Multi Frequency Synthesis Imaging with Wideband EVLA Data

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

NRAO

Outline

- Continuum Imaging of wide-band (E)VLA data.
- Algorithms
  - multi-scale maps of continuum flux, spectral index and curvature
- Application to CygA and M87 data
  - taken with EVLA receivers and the VLA correlator
- Frequency-dependent Primary Beam correction
  - preliminary results

Data from wideband receivers

- Nearly continuous coverage across a wide band

=> increased sensitivity $I_{rms} \propto \frac{1}{\sqrt{\delta \nu}}$

- A large total frequency range

=> can measure spectral features.

For a Power Law Spectrum across a 2:1 bandwidth...

$$\alpha = -0.5, \quad \nu_{max} = 2\nu_{min}, \quad \nu_0 = 1.5\,\nu_{min}$$

Need SNR > 6 to measure spectral index

Need SNR > 100 to measure spectral curvature

Imaging with wideband data

At different frequency channels...

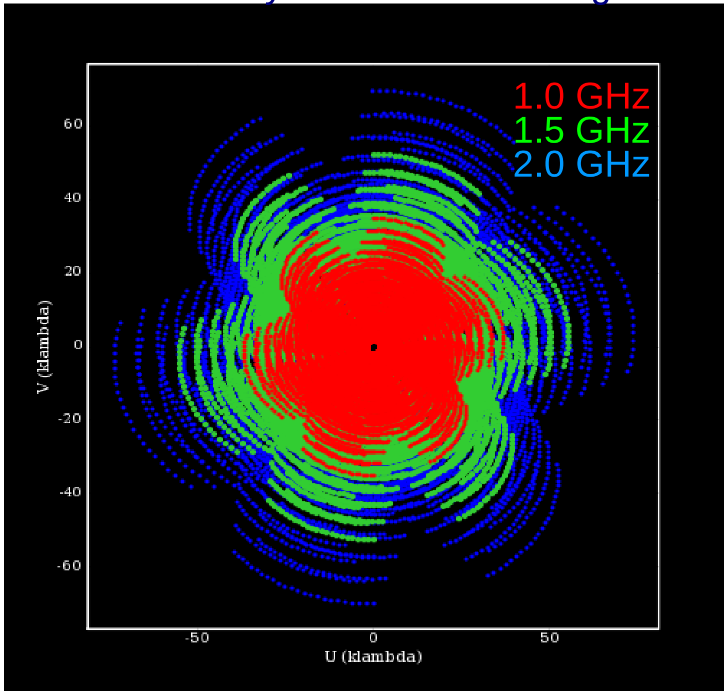
- UV coverage and angular resolution change

$$u = \frac{b}{\lambda} = \frac{b\,\nu}{c}$$

- Antenna field-of-view changes

$$fov = \frac{\lambda}{D} = \frac{c}{\nu\,D}$$

VLA C-Array L-Band uv-coverage



Combine all data :

- Higher Sensitivity
- Higher Angular Resolution
- Better Imaging Fidelity
- Wider Field of View

MFS : Multi-Frequency Synthesis Imaging

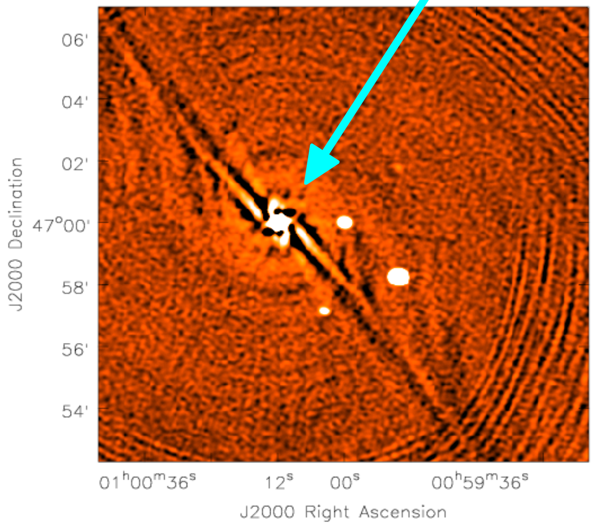
- Flat spectrum sources + Narrow field : Standard deconvolution algorithms

- With spectral structure :

  Standard deconvolution with MFS will turn spectral features into spurious spatial structure.

  Dynamic Range ~ 1000 for
  α = -1.0 across 1 GHz at L-Band. *(Conway et al, 1990)*

$\alpha = -0.5 \quad to \quad -2.0$



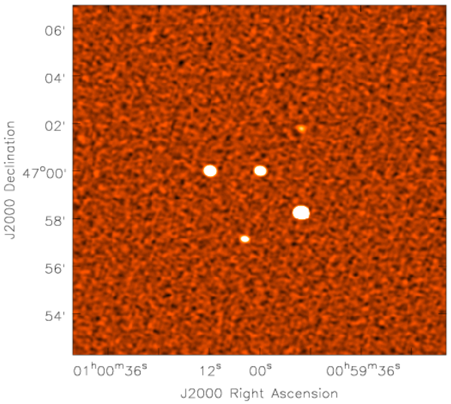
- Varying field-of-view :

  Frequency-dependent Primary Beams will introduce spurious spectral structure for off-center sources.

α_{PB} = -1.0 at the half-power point for 1 GHz at L-Band for (E)VLA antennas.

