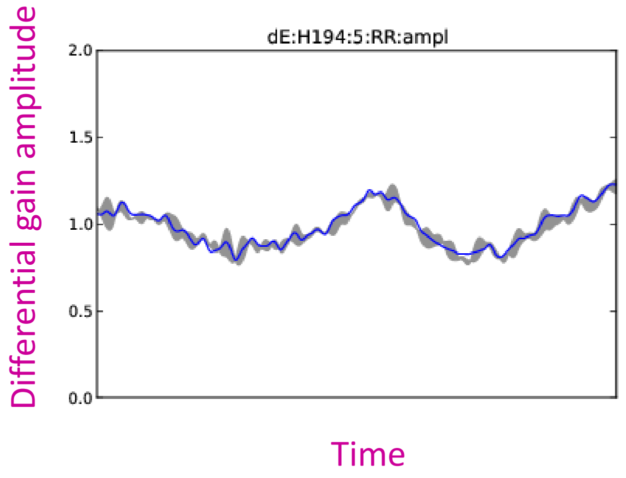
Differential gain: Unknown/unmodeled direction-dependent effects in the direction of source *s*

- The full Jones matrix is then given by:

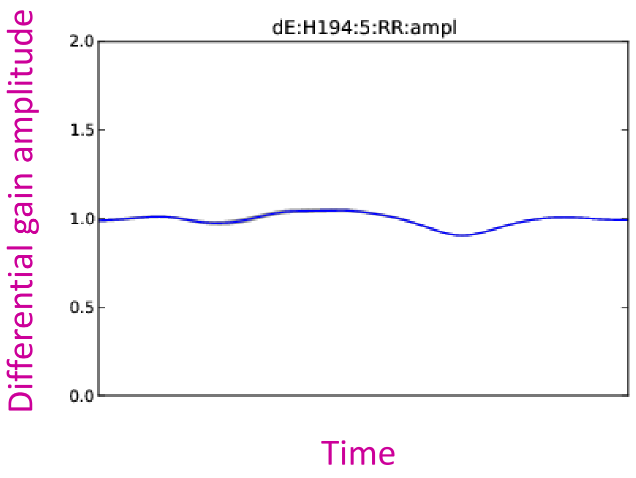
$$\boldsymbol{J} = \boldsymbol{G}\sum_{s}\boldsymbol{E}^{(s)}\,\Delta\boldsymbol{E}^{(s)}$$

Differential gain plots

Without primary beam



With primary beam



- Flattened differential gain curves
- Less unmodeled source suppression in image
- Differential gains can be smoothed over longer time and frequency intervals, thus decreasing the degrees of freedom needed for differential gain solutions

→ Possible because once the primary beam has been incorporated into the calibration process, the residual direction-dependent effects (like antenna pointing errors) vary slowly with time and frequency

3C147 and the field around it

JVLA at L-band

D & C configurations (6 & 8 hours)

