Wide Bandwidth Imaging

14th NRAO Synthesis Imaging Workshop

13 – 20 May, 2014, Socorro, NM

Urvashi Rau
National Radio Astronomy Observatory

Why do we need wide bandwidths ?

Broad-band receivers => Increased 'instantaneous' imaging sensitivity

Continuum sensitivity :
(at field-center)

$$\sigma_{cont} = \frac{\sigma_{chan}}{\sqrt{(N_{chan})}} \propto \frac{T_{sys}}{\sqrt{N_{ant}(N_{ant}-1)\ \delta\tau\,\delta\nu}}$$

50 MHz → 2 GHz => Theoretical improvement : $\sqrt{\frac{2\,GHz}{50\,MHz}} \approx 6$ times.

In practice, effective broadband sensitivity for imaging depends on bandpass shape, data weights, and regions of the spectrum flagged due to RFI. For VLA L-band, we typically use 70% of the band.

Why do we need wide bandwidths ?

Broad-band receivers => Increased 'instantaneous' imaging sensitivity

Continuum sensitivity : (at field-center) $\sigma_{cont} = \frac{\sigma_{chan}}{\sqrt{(N_{chan})}} \propto \frac{T_{sys}}{\sqrt{N_{ant}(N_{ant}-1)\ \delta\tau\delta\nu}}$

50 MHz → 2 GHz => Theoretical improvement : $\sqrt{\frac{2\,GHz}{50\,MHz}} \approx 6$ times.

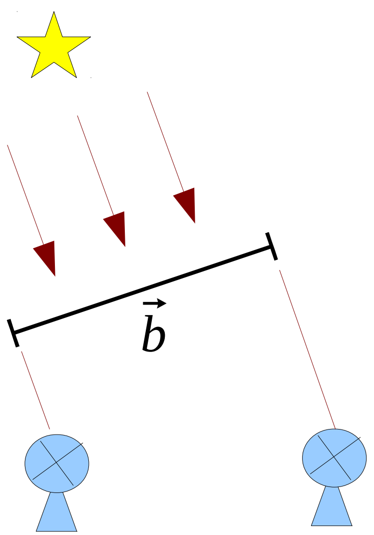
In practice, effective broadband sensitivity for imaging depends on bandpass shape, data weights, and regions of the spectrum flagged due to RFI. For VLA L-band, we typically use 70% of the band.

Some bandwidth jargon.....

Frequency Range :	ν_{min}, ν_{max}	(1 – 2 GHz)	(4 – 8 GHz)	(8 – 12 GHz)
Bandwidth :	$\nu_{max} - \nu_{min}$	1 GHz	4 GHz	4 GHz
Bandwidth Ratio :	$\nu_{max} : \nu_{min}$	2 : 1	2 : 1	1.5 : 1
Fractional Bandwidth :	$(\nu_{max} - \nu_{min}) / \nu_{mid}$	66%	66%	40%

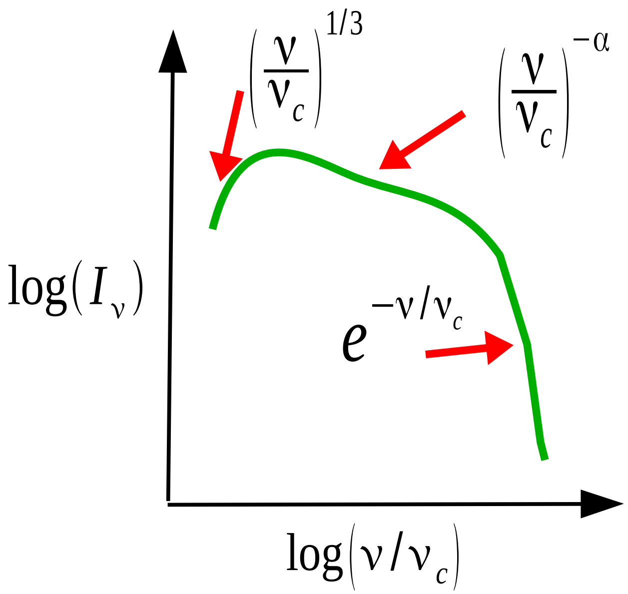
The instrument and the sky change with frequency...

UV-coverage



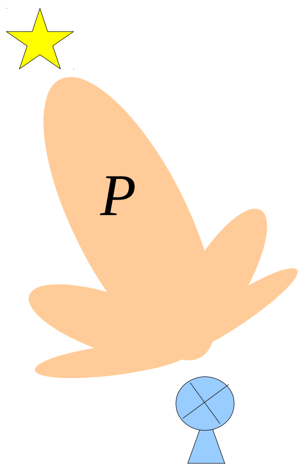
$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

Sky Brightness



$$I(\nu)$$

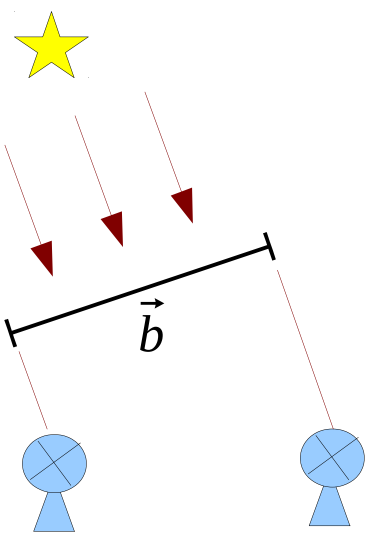
Primary Beam



$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

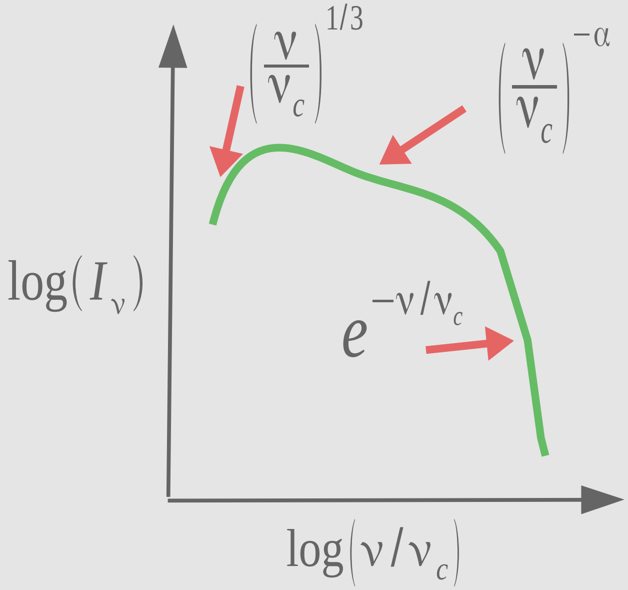
The instrument and the sky change with frequency...

UV-coverage



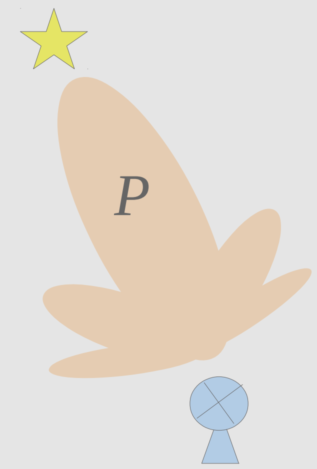
$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