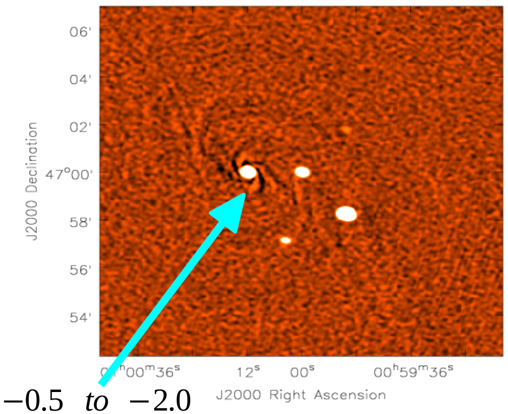
MFS for point sources

(A) Spectral Line Imaging



- Deconvolve each channel separately
- Combine all images
- Deconvolve on continuum residuals

(B) MFS with a spectral model



$\alpha = -0.5$ *to* -2.0

MF-CLEAN

(Sault,Wieringa,1994)

Spectrum : Linear

Flux : Point-Sources

Output : Stokes I, Spectral Index

- Image Fidelity

  (A) Single frequency uv-coverage

  (B) Multi-Frequency uv-coverage

- Angular Resolution of Spectral Index/Curvature maps

  (A) Lowest (u_{max} at ν_{min})

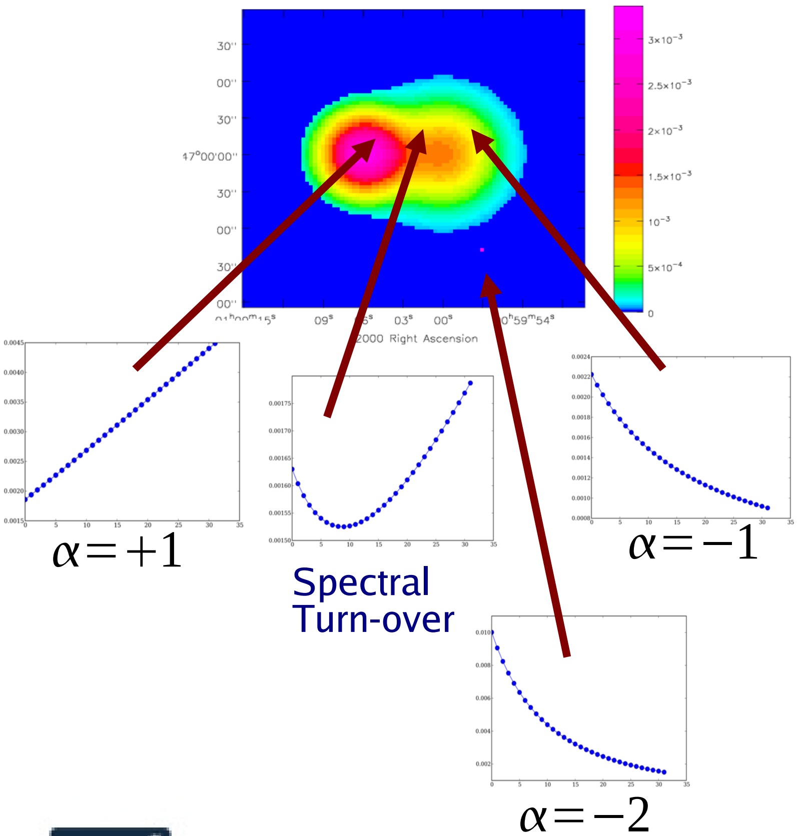
  (B) Highest (u_{max} at ν_{max})

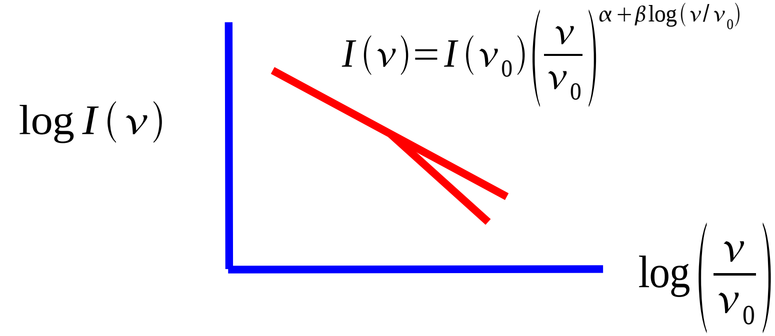
... both (A) and (B) are not always suitable for extended emission.

Multi-scale MFS

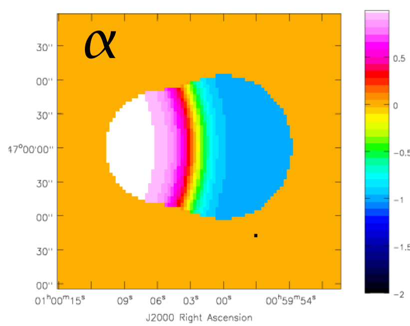
EVLA C-array simulation, 1-2 GHz.