640 MHz bandwidth

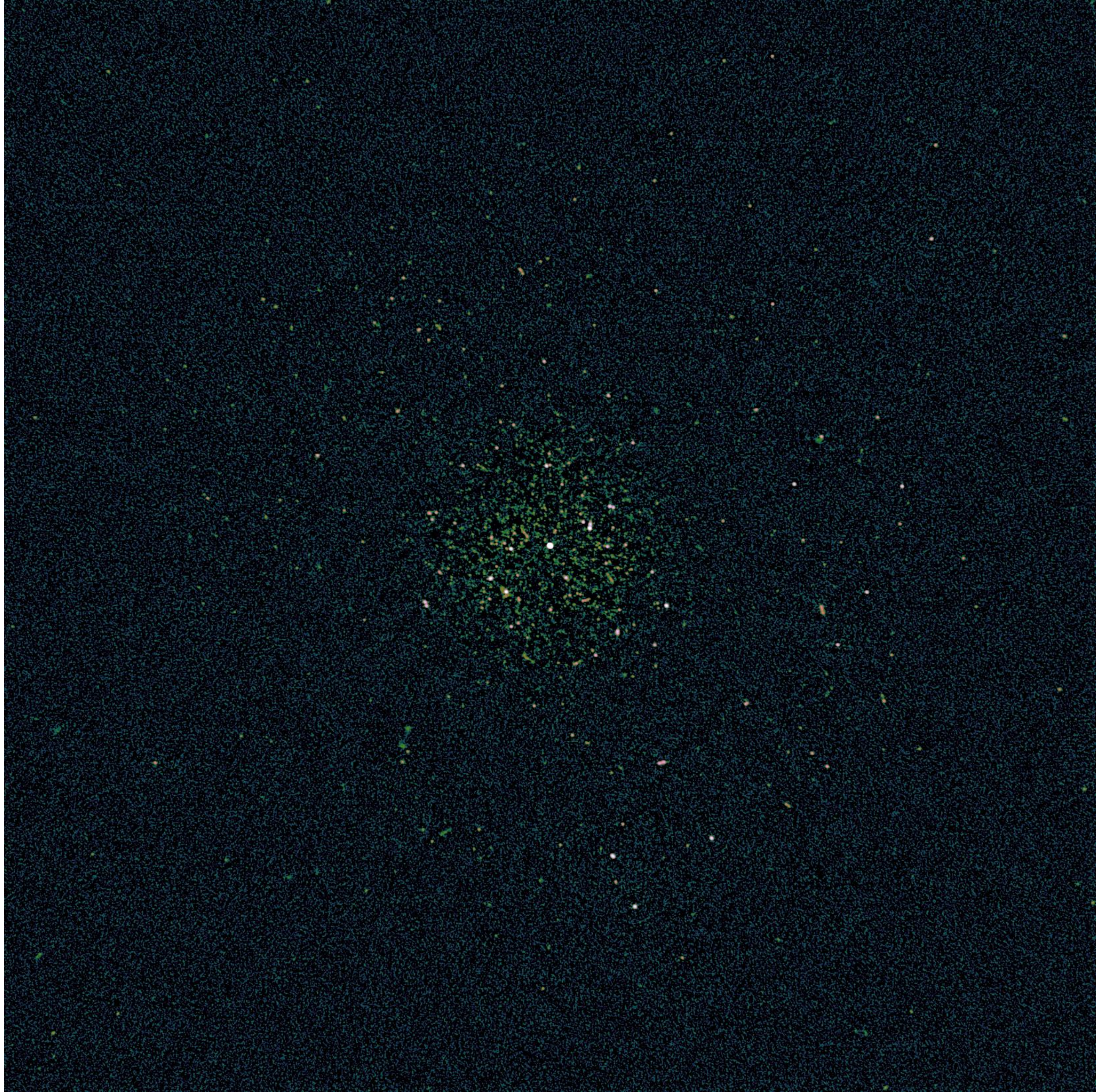


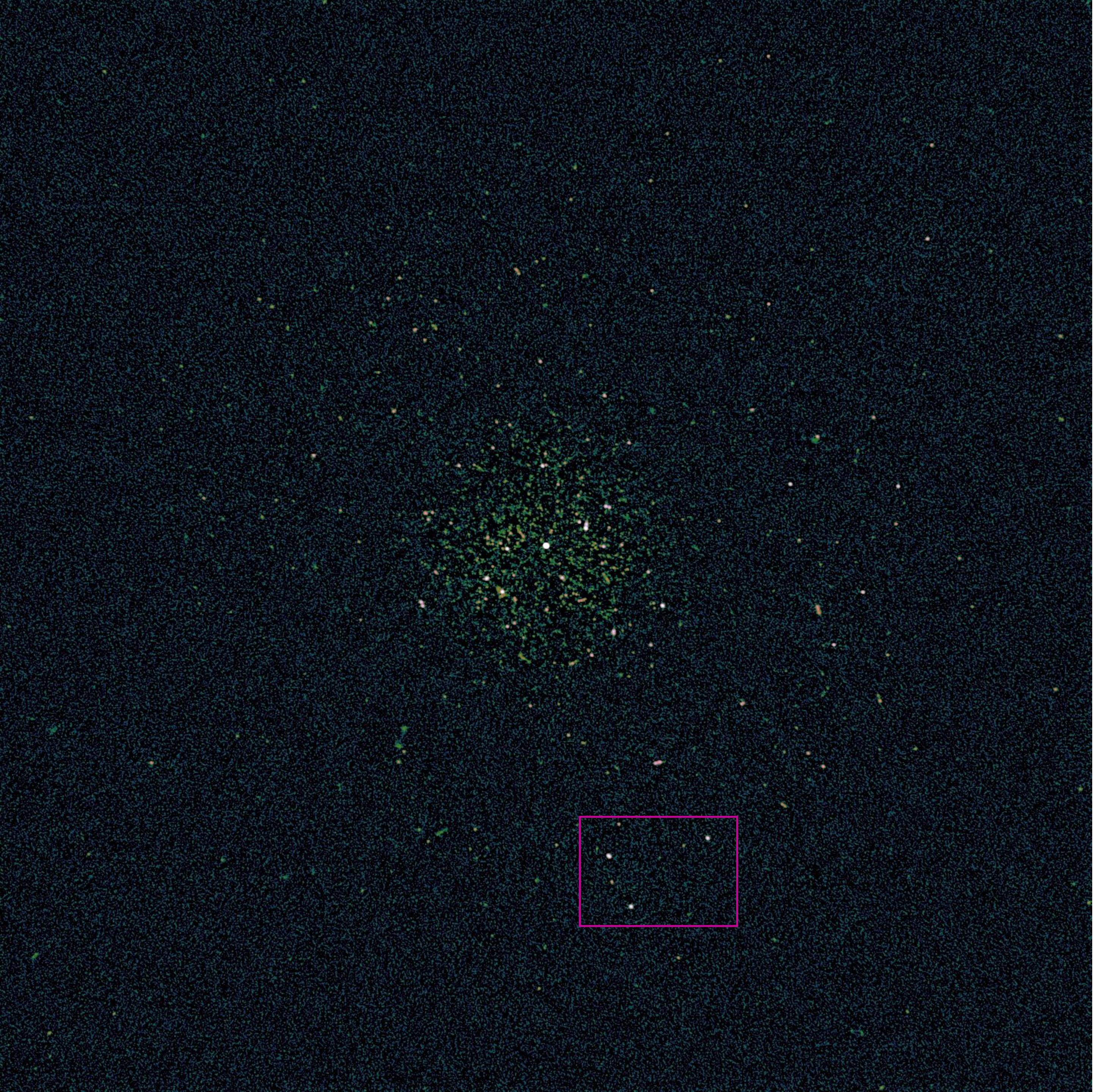
Image out to second sidelobe