Sky Brightness



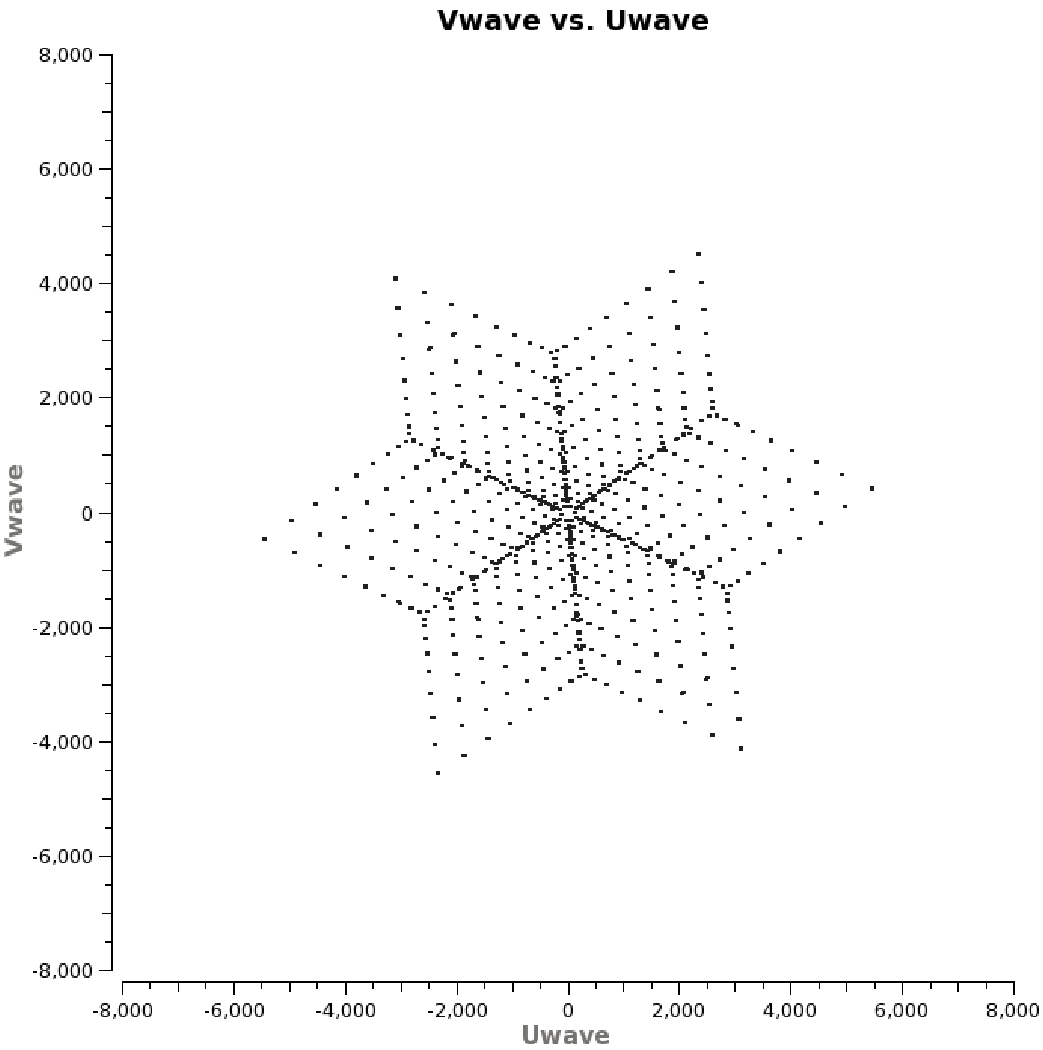
$$I(\nu)$$

Primary Beam

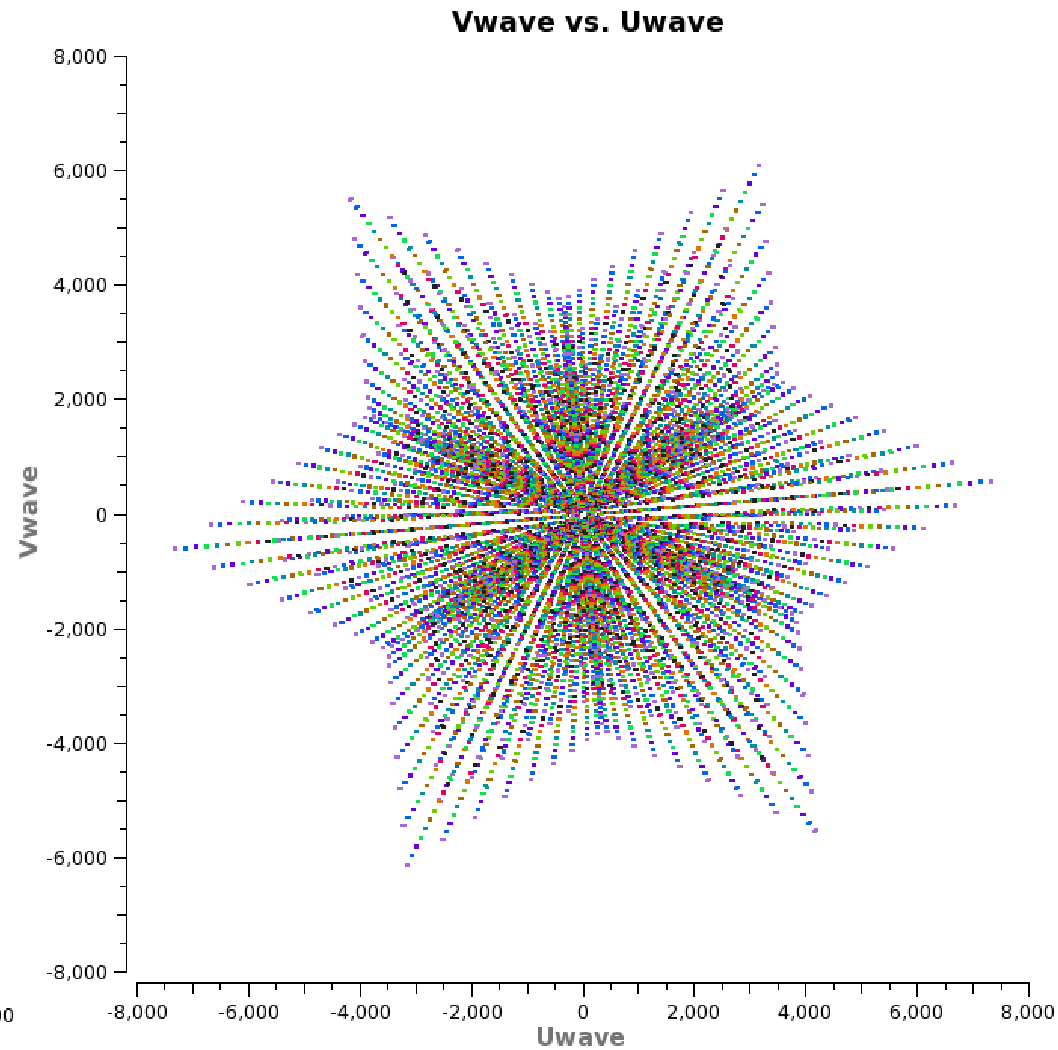


$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

Multi-Frequency-Synthesis – UV coverage

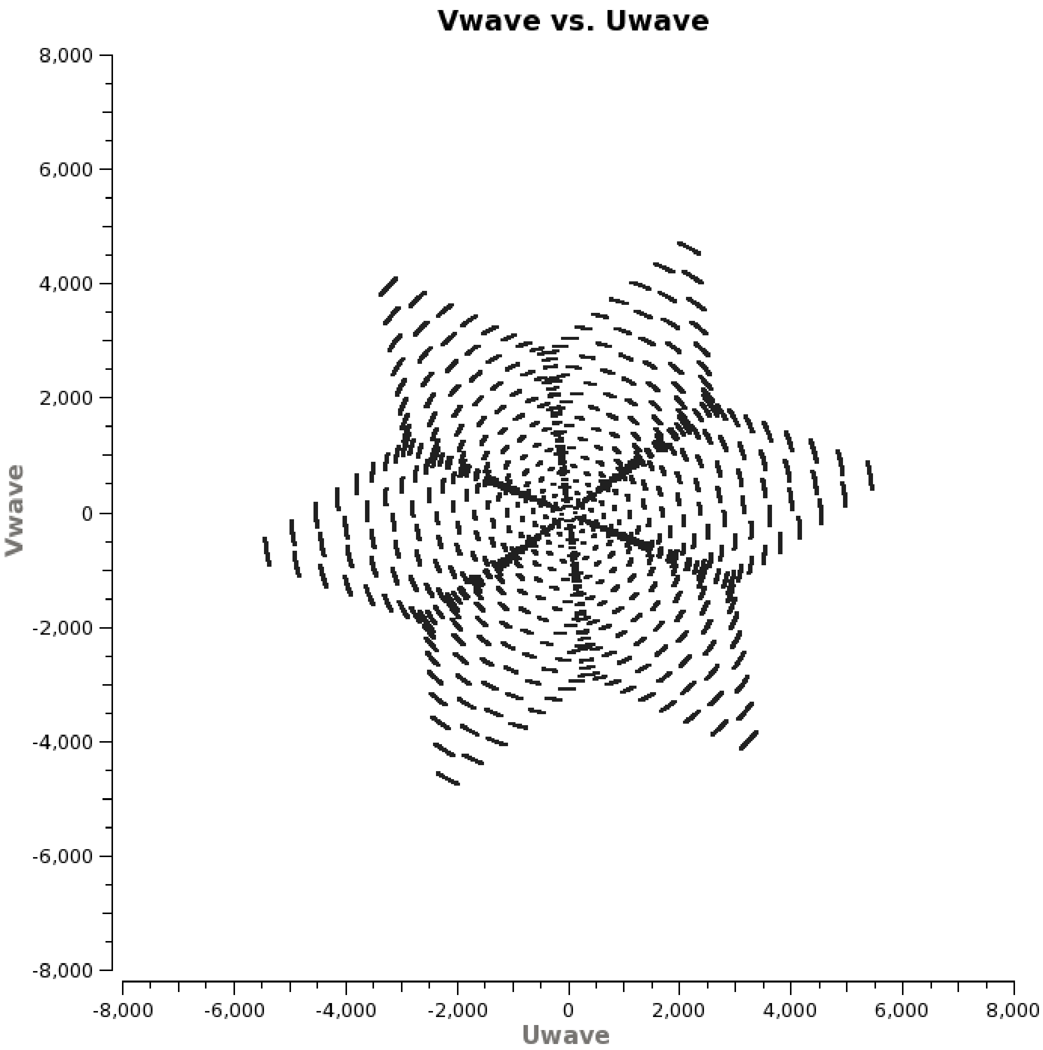


1.5 GHz

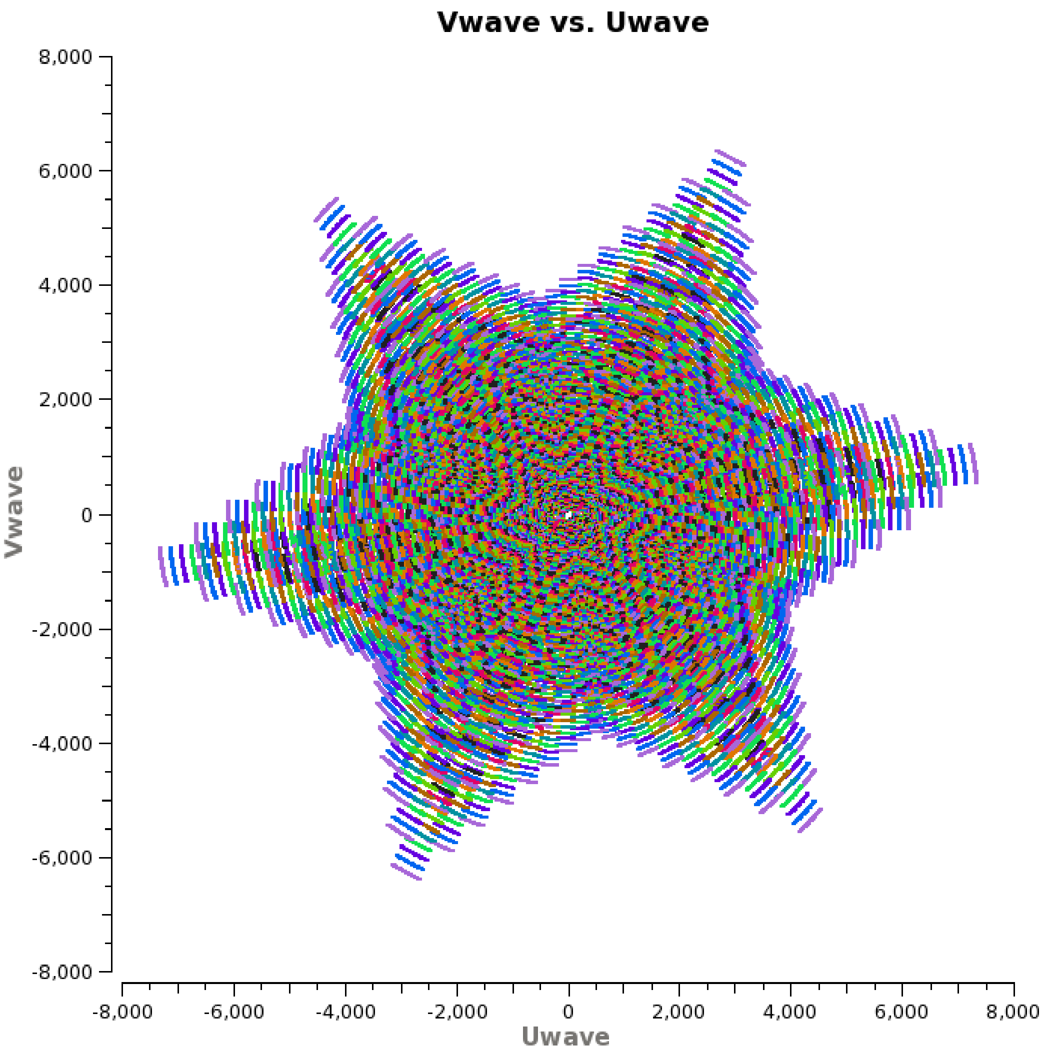


1 – 2 GHz

Multi-Frequency-Synthesis – UV coverage

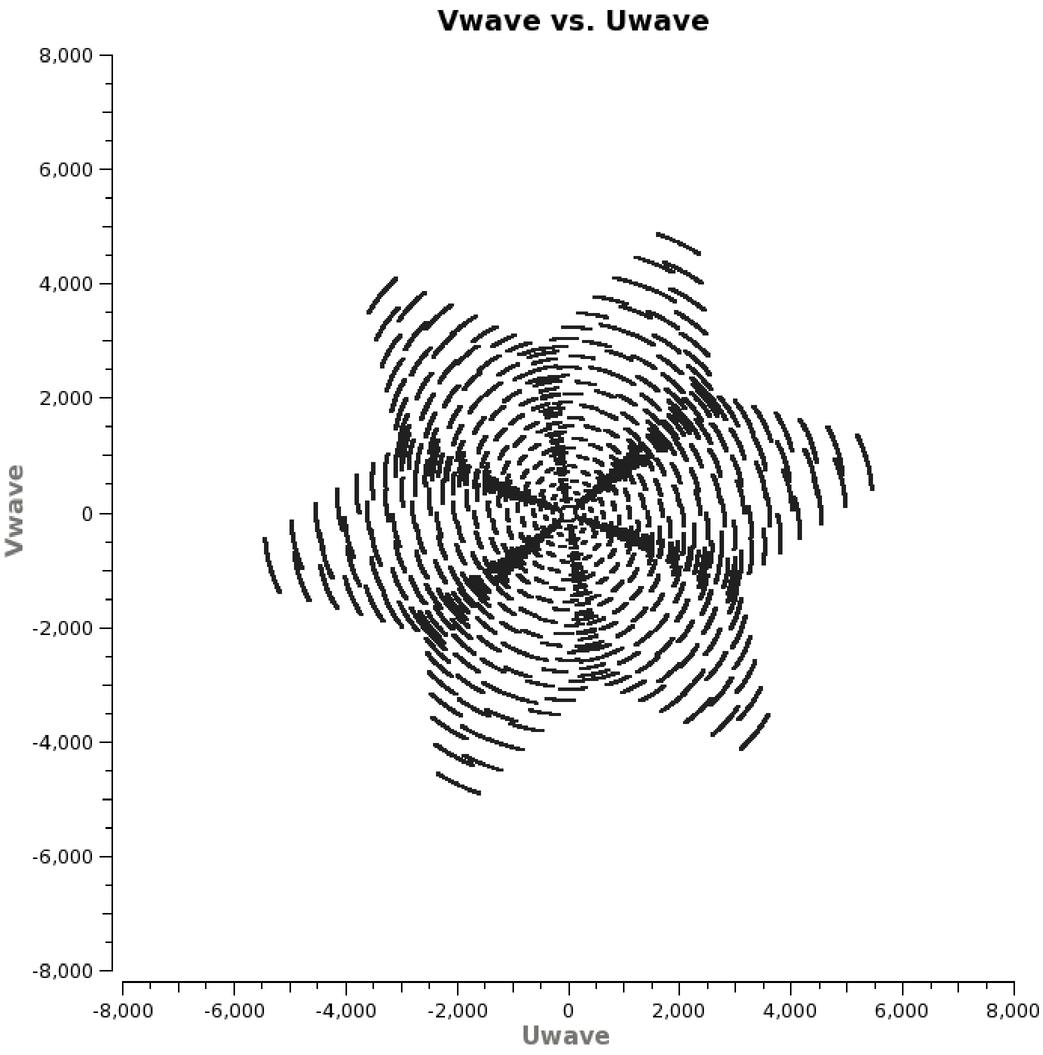


1.5 GHz

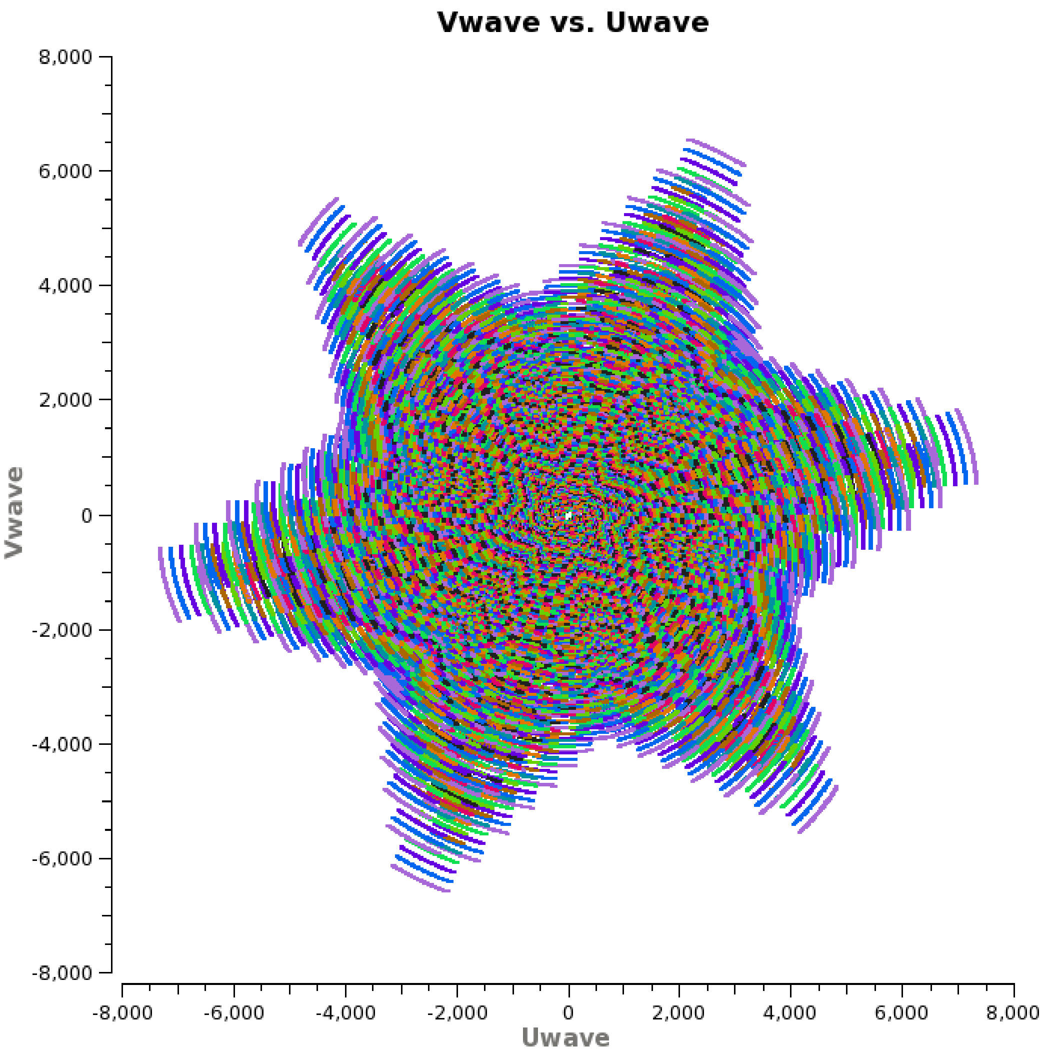


1 – 2 GHz

Multi-Frequency Synthesis – UV coverage

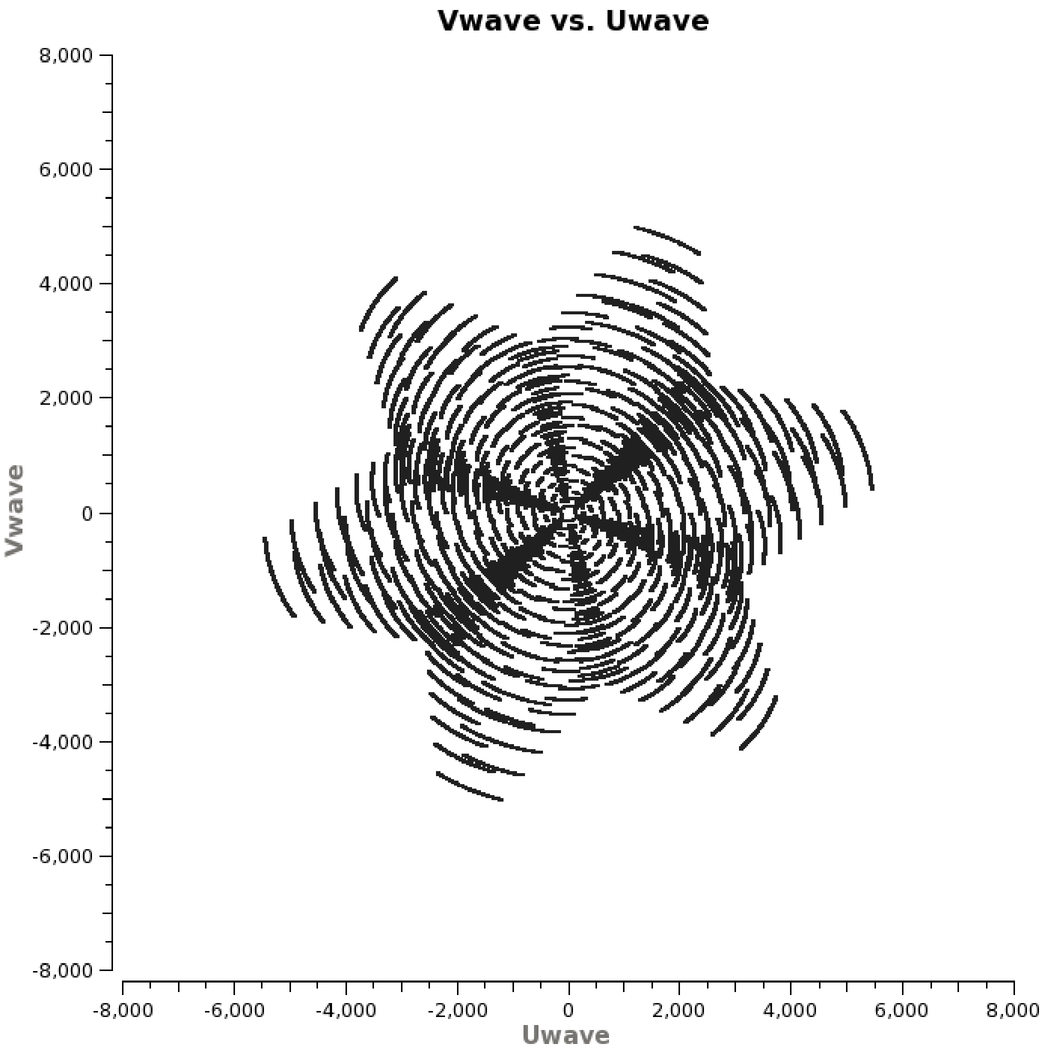


1.5 GHz

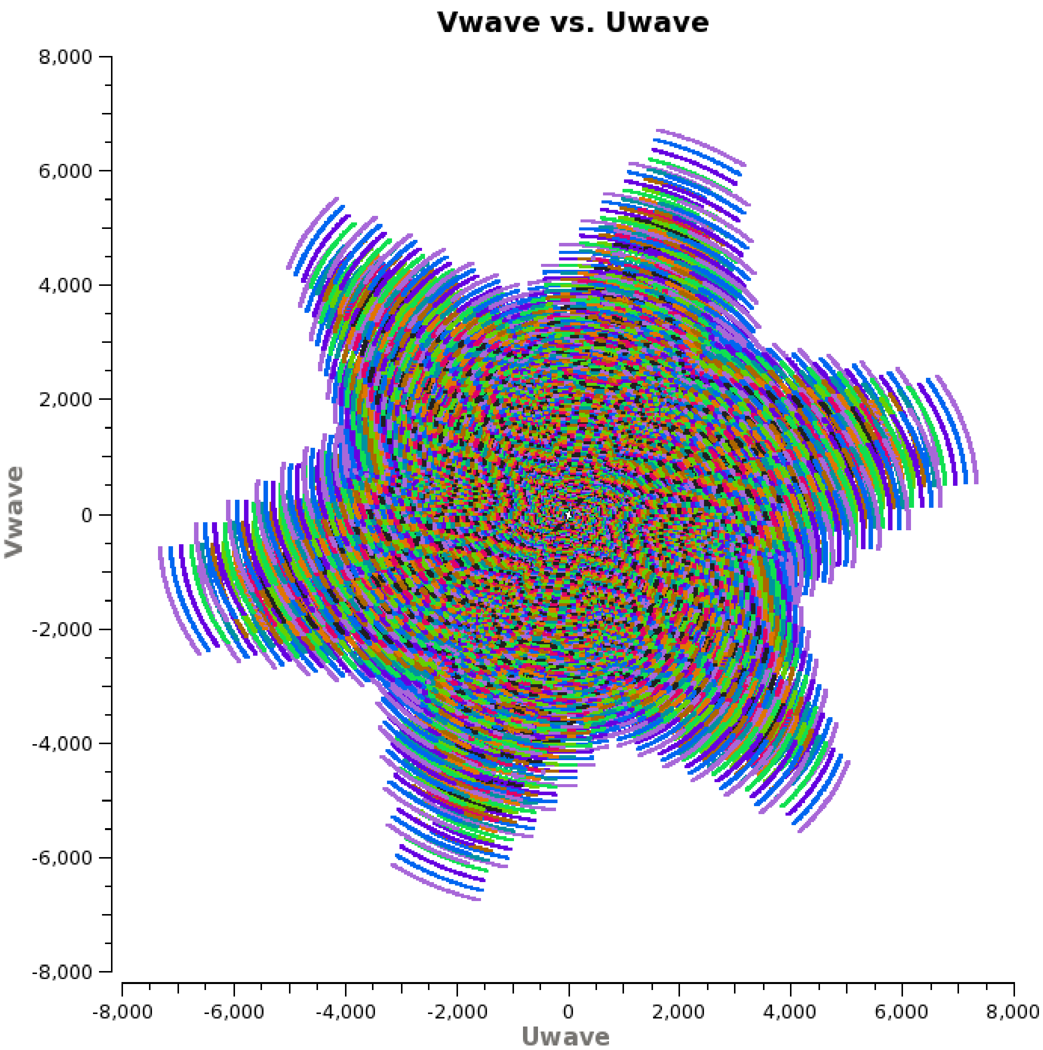


1 – 2 GHz