Image at Reference Frequency

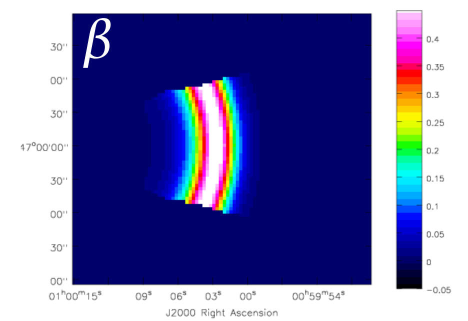




Spectral Flux Model : Power Law with varying index



Average Spectral Index

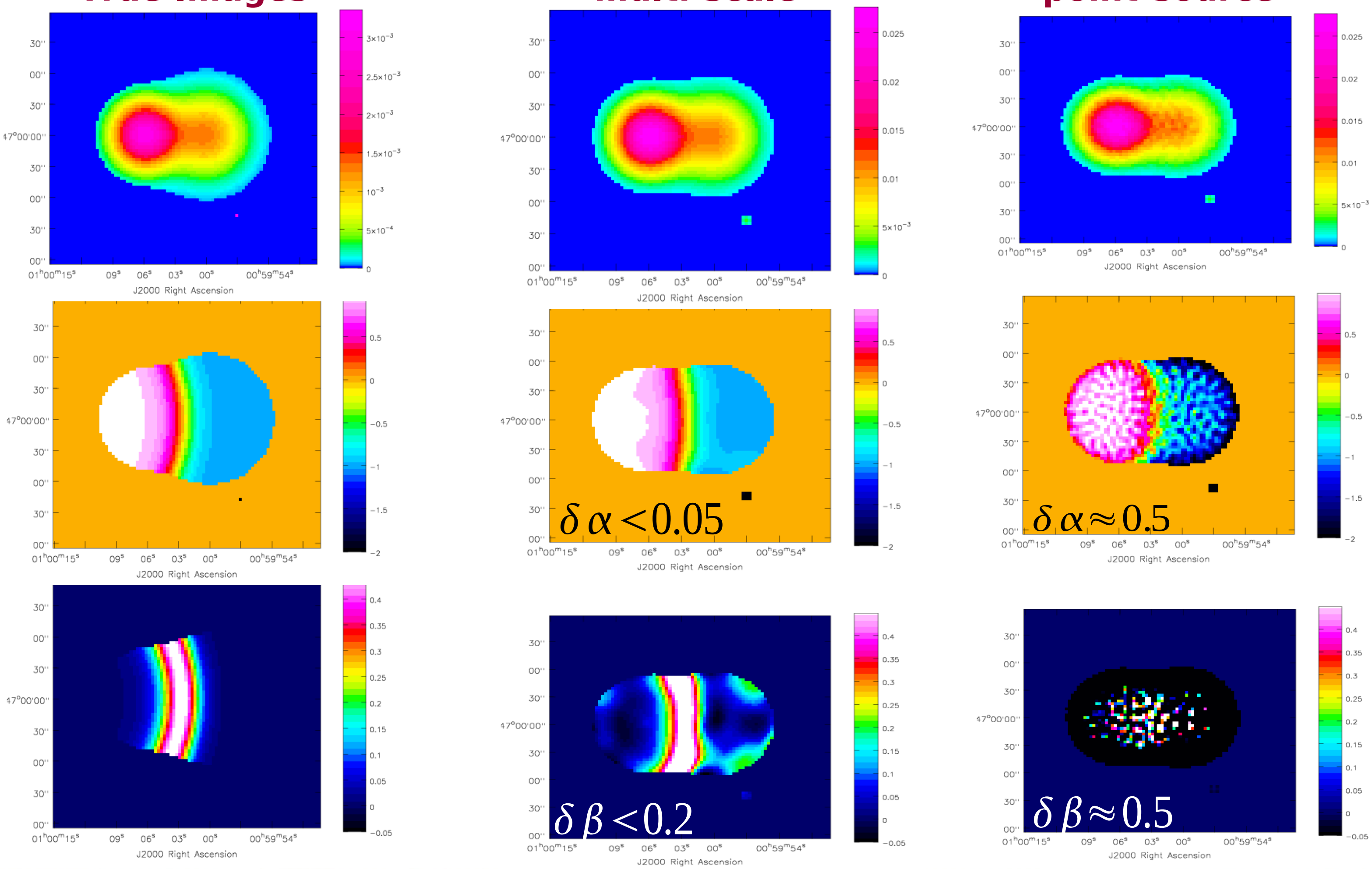


Gradient in Spectral Index

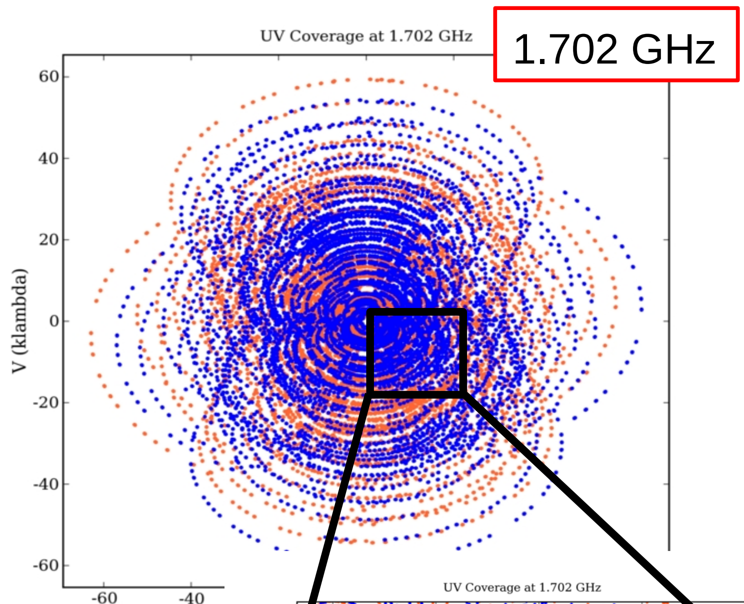
MS-MFS simulations

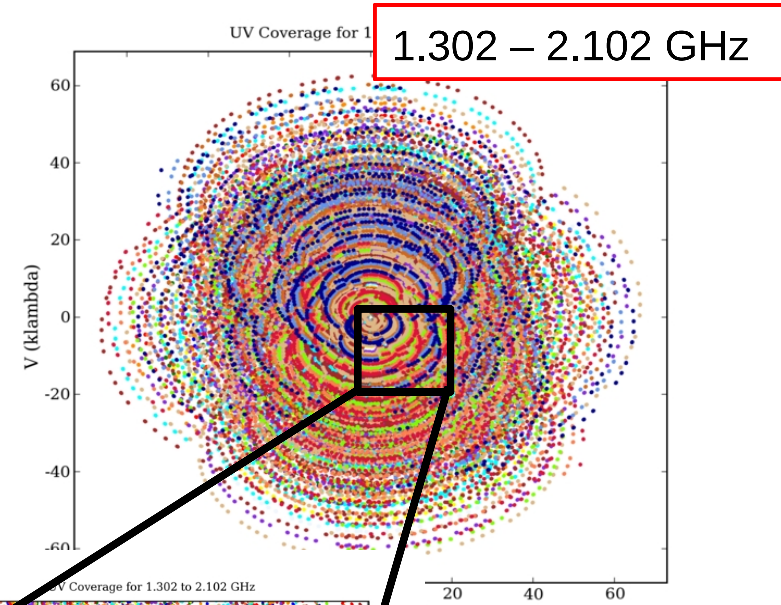
MFS

	True Images	multi-scale	point-source
Image at reference frequency $I(\nu_0)$			
Average Spectral Index α			
Gradient in Spectral Index β			