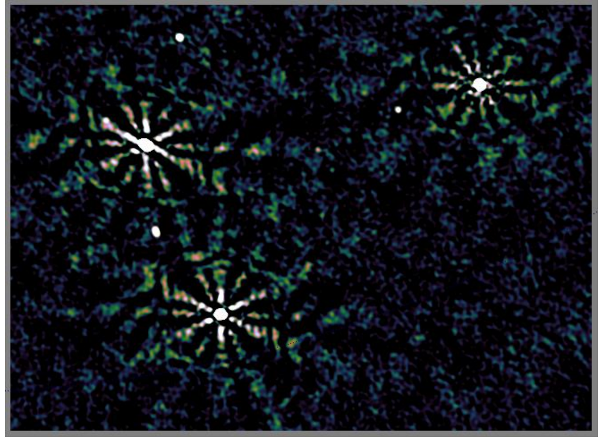
Confusion-limited in main lobe

22.82 Jy peak

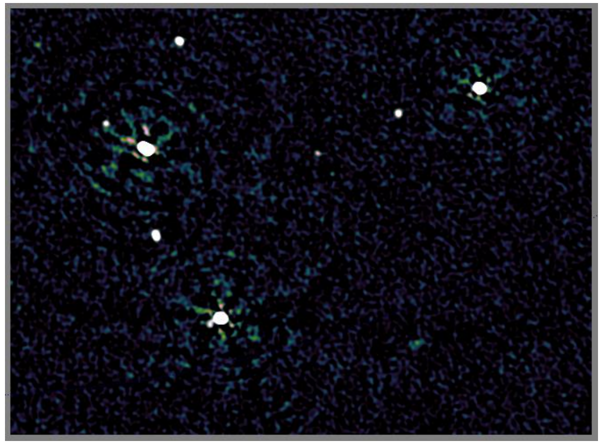