Multi-Frequency Synthesis – UV coverage

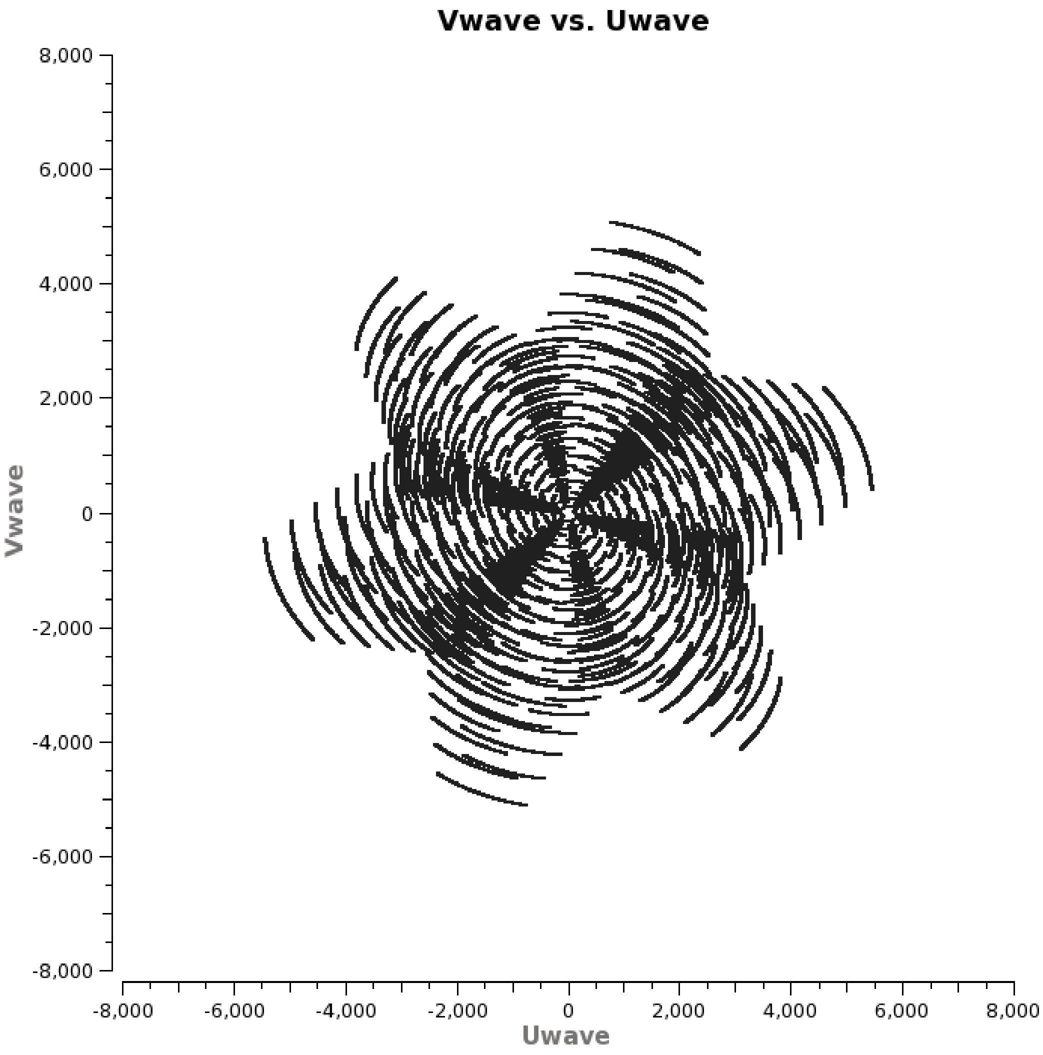


1.5 GHz

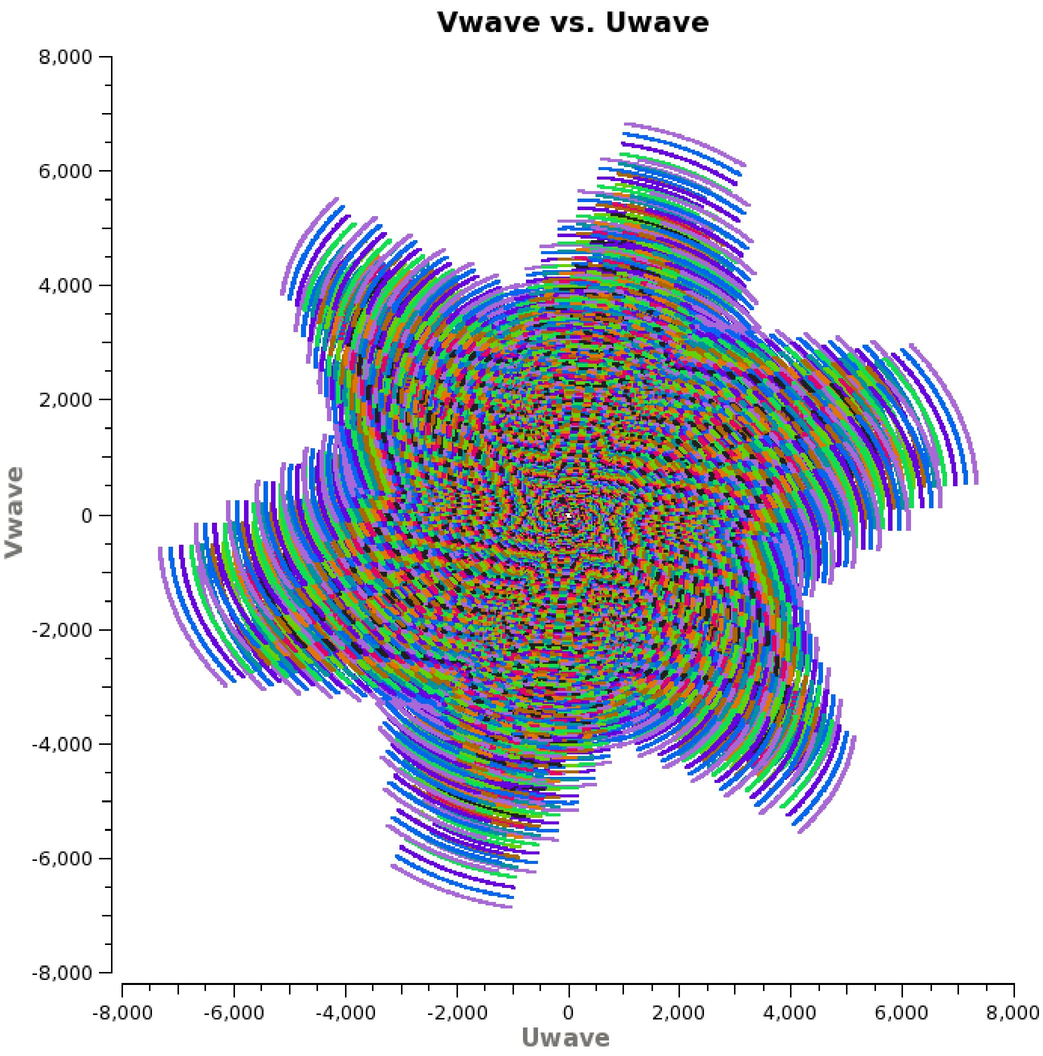


1 – 2 GHz

Multi-Frequency Synthesis – UV coverage

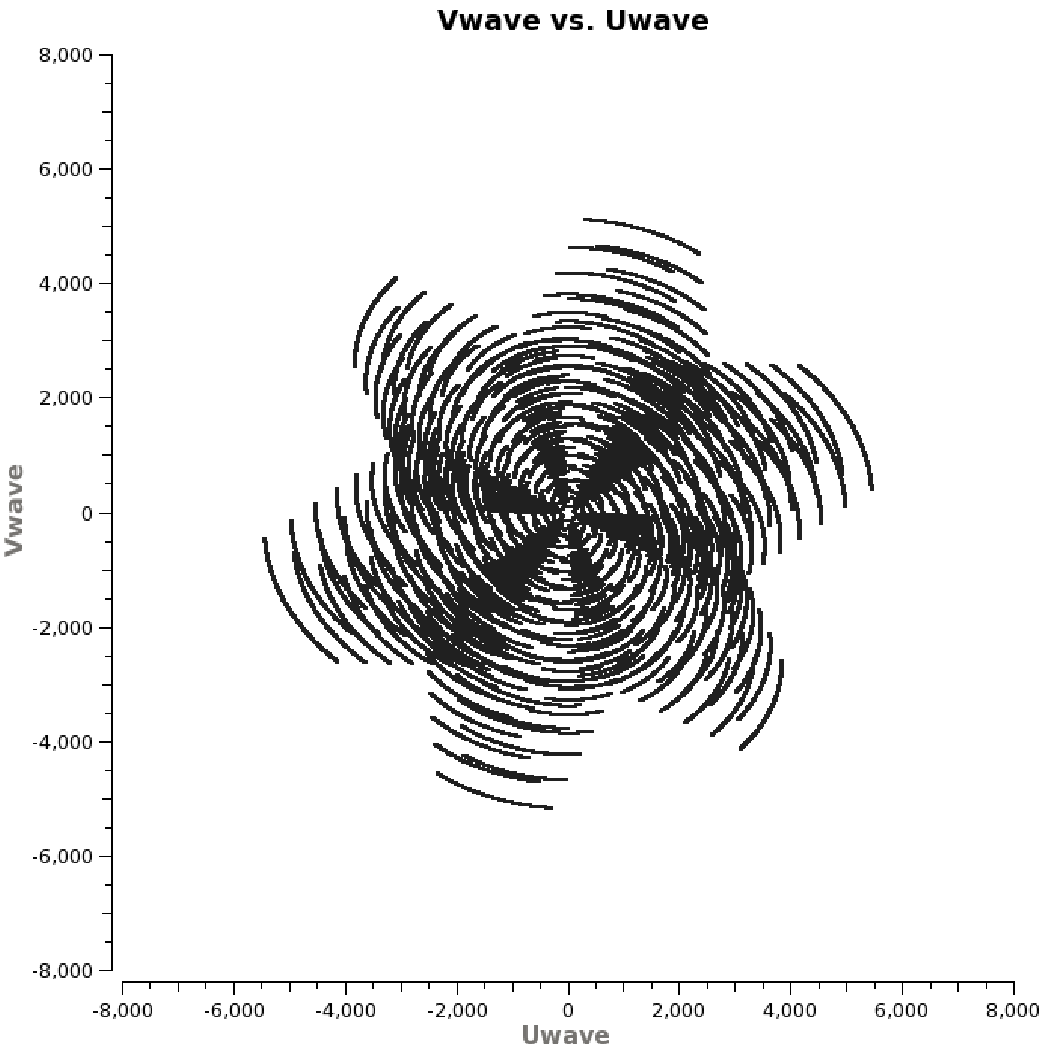


1.5 GHz

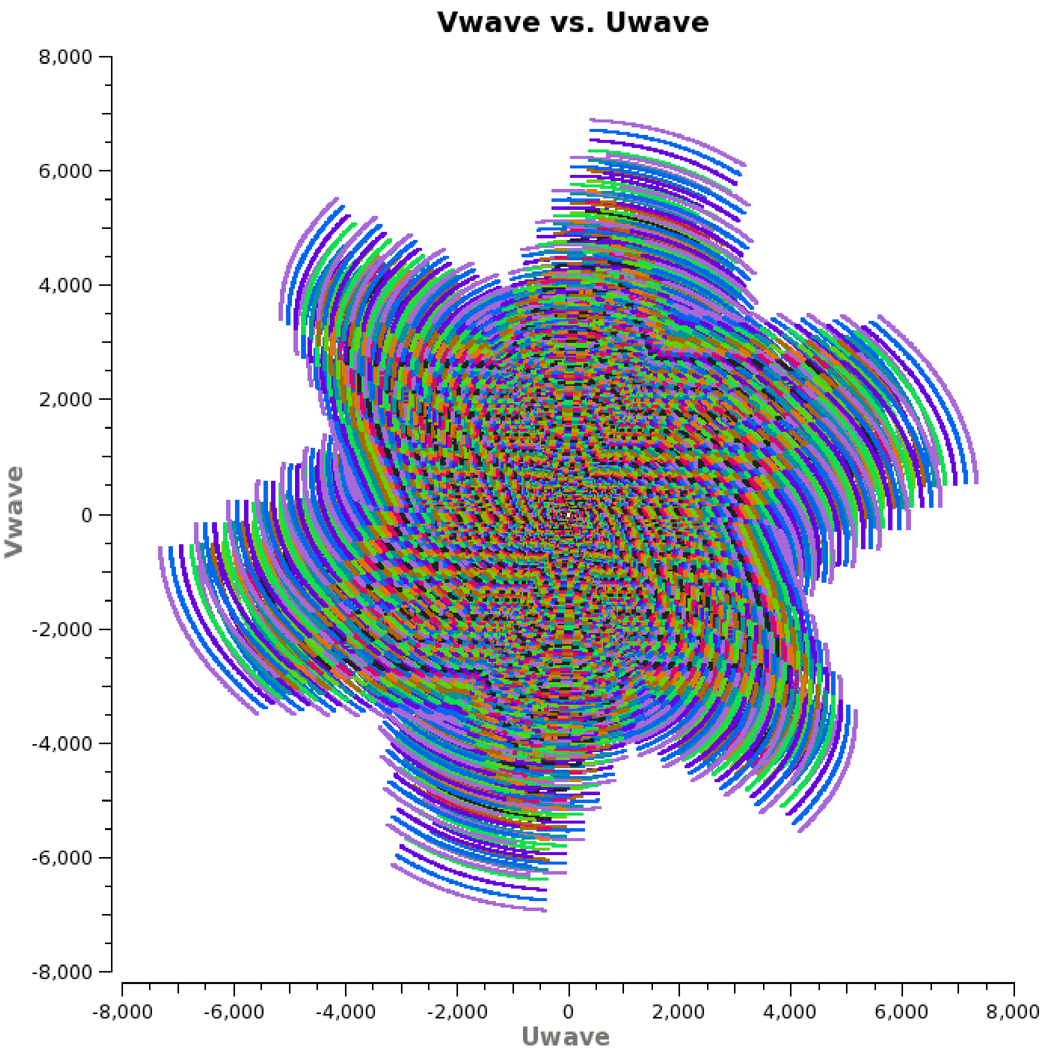


1 – 2 GHz

Multi-Frequency Synthesis – UV coverage

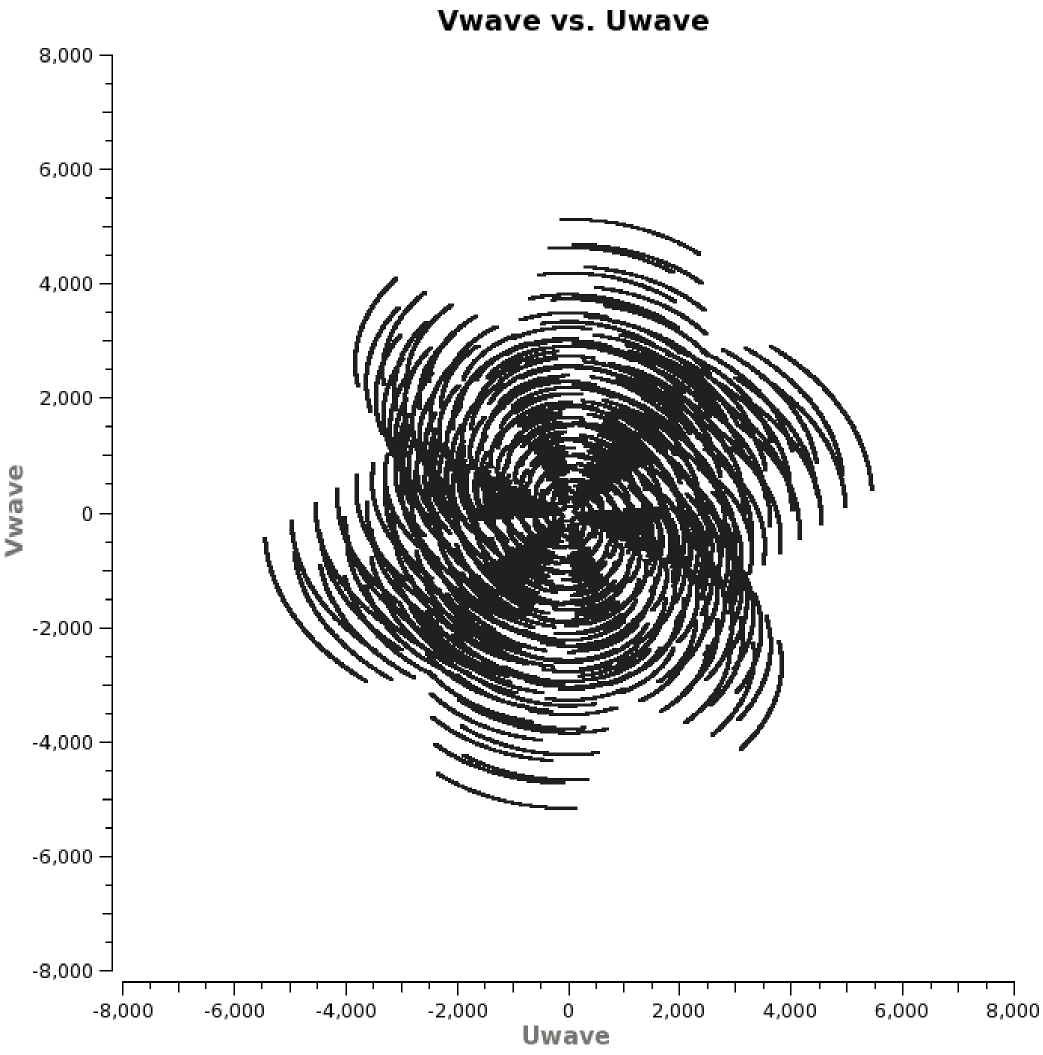


1.5 GHz

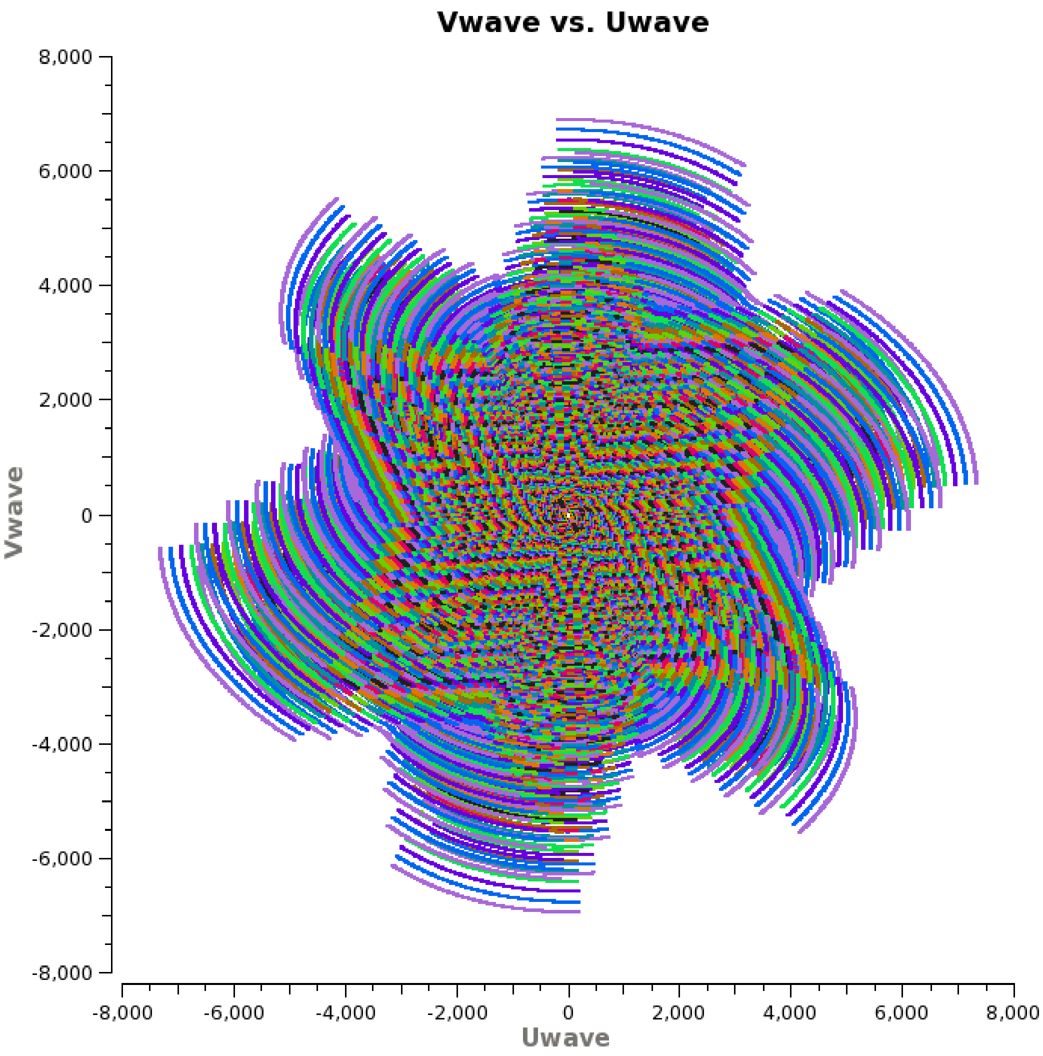


1 – 2 GHz

Multi-Frequency Synthesis – UV coverage

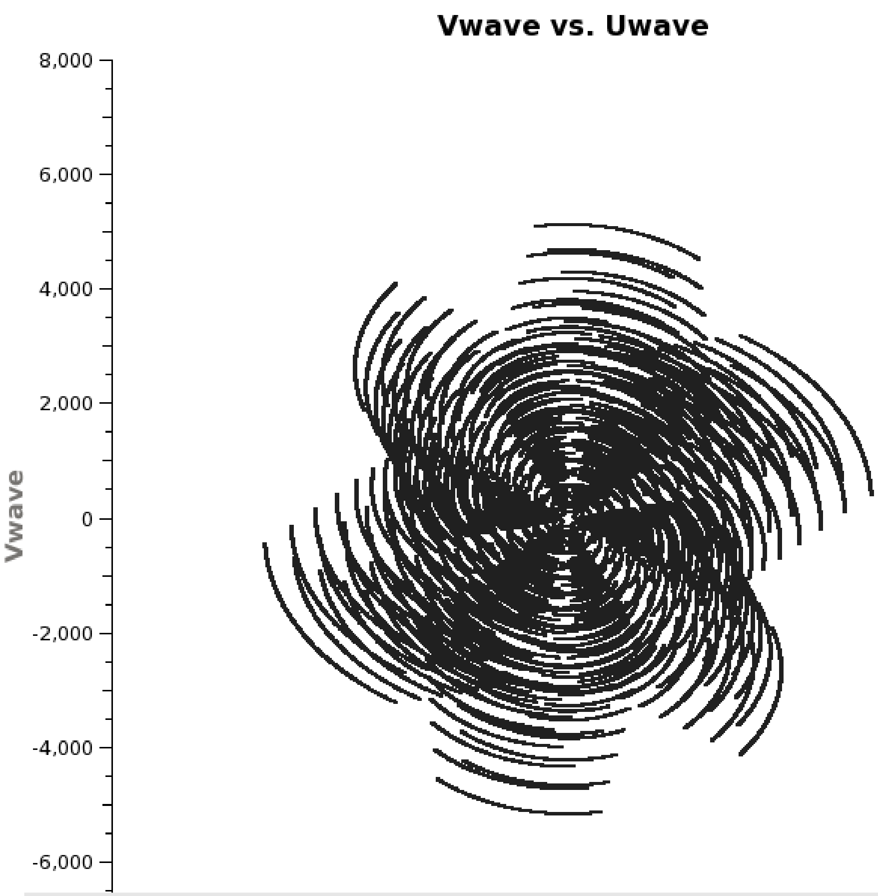


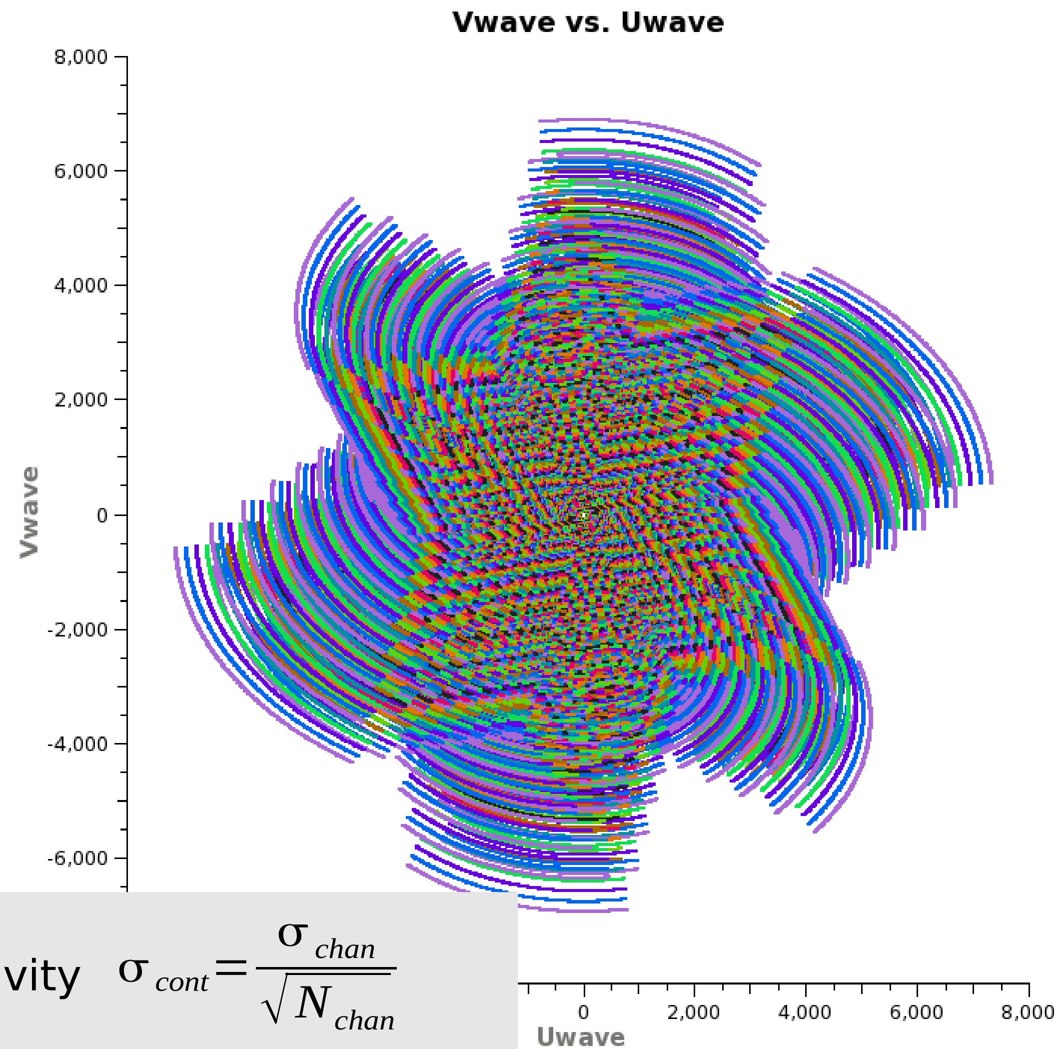
1.5 GHz



1 – 2 GHz

Multi-Frequency Synthesis – UV coverage

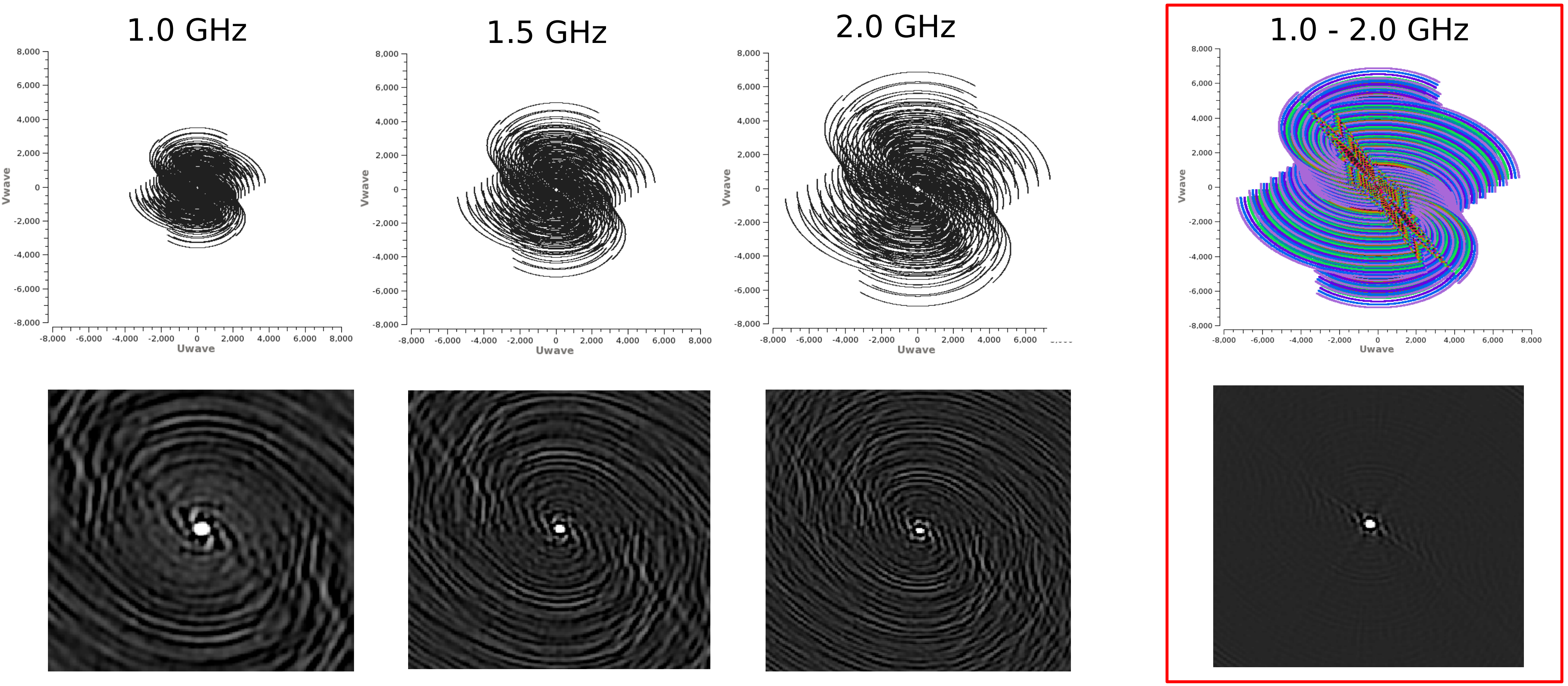