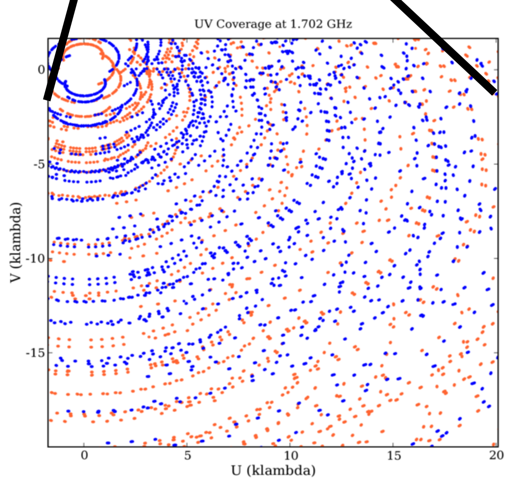
Synthesized wideband EVLA uv-coverage

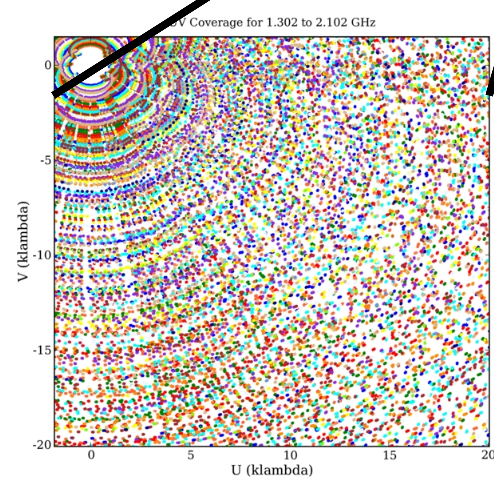




uv-grid cell size
~ 0.2 klambda

< 0.5 visibilities
per uv-grid cell

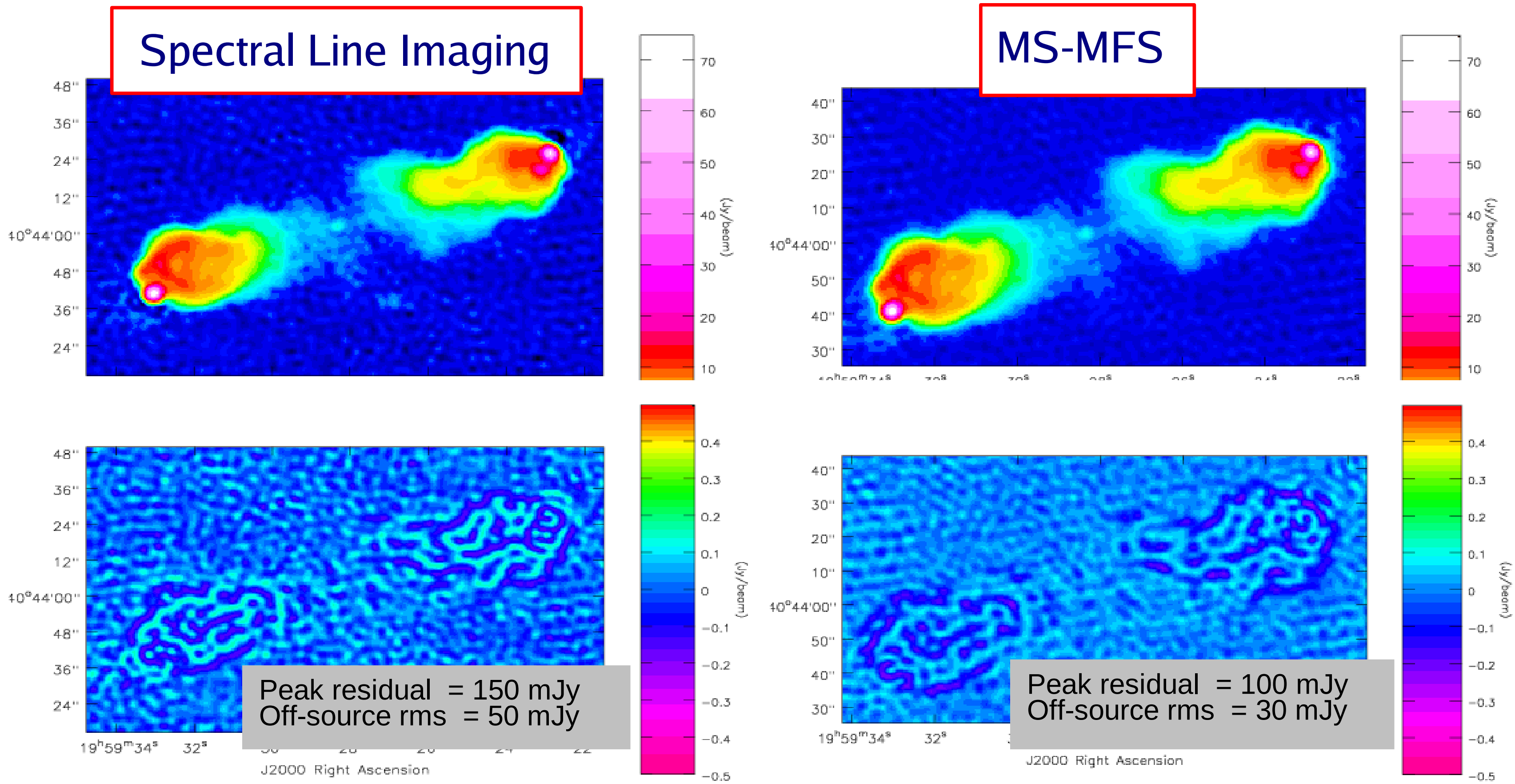




>1 visibility points
per uv-grid cell

=> Good for
Spectral Structure at
multiple scales

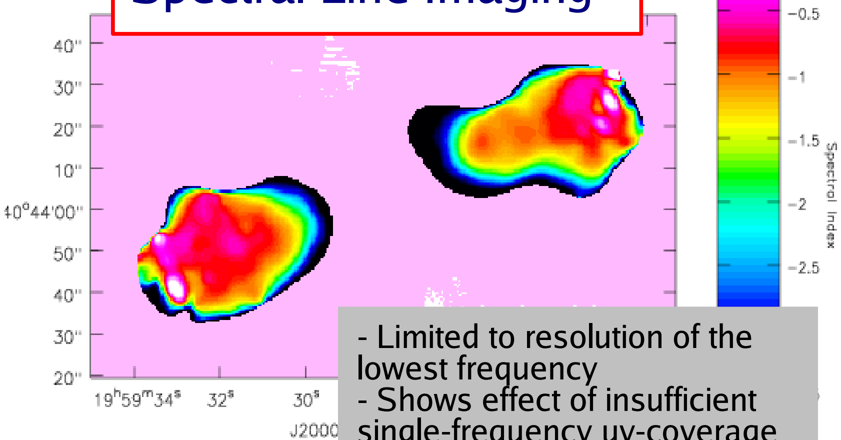
CygA : Stokes I (images and residuals)