4.5 µJy noise

→ 5 million dynamic range





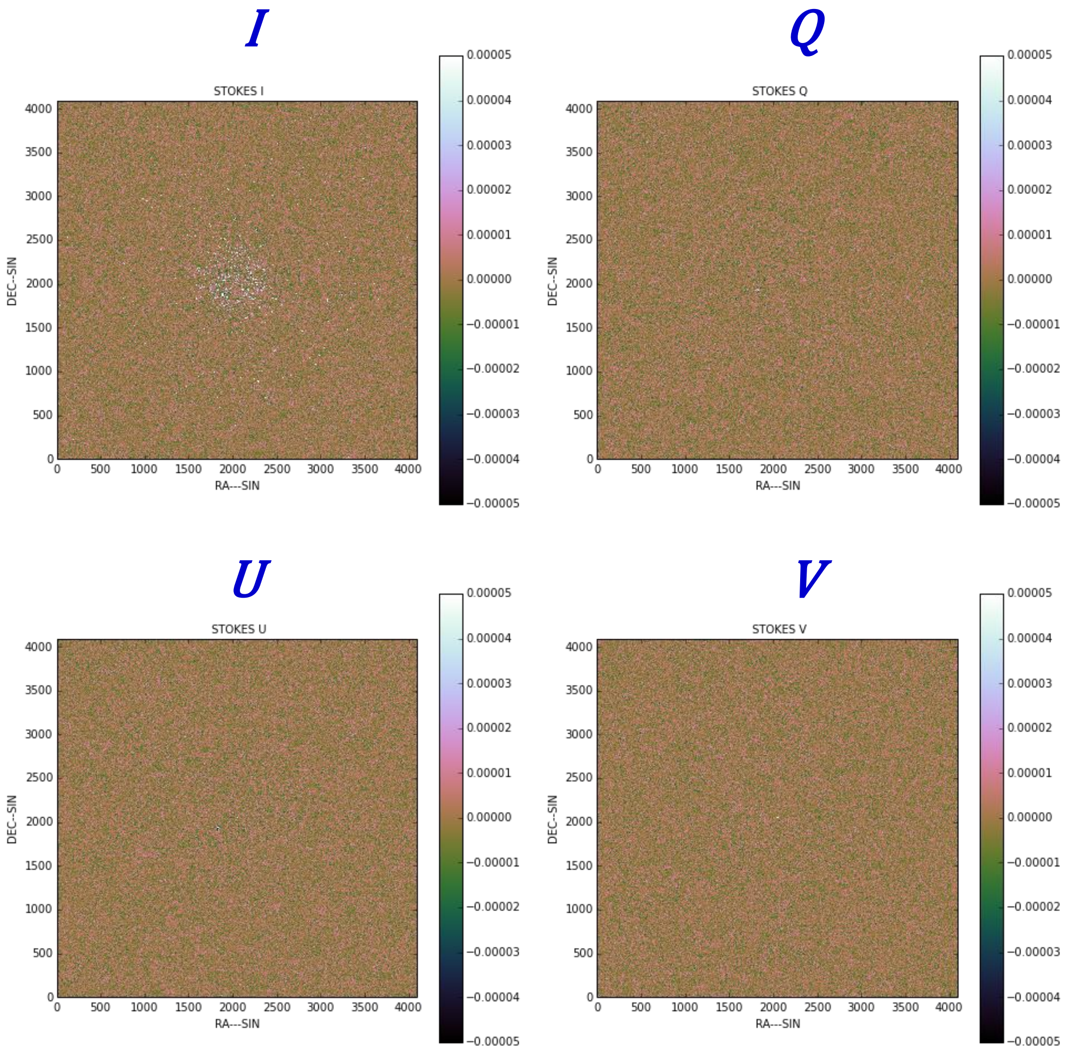
With neither primary beam nor differential gains