- Overlapping UV-coverage => better sensitivity $\sigma_{cont} = \frac{\sigma_{chan}}{\sqrt{N_{chan}}}$
- Increased UV-filling => better imaging-fidelity
- Larger spatial-frequency range => better angular-resolution $\frac{\lambda}{b_{max}}$

Imaging Properties change with frequency

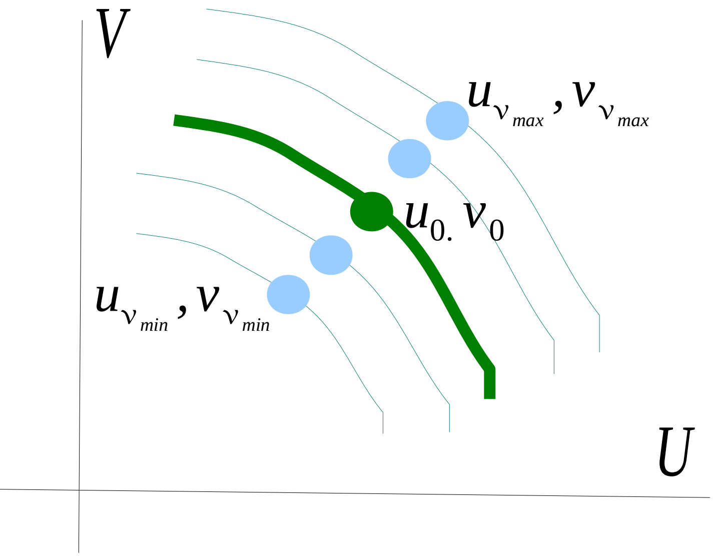
- Angular-resolution increases at higher frequencies
- Sensitivity to large scales decreases at higher frequencies
- Wideband UV-coverage has fewer gaps => lower Psf sidelobe levels



Measure visibilities in frequency ‘channels’ and place them at their correct locations on the UV-plane.