- both algorithms work well
- both have similar residual errors due to deconvolution.

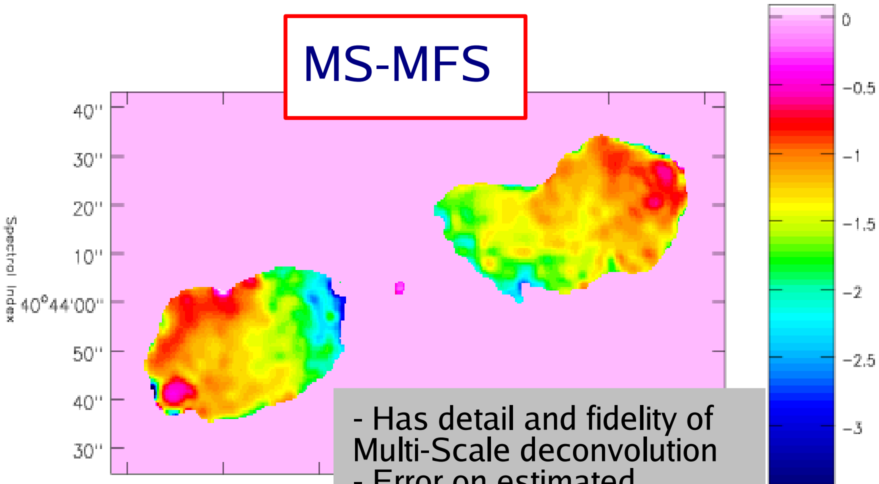
CygA : Spectral index

Spectral Line Imaging



- Limited to resolution of the lowest frequency
- Shows effect of insufficient single-frequency uv-coverage

MS-MFS

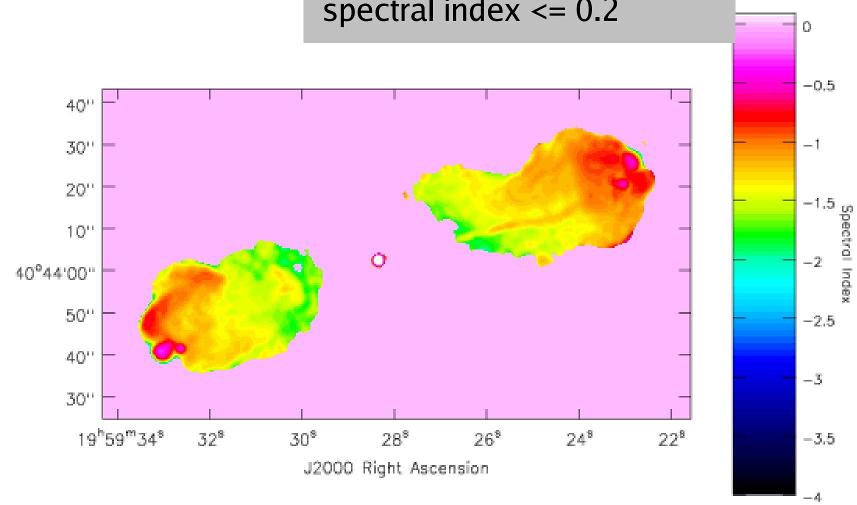


- Has detail and fidelity of Multi-Scale deconvolution
- Error on estimated spectral index <= 0.2

For comparison,

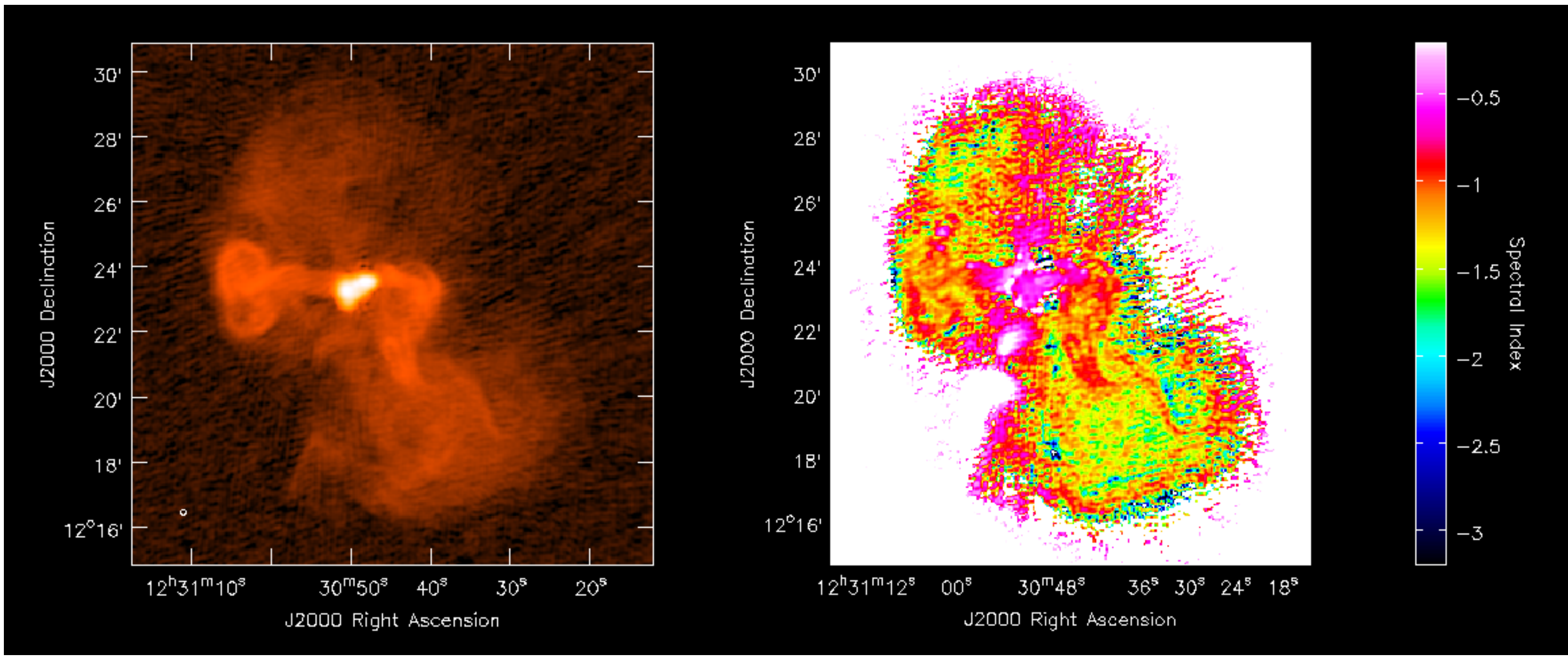
Spectral Index Map constructed from images at 1.4GHz and 4.8GHz, obtained from C.Carilli et al, Ap.J. 1991. (VLA A,B,C,D Array at L and C band)

Map has been smoothed to 1 arcsec.



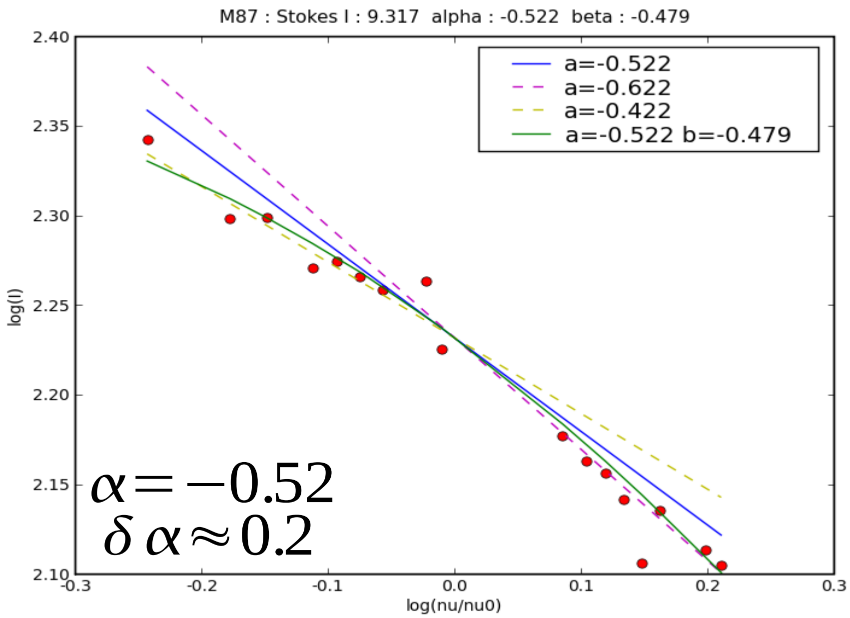
M87 : Stokes I , Spectral Index

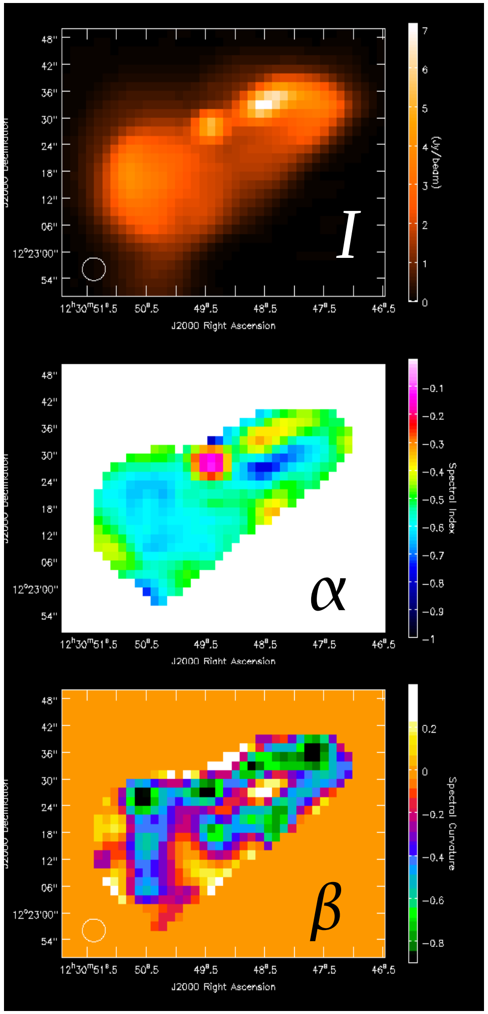
Total Intensity Image   Spectral Index Map



VLA C-array : Cycle through 16 frequencies between 1.18 –1.86 GHz, 25MHz bands, RR,LL
~ 30 mins per frequency, spread across 10 hrs
=> 10 x 3min 'snapshots' per frequency

M87 : Spectral Curvature (core+inner jet)



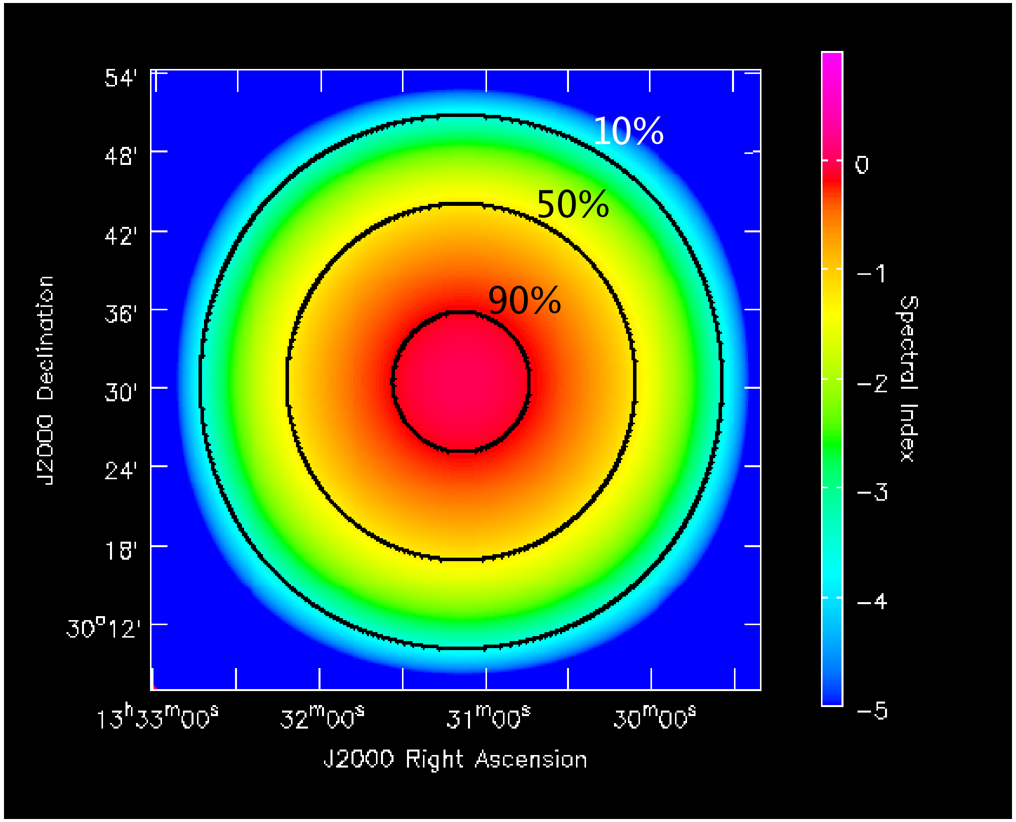


Points : from spectral line maps

Lines : from MS-MFS

- Need SNR > 100 to fit spectral variation ~ 0.2

Frequency dependant primary beam



Varying Field-Of-View :

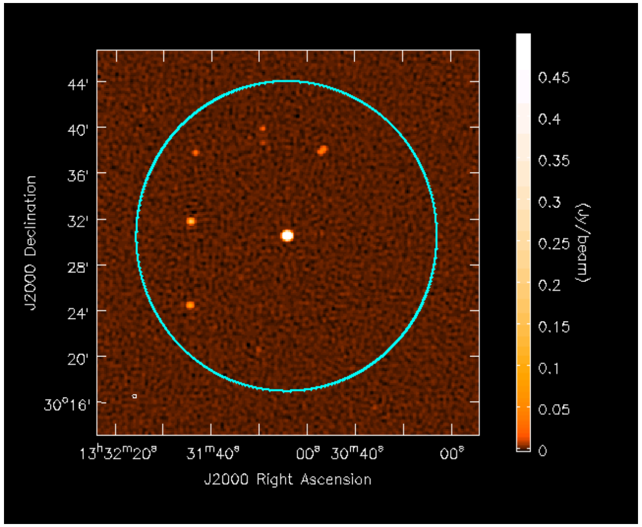
- Introduces a spurious spectral index
- Can be corrected during imaging and weighted by noise during deconvolution.

Contours : Average Primary Beam at 10%, 50% and 90% level.

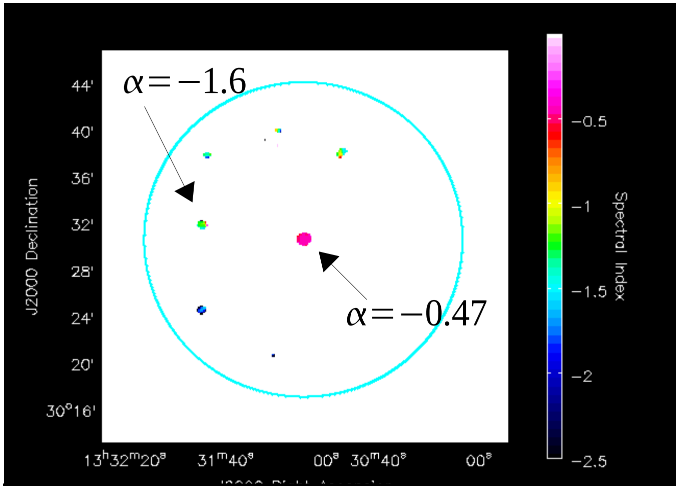
Colors : Spectral Index of the primary beam within the main lobe.

Frequency-dependent PB correction

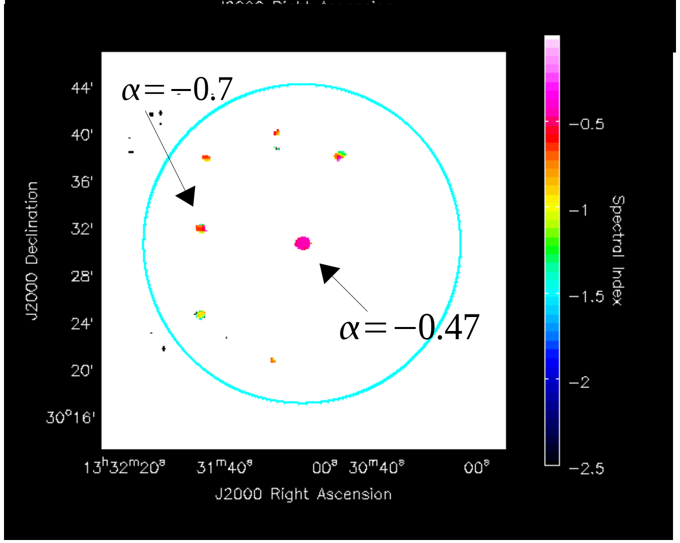
3C286 field (1.2 GHz to 1.8 GHz)



Without PB correction



With PB correction



Current error bar on the
PB-corrected spectral index ~ 0.15

(from another observation of 3C147 at 40% of PB)

Computation/Performance

	Spectral-Line Imaging	MS-MFS
Number of deconvolution runs	N_{chan}	1
Data I/O per solver Major Cycle	N_{vis} / N_{chan}	N_{vis}
Memory Use per deconvolution run (multi-scale)	Image Size x N_{scales}^2	Image Size x $(N_{taylor} \times N_{scales})^2$
Runtime (for few GB of EVLA data on CygA, M87)	~ 30 hours parallelized : ~ 7.5 hours (theoretical –for 4 nodes)	~ 12 hours parallelized : ~ 4 hours (measured –on 4 nodes)

Trade-Off between source complexity, available uv-coverage, desired angular resolution of spectral index map, and algorithm simplicity/stability.

Summary

- Wide-Band receivers provide increased uv-coverage and sensitivity and measure spectra.

- Continuum Imaging :
  - Model both spatial and spectral structure (spectral index and curvature)
  - Correct for a frequency-dependent primary beam

- Point Sources : Algorithms can get to 10^6 dynamic range
- Extended Emission : Algorithms can get to $>10^5$ dynamic range

  (limited by multiscale algorithms)

- Spectral Structure (for 2:1 bandwidth)

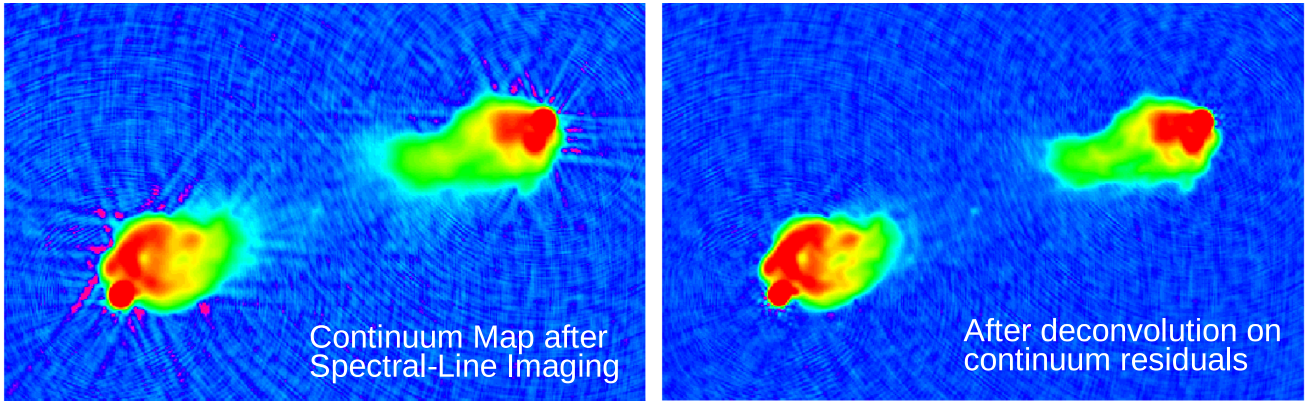
  Need SNR > 6 to measure spectral index ~ 0.5

  Need SNR > 50 to measure spectral index variation (curvature) ~ 0.2

- Work in progress : PB measurement (holography) across L-Band, modelling and correction during MFS deconvolution, and error analysis.

Hybrid Algorithm –extended emission

Spectral-Line Imaging + Deconvolution on continuum residuals



Cygnus-A+ simulation (40 channels, L-Band to C-Band, 4 hours) => Ideal data

Target dynamic range : 10^6
Target pt-source rms : 10 uJy

Max Dynamic range : 10^6
(component image)

Max Dynamic range : 10^5
(restored image)

Simple hybrid algorithm can handle arbitrary spectra and will suffice (upto calibration limits)

- for point sources
- for extended sources if there is sufficient uv-coverage per channel