With primary beam but no differential gains

With primary beam and differential gains

Full-polarization images



All Stokes images almost free of calibration artefacts

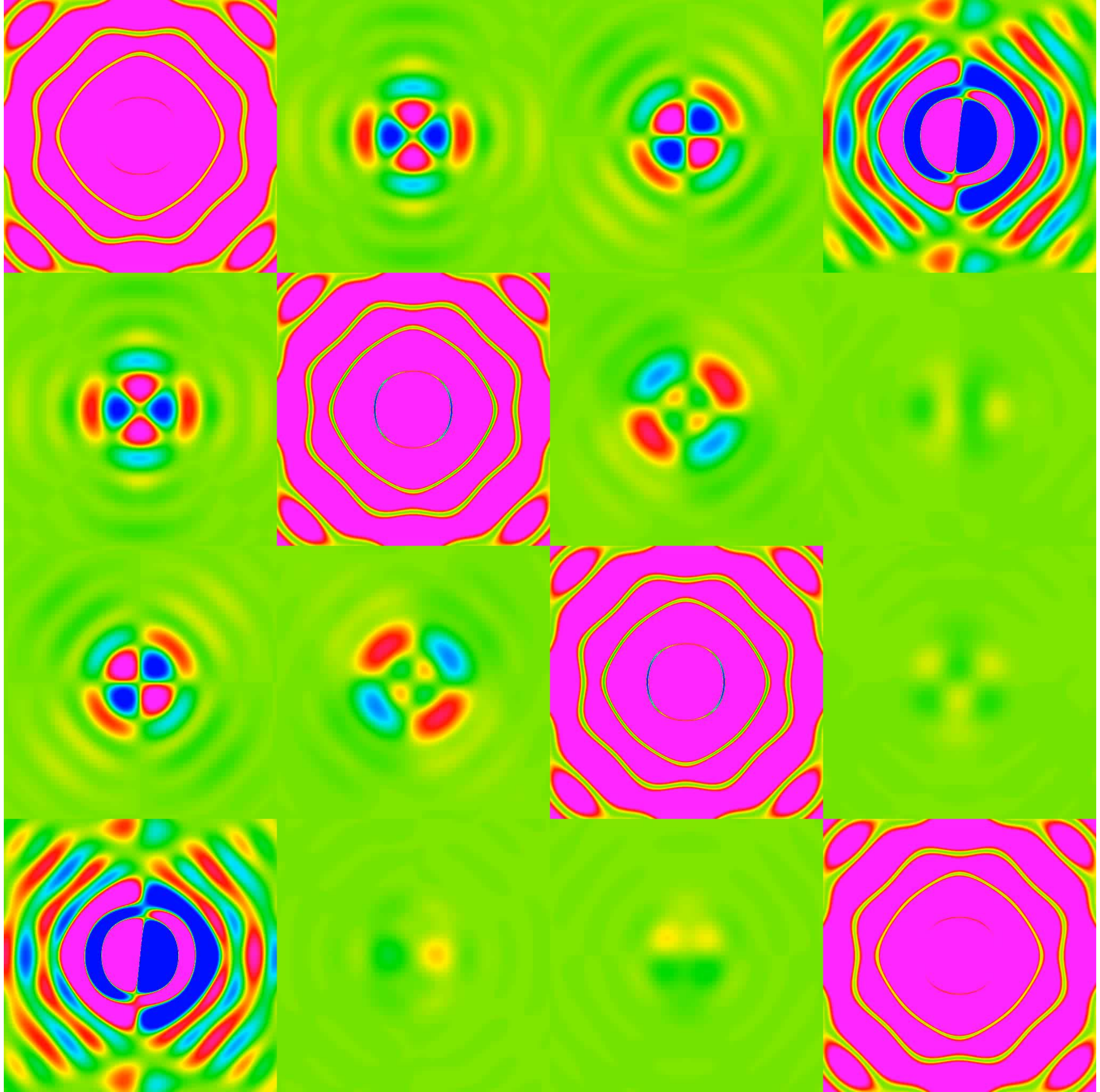
Accuracy of beam model

- Is our full-polarization beam model from cassbeam accurate?