Bandwidth smearing (chromatic aberration)

Suppose the entire receiver bandwidth was measured in one channel ν_0

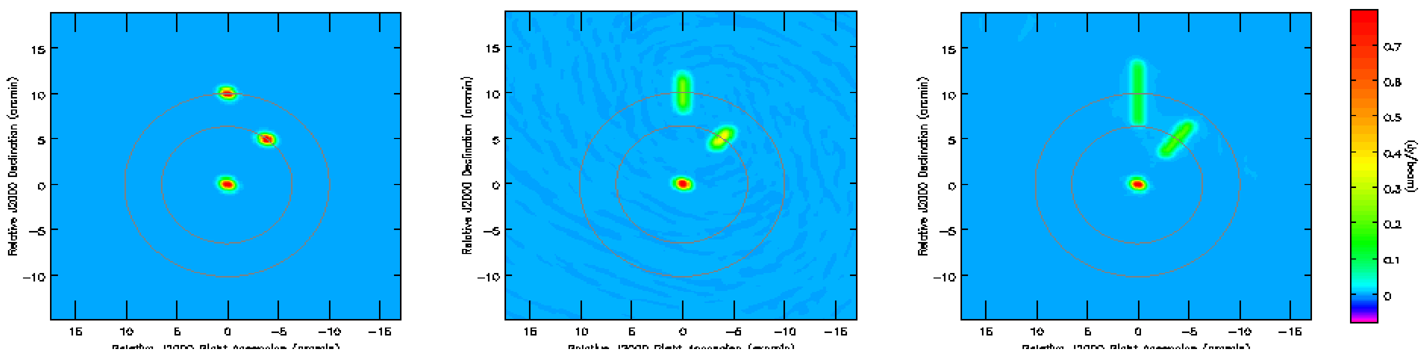


$V(u_\nu)$ is mistakenly mapped to $\frac{\nu_0}{\nu} u_\nu$

Similarity theorem of Fourier-transforms :

Radial shift in source position with frequency.
=> Radial smearing of the sky brightness

2 MHz 200 MHz 1.0 GHz



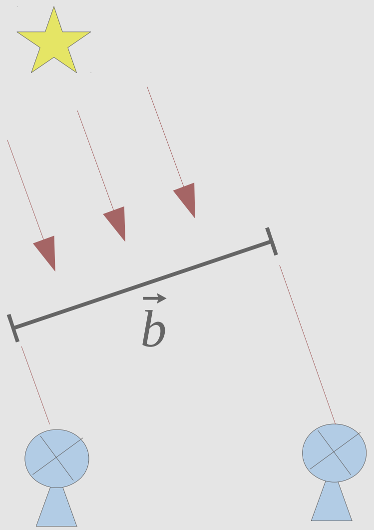
Excessive channel averaging during post-processing has a similar effect.

Bandwidth smearing limit for HPBW field-of-view : $\delta\nu < \frac{\nu_0 D}{b_{max}}$

Bandwidth Smearing limits at L-Band (1.4 GHz),
33 MHz (VLA D-config), 10 MHz (VLA C-config),
3 MHz (VLA B-config), 1 MHz (VLA A-config)

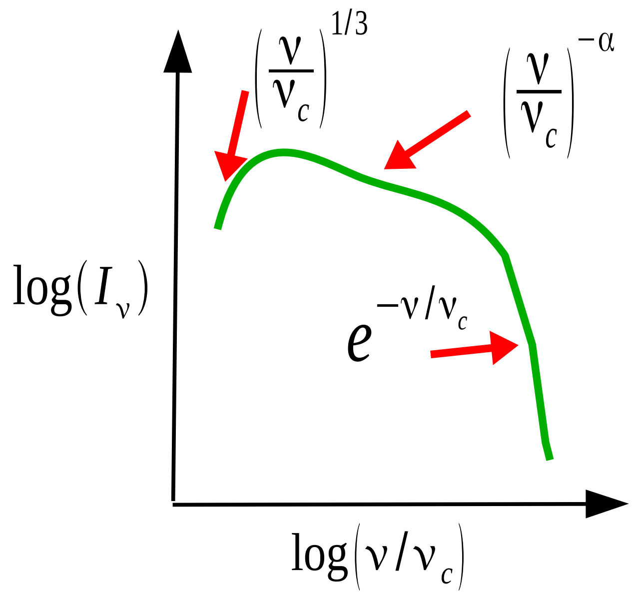
The instrument and the sky change with frequency...

UV-coverage



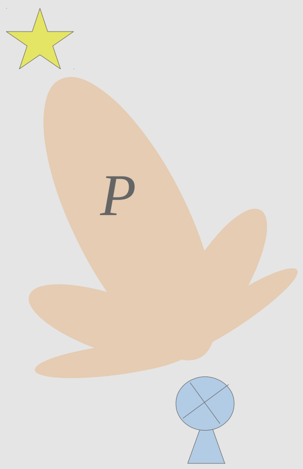
$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

Sky Brightness



$$I(\nu)$$

Primary Beam



$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

Imaging Equations

Narrow Band / Flat spectrum sky

$$I^{obs} = I^{sky} * PSF$$

$$I^{obs}_{wb} \approx I^{sky} * \left[\sum_{\nu} PSF_{\nu} \right]$$

Image reconstruction

= deconvolution : remove the effect of the instrument's response to a flat spectrum point source.

= non-linear fitting of a narrow-band model of the sky to the data

(Ref : Imaging and Deconvolution lecture)

Wide Band Sky with spectral structure

$$I^{obs}_{wb} = \sum_{\nu} \left[I^{sky}_{\nu} * PSF_{\nu} \right]$$

Wideband Image reconstruction

= Treat each frequency separately

(Ref : Spectral Line Analysis lecture)

(or)

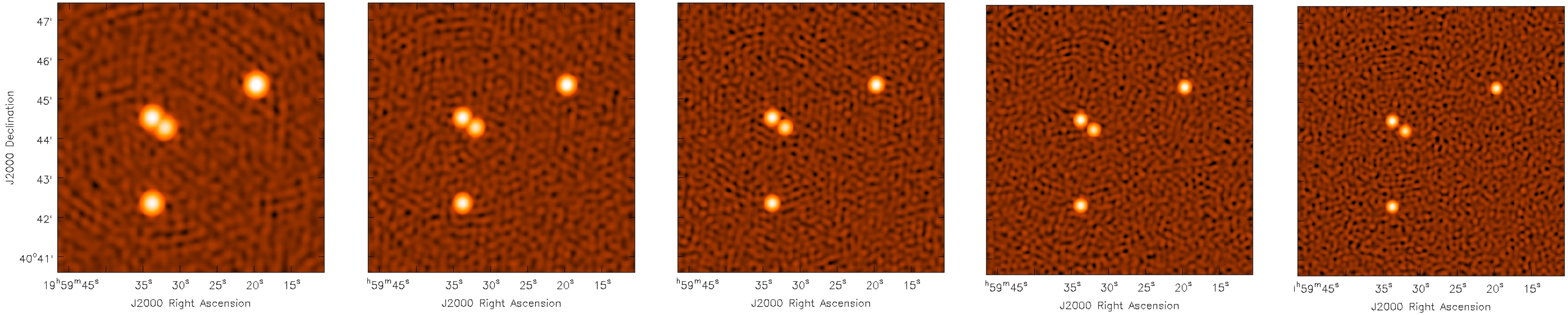
= joint deconvolution : remove the effect of the instruments response to a point source with spectral features

= non-linear fitting of a wide-band model of the sky to the data

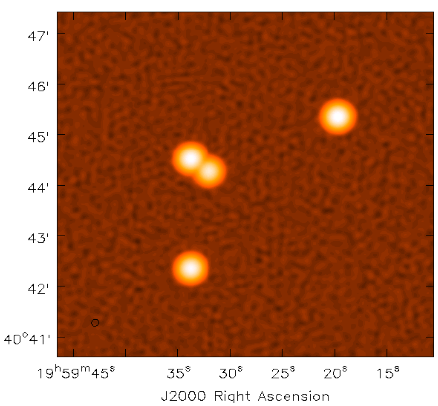
Single-channel vs MFS imaging – Angular Resolution

3 flat-spectrum sources + 1 steep-spectrum source (1-2 GHz)

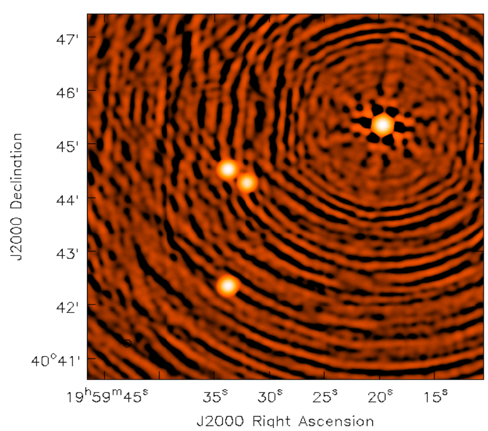
Images made at multiple frequencies (Spectral Cube / Image Cube)



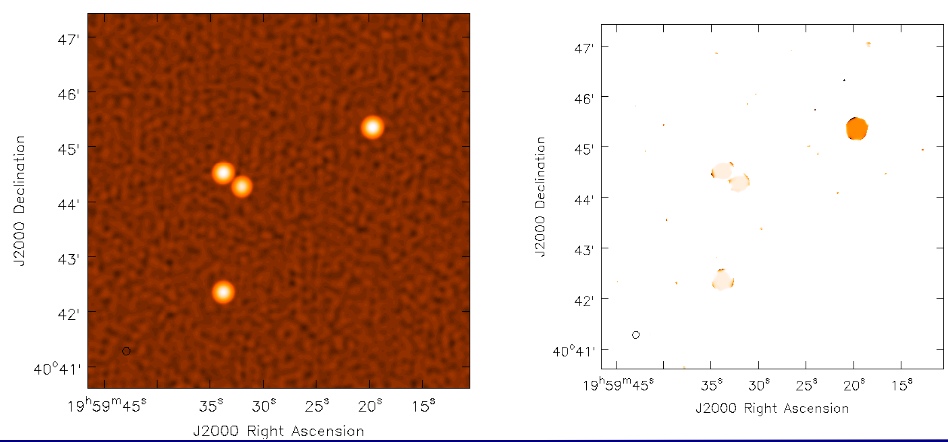
Combine single-frequency images (after smoothing)



Do MFS using all data, but ignore spectra



Do MFS using all data
+ Model and fit for spectra too
= Intensity and Spectral-Index



Algorithm : Multi-Term MFS (with multi-scale)

Sky Model : Collection of multi-scale flux components whose amplitudes follow a Taylor polynomial in frequency

Reconstruction Algorithm : Linear least squares + deconvolution

Data Products : Taylor-Coefficient images $I^m_{0,} I^m_{1,} I^m_{2,} \ldots$

that represent the sky spectrum $I^{sky}_{\nu} = \sum_t I_t \left(\frac{\nu - \nu_0}{\nu_0} \right)^t$

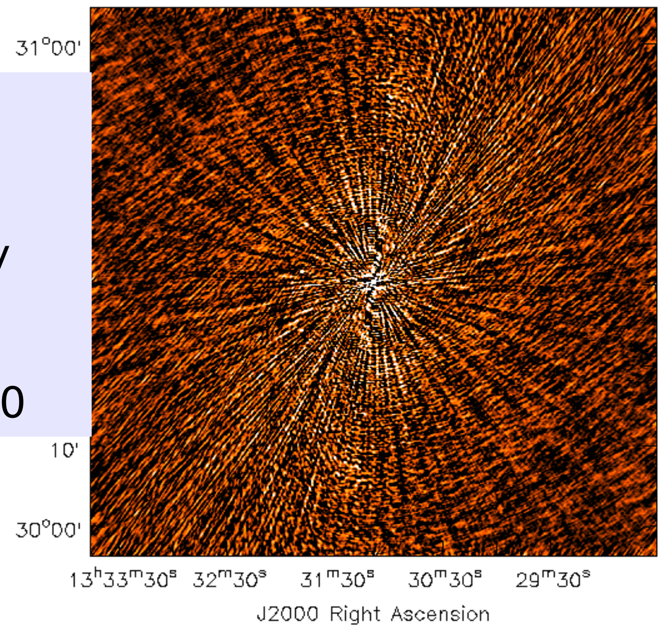
Interpretation :

- As a power-law (spectral index and curvature)

$$I_\nu = I_{\nu_0} \left(\frac{\nu}{\nu_0} \right)^{\alpha + \beta \log(\nu/\nu_0)} \longleftrightarrow \quad I^m_0 = I_{\nu_0} \quad I^m_1 = I_{\nu_0} \alpha \quad I^m_2 = I_{\nu_0} \left(\frac{\alpha(\alpha-1)}{2} + \beta \right)$$

Sault &Wieringa, 1994
Rau &Cornwell, 2011

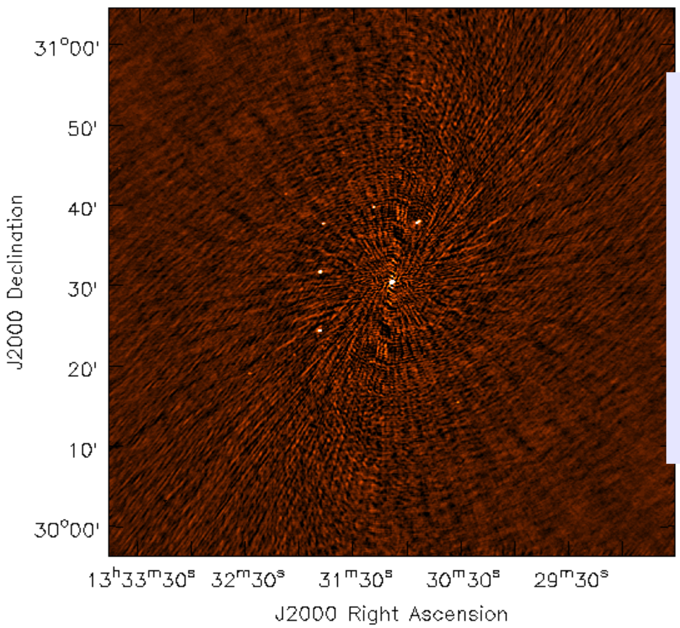
Dynamic-range with MS-MFS : 3C286 example : Nt=1,2,3,4



NTERMS = 1

Rms :
9 mJy -- 1 mJy

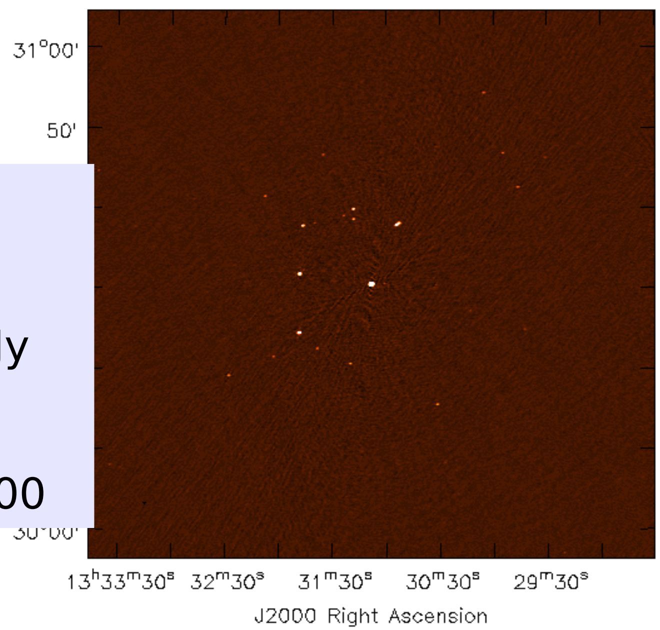
DR :
1600 - 13000



NTERMS = 2

Rms :
1 mJy -- 0.2 mJy

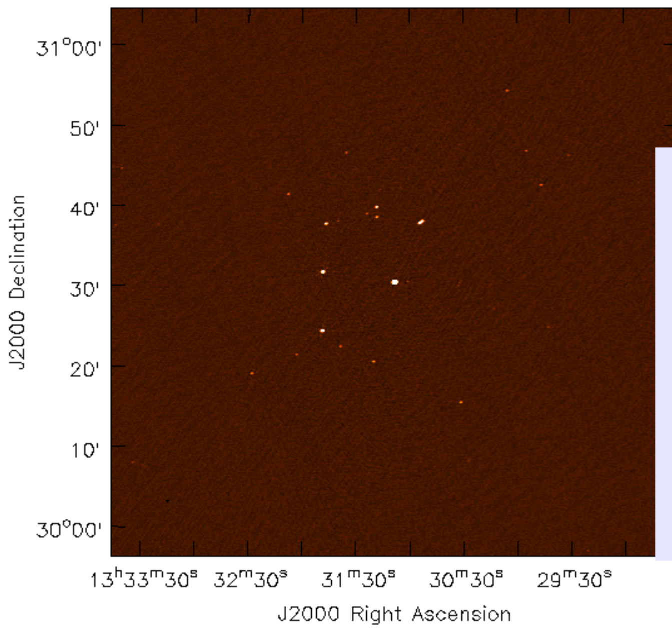
DR :
10,000 - 17,000



NTERMS = 3

Rms :
0.2 mJy -- 85 uJy

DR :
65,000 - 170,000



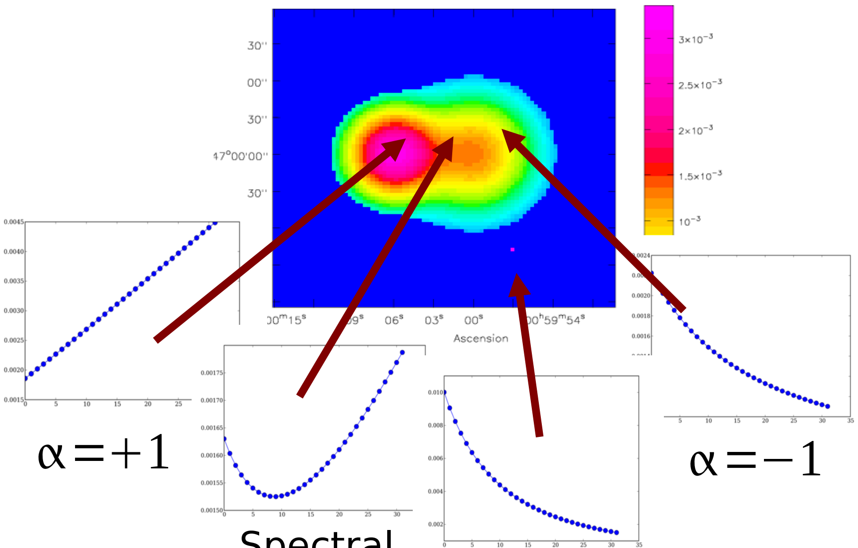
NTERMS = 4

Rms
0.14 mJy -- 80 uJy

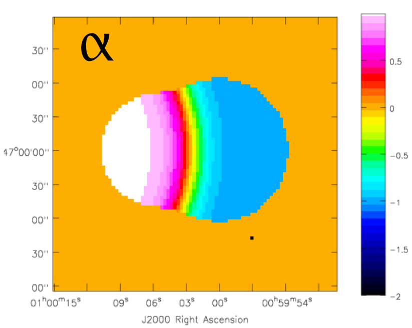
DR :
>110,000
- 180,000

Example of wideband-imaging on extended-emission

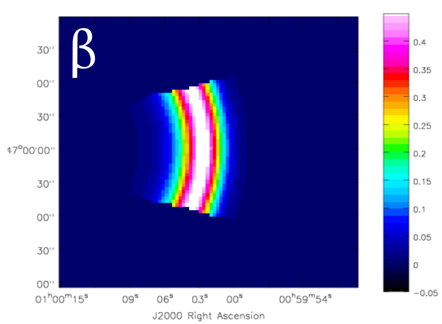
Intensity Image



Average Spectral Index

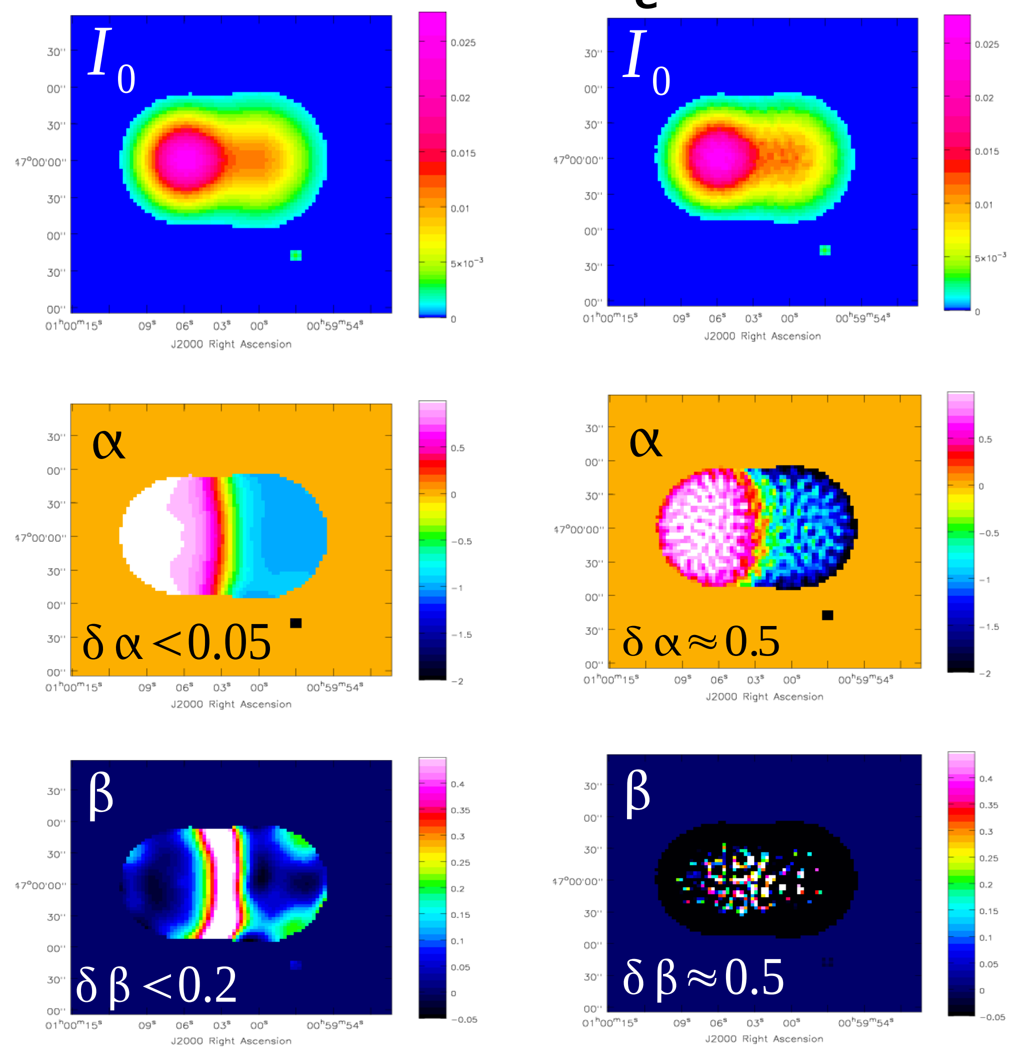


Gradient in Spectral Index



MFS

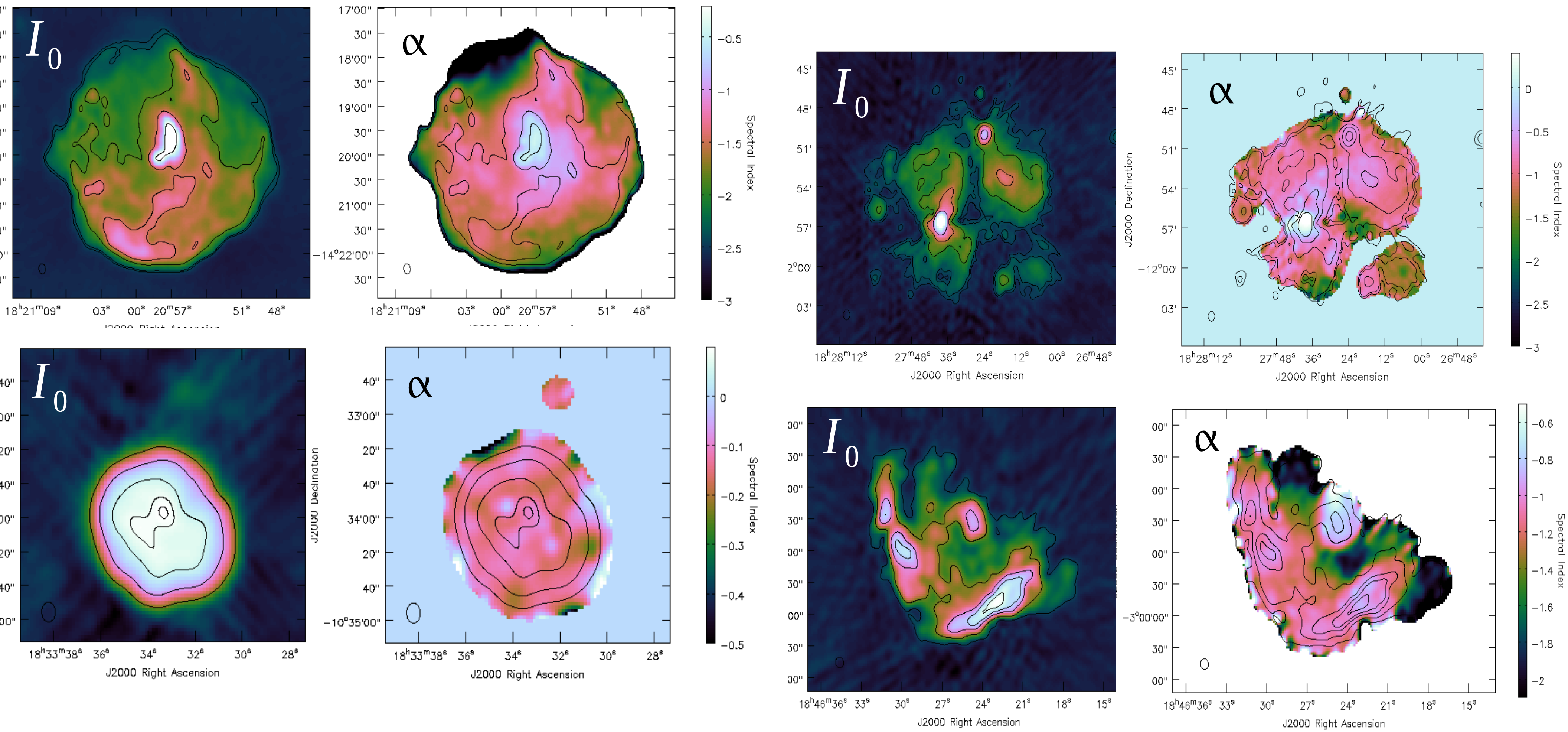
multi-scale | **point-source**



=> Spectral-index error is dominated by 'division between noisy images'
– a multi-scale model gives better spectral index and curvature maps

Supernova Remnants at L and C Band

[Bhatnagar et al, 2011]



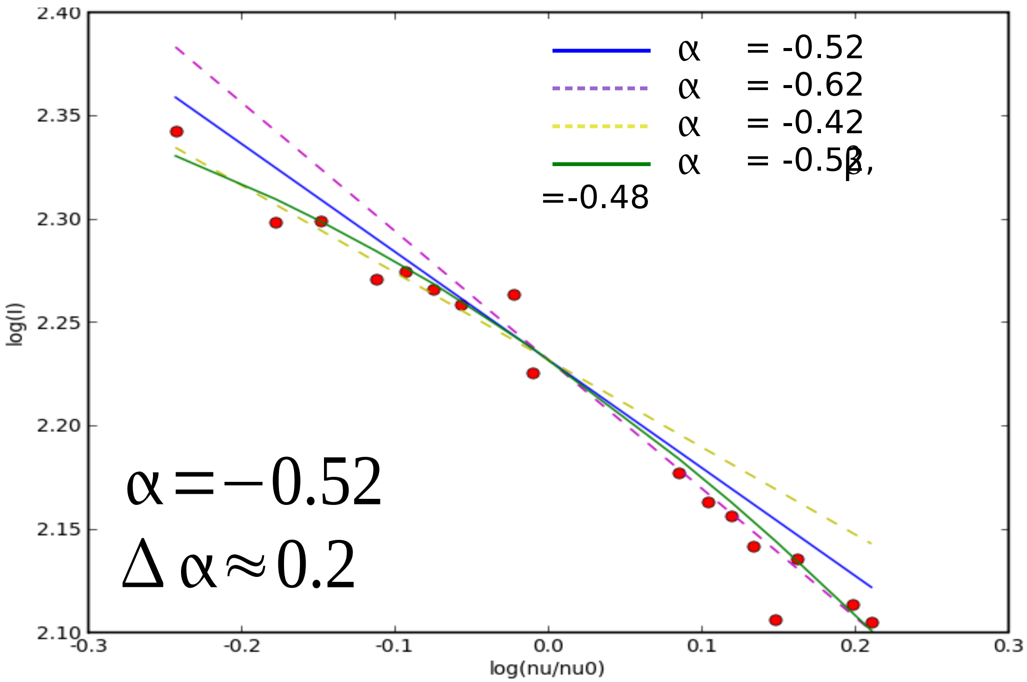
These examples used nterms=2, and about 5 scales.

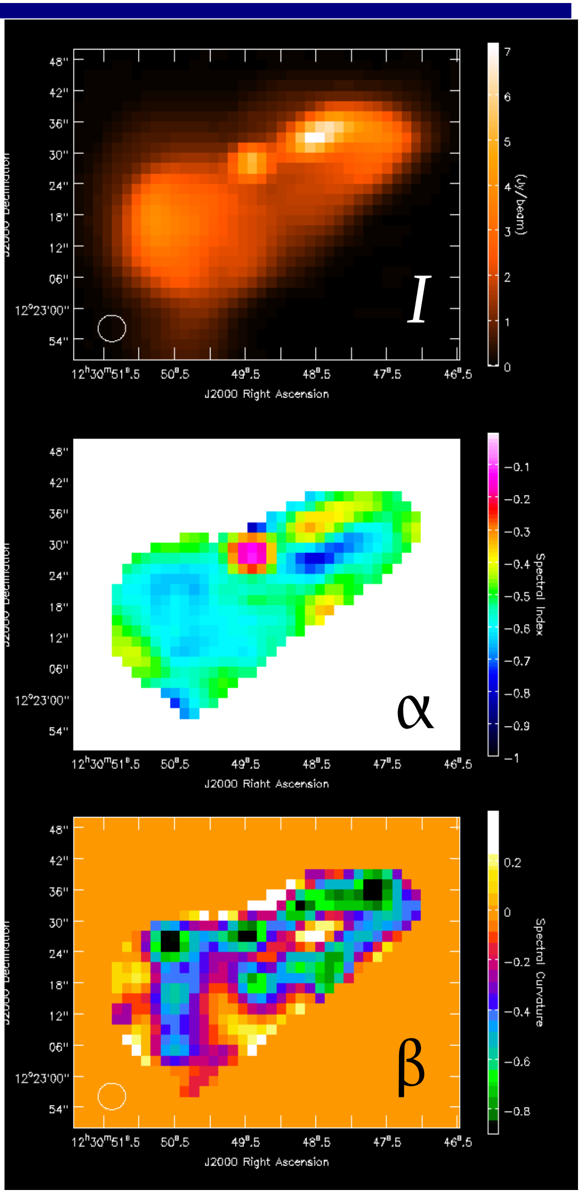
=> Within 1-2 Ghz and 4-8 GHz, spectral-index error is < 0.2 for SNR>100.

=> Dynamic-range limit of few x 1000 ---> residuals are artifact-dominated

Spectral Curvature

Data : 10 VLA snapshots at 16 frequencies (1.2 – 2.1 GHz)





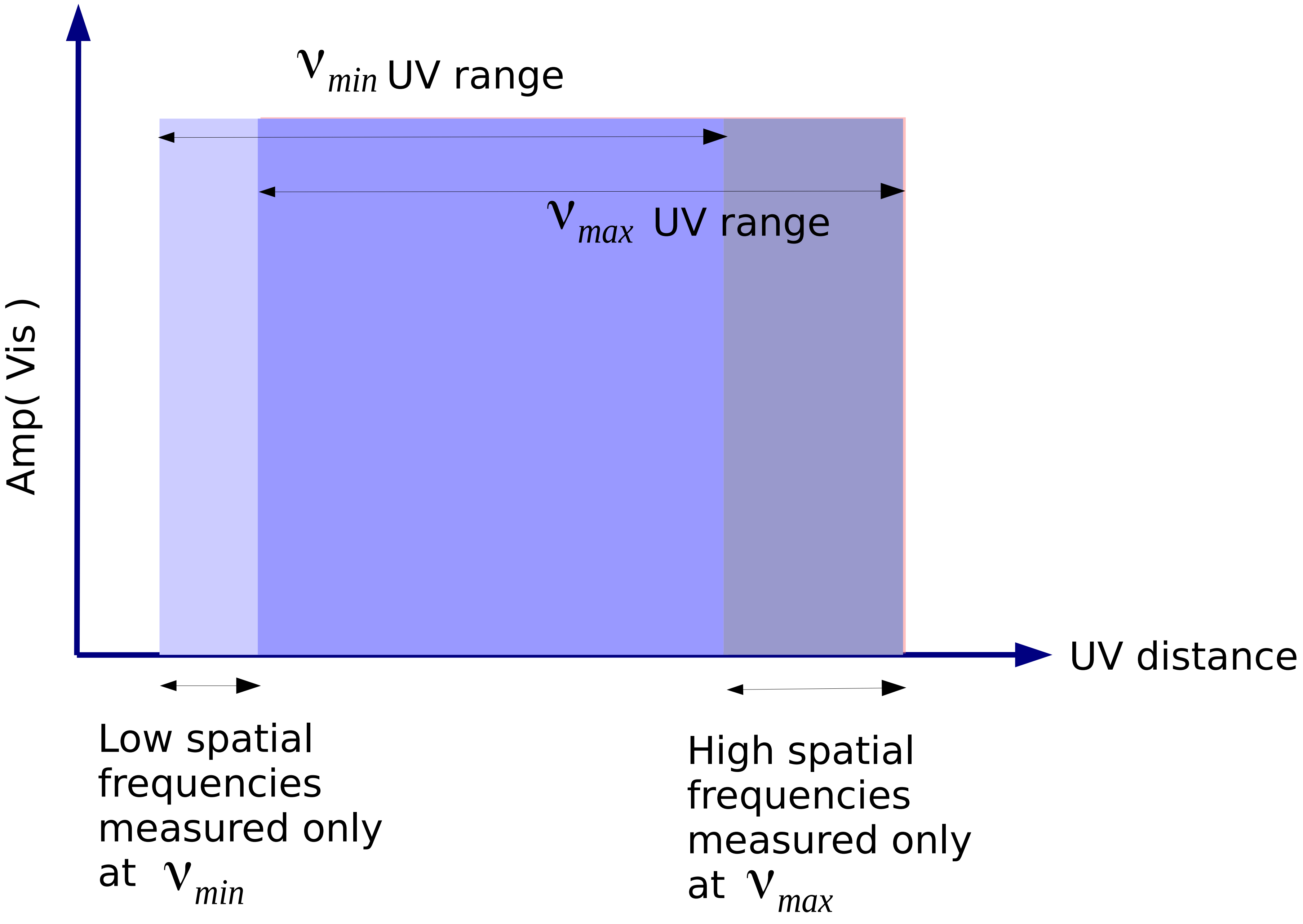
From existing P-band (327 MHz), L-band(1.42 GHz) and C-band (5.0 GHz) images of the core/jet

P-L spectral index : -0.36 ~ -0.45
L-C spectral index : -0.5 ~ -0.7

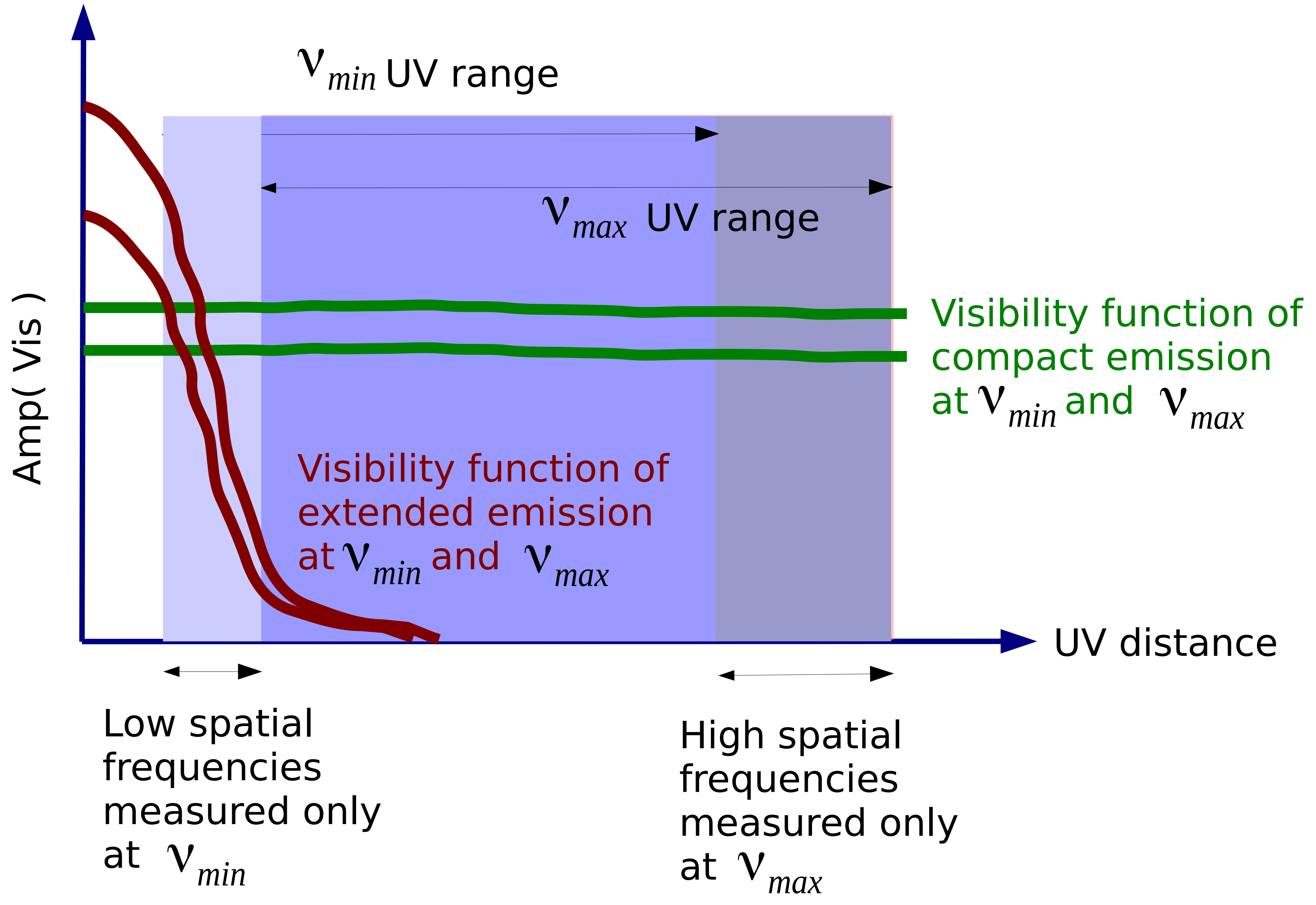
=> Need SNR > 100 to fit spectral index variation ~ 0.2 (at the 1-sigma level ...)

=> Be very careful about interpreting β

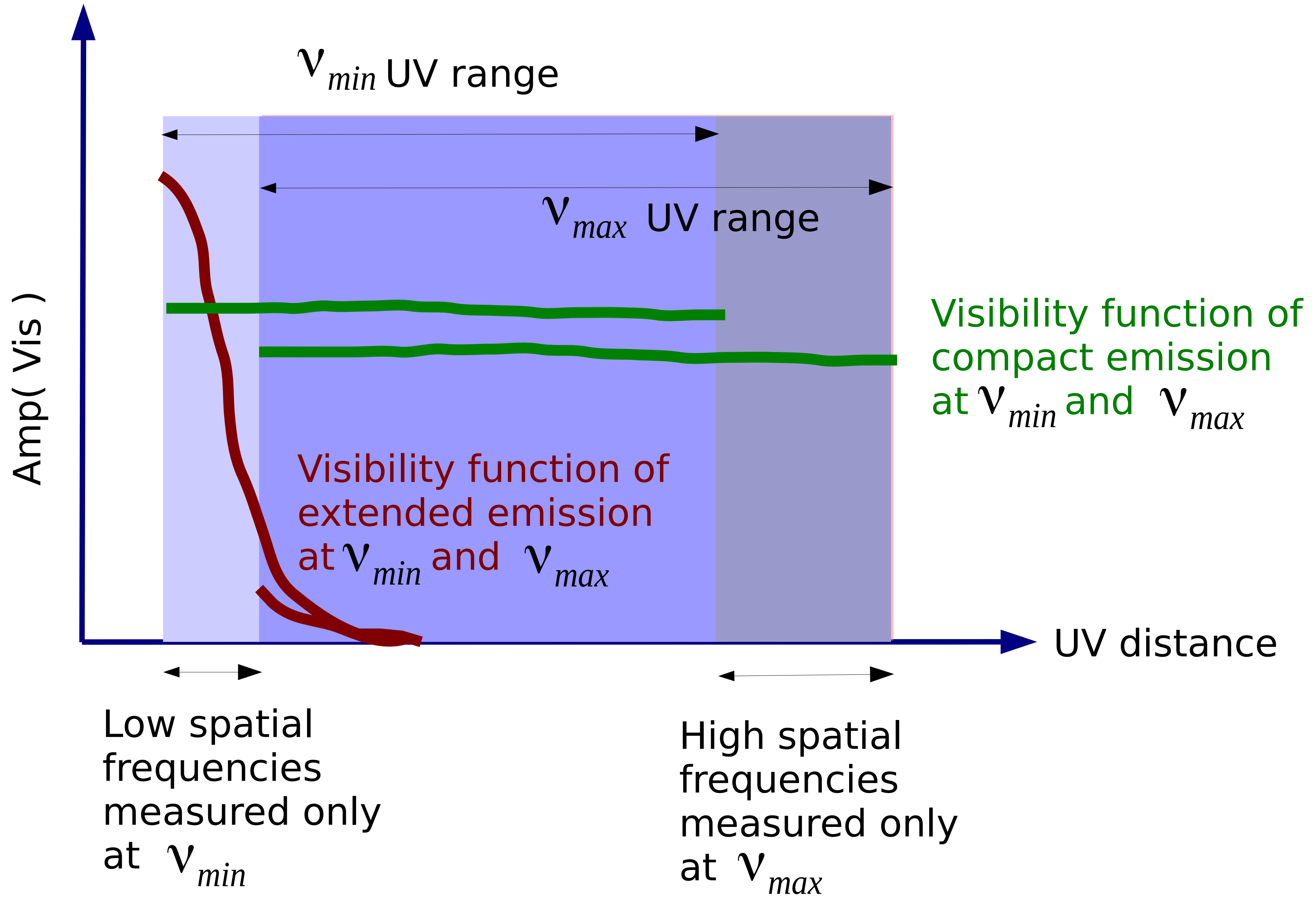
For which scales can we reconstruct the spectrum ?



For which scales can we reconstruct the spectrum ?

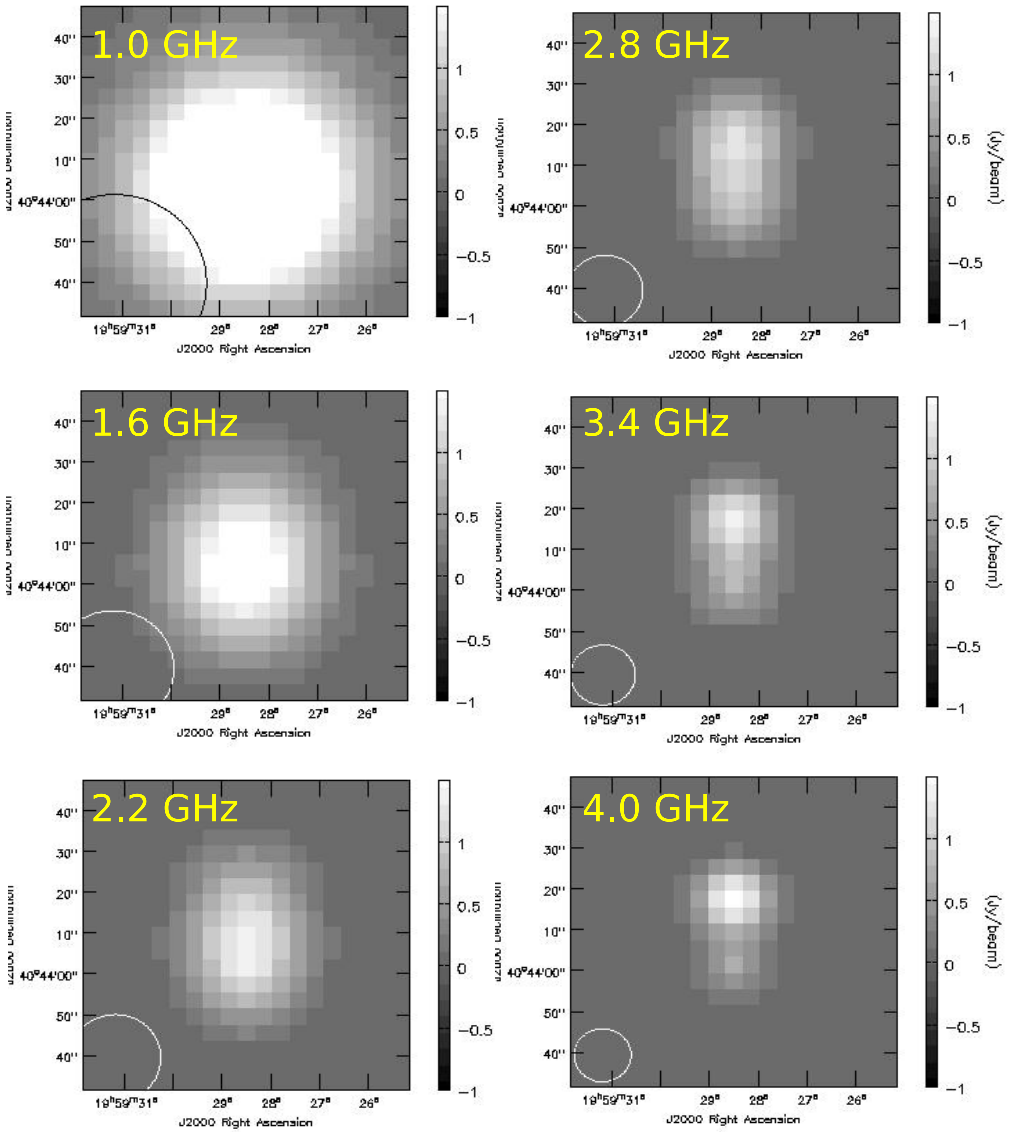


For which scales can we reconstruct the spectrum ?

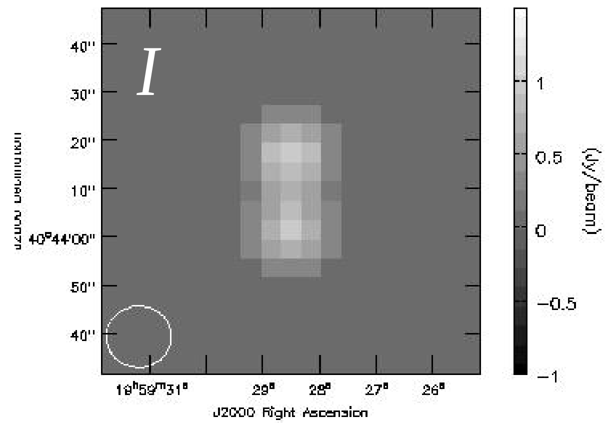


Moderately Resolved Sources + High SNR

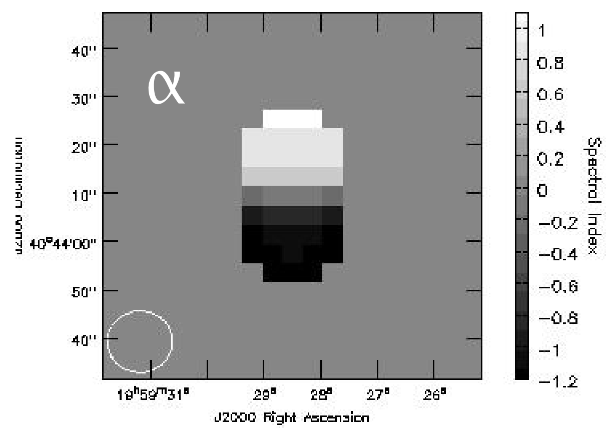
Can reconstruct the spectrum at the angular resolution of the highest frequency (only high SNR)



Restored Intensity image

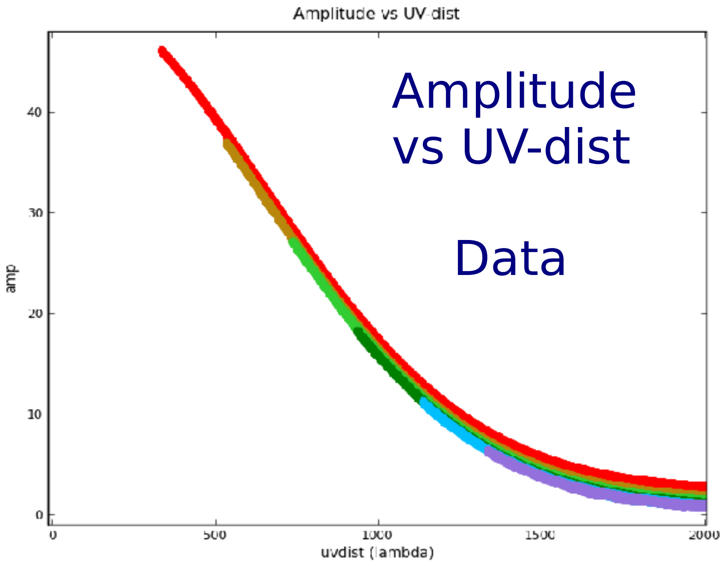


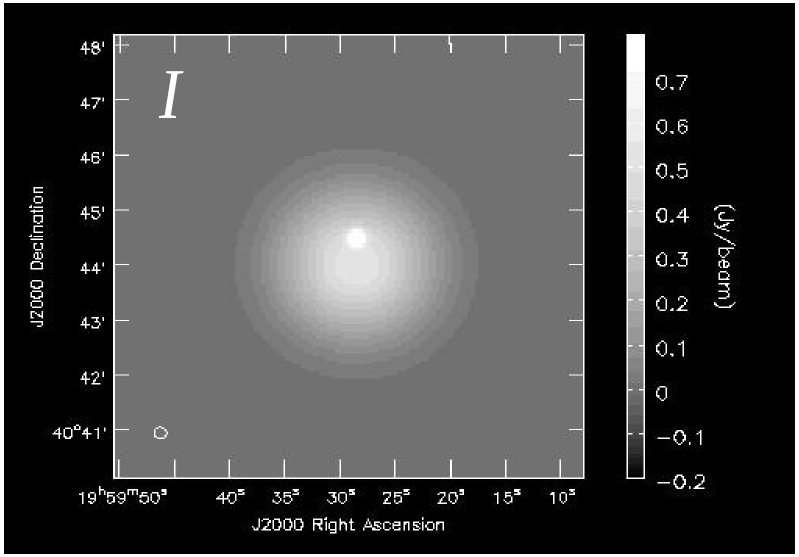
Spectral Index map



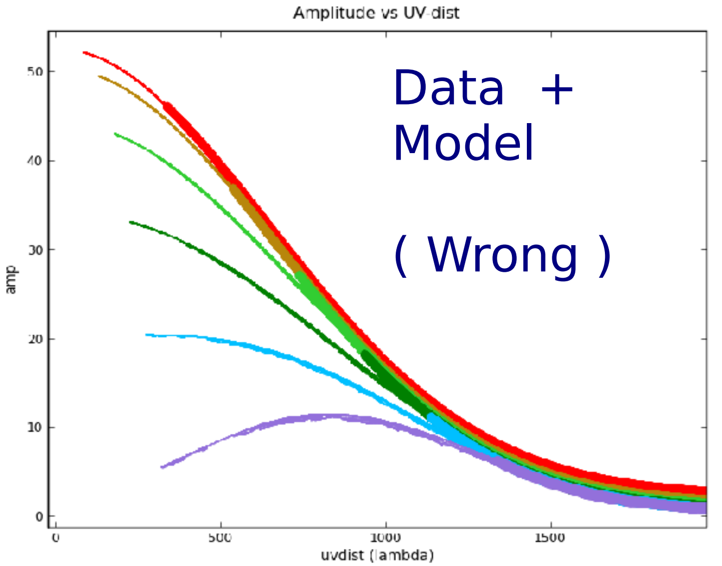
Very large spatial scales – Unconstrained spectrum

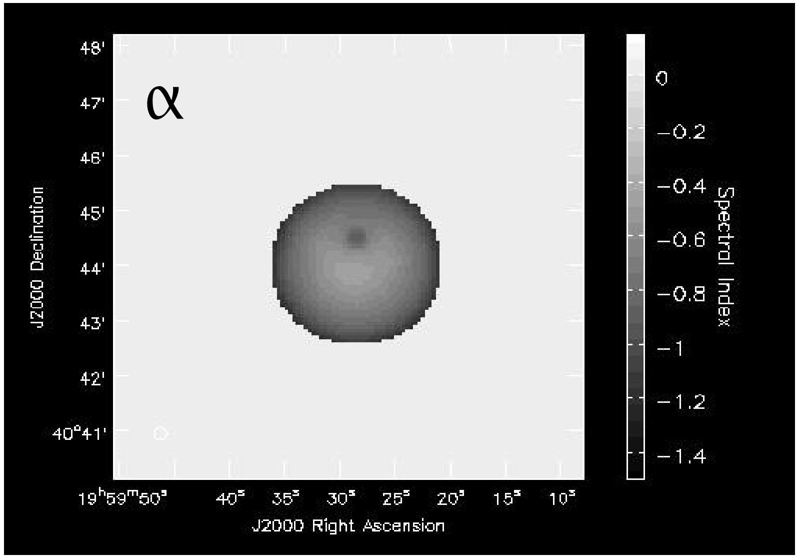
The spectrum at the largest spatial scales is NOT constrained by the data





True sky has one steep spectrum point, and a flat-spectrum extended emission



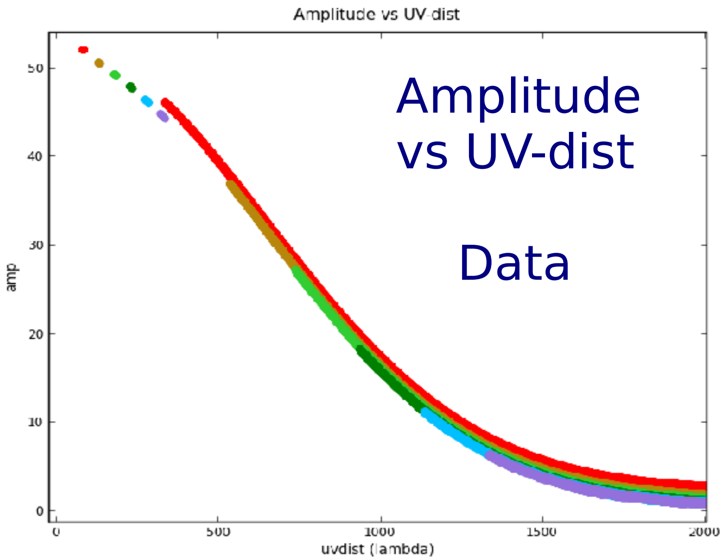


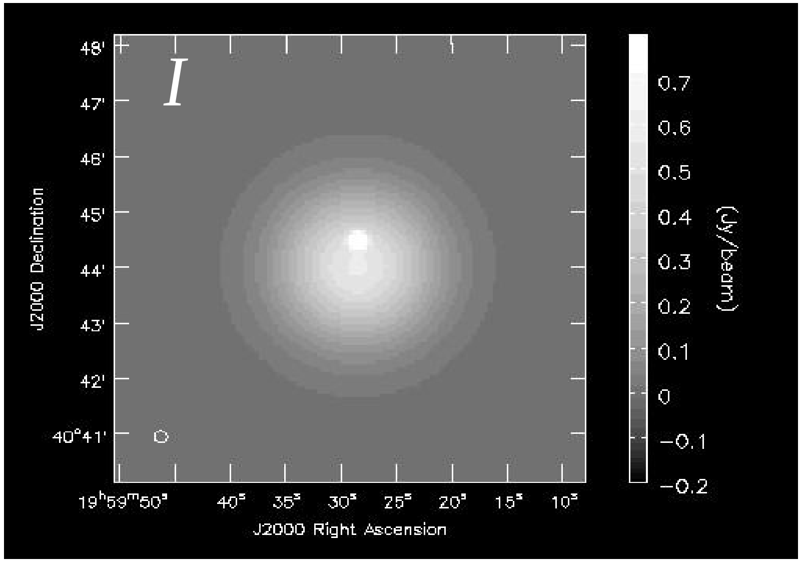
No short spacings to constrain the spectra

=> False steep spectrum reconstruction

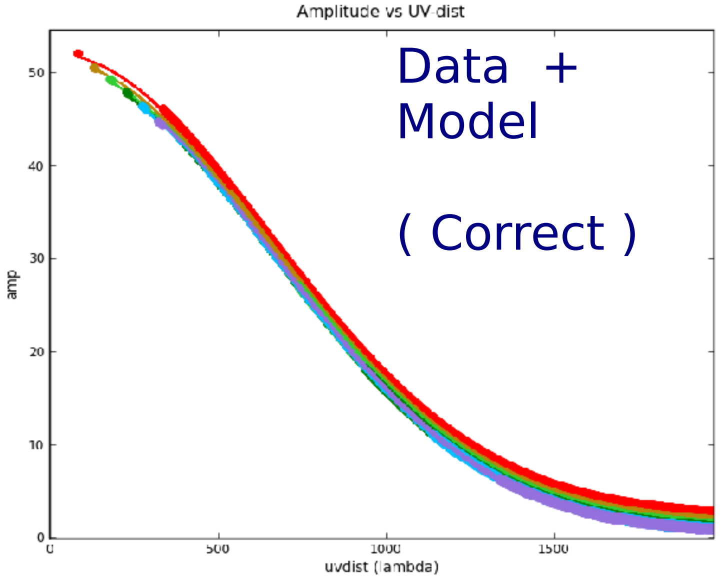
Very large spatial scales – Need additional information

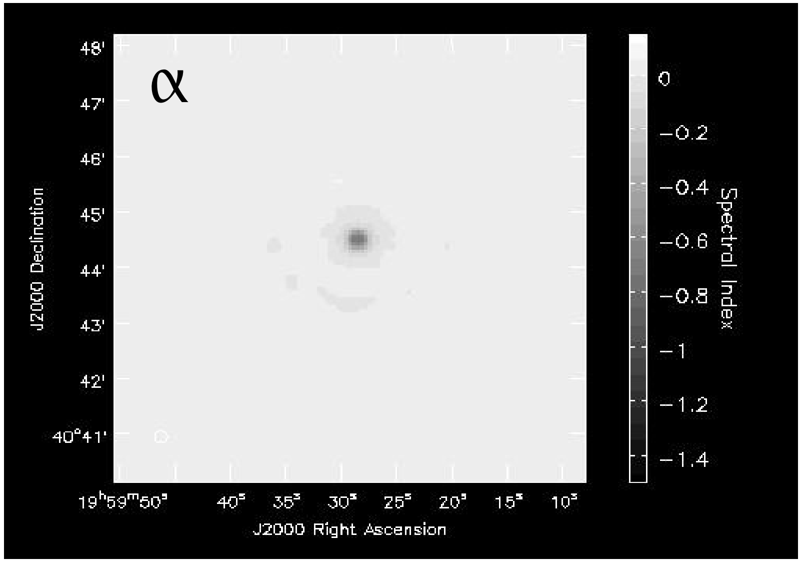
External short-spacing constraints (visibility data, or starting image model)





True sky has one steep spectrum point, and a flat-spectrum extended emission





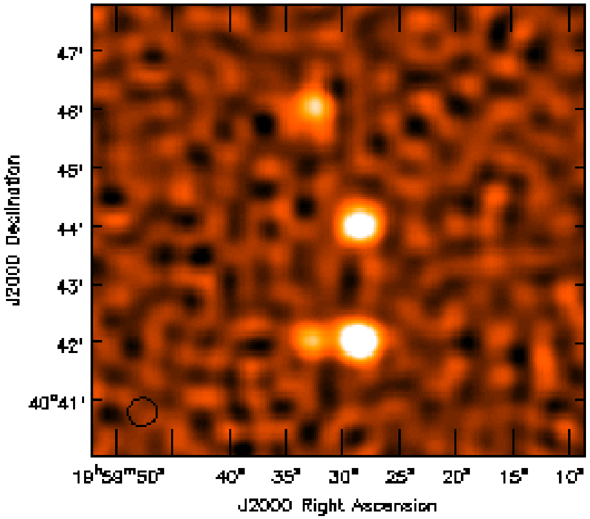
With short spacing info,

Correct reconstruction of a flat spectrum

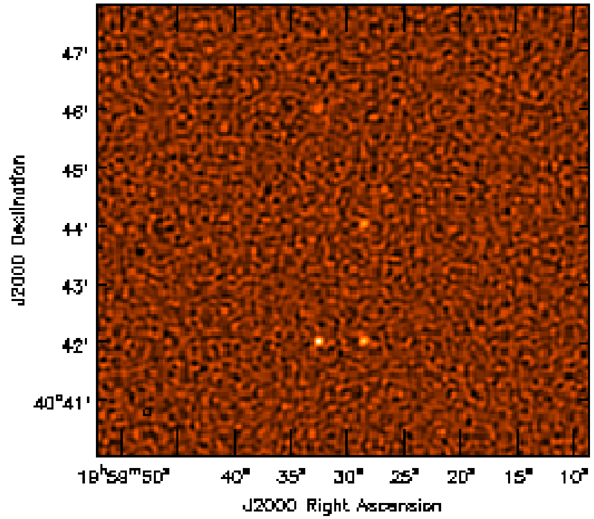
Spectral Index Accuracy (for low signal-to-noise)

Accuracy of the spectral-fit increases with larger bandwidth-ratio

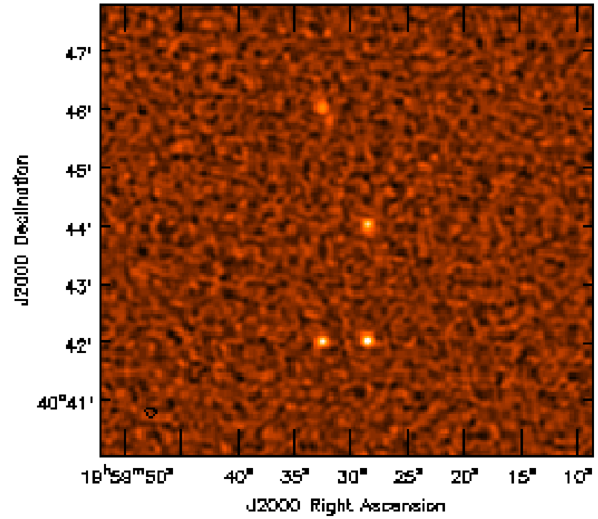
1 – 2 GHz, 4 hr



4 - 8 GHz , 4 hr



1 – 2 GHz, 4 - 8 GHz, 2 hrs each



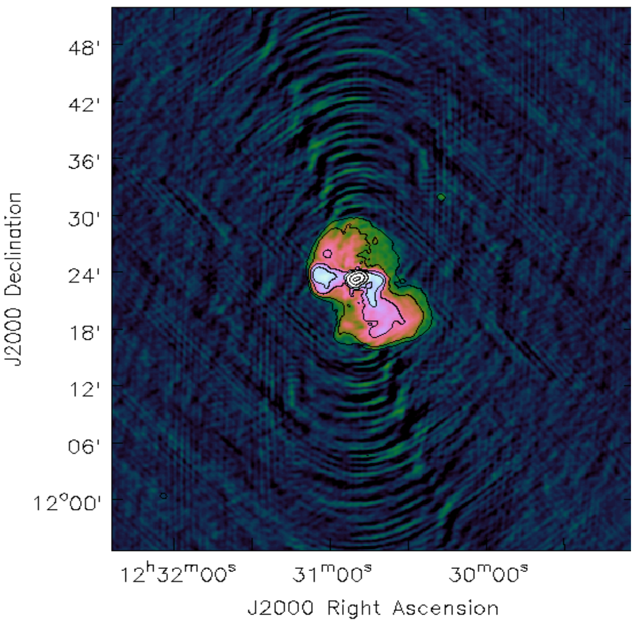
RMS
5 uJy/bm