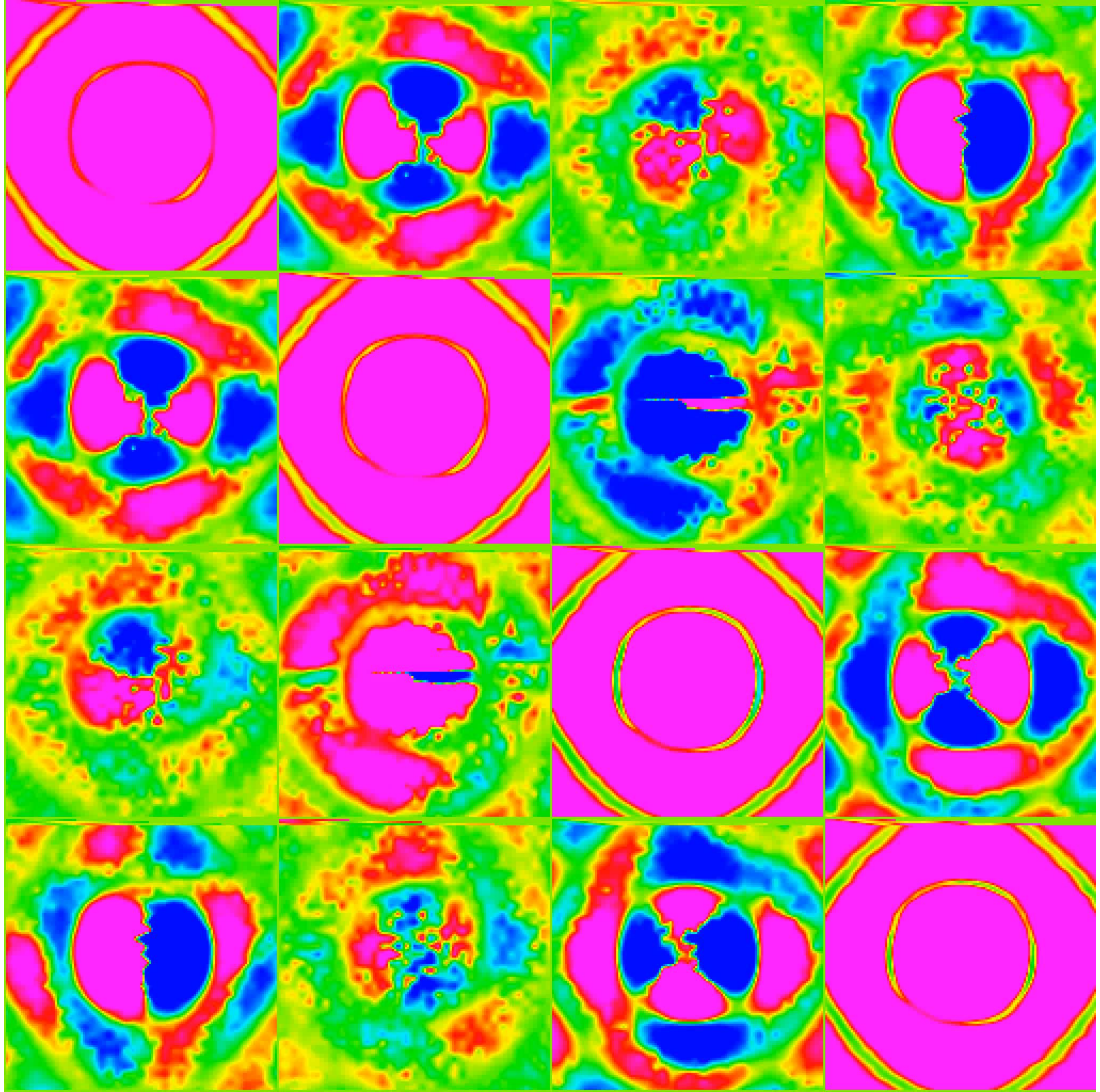
  → Compare with beams from holography measurements.

- Instructive to compare the Mueller matrix (which relates input and output Stokes parameters) for simulated and measured beams.

Mueller matrix for simulated beams



Mueller matrix for measured beams



Conclusion

- Primary beam effects successfully incorporated in calibration of wide-band JVLA data of the field around 3C147, in full polarization, to produce a wide-field image with an unprecedented dynamic range of 5 million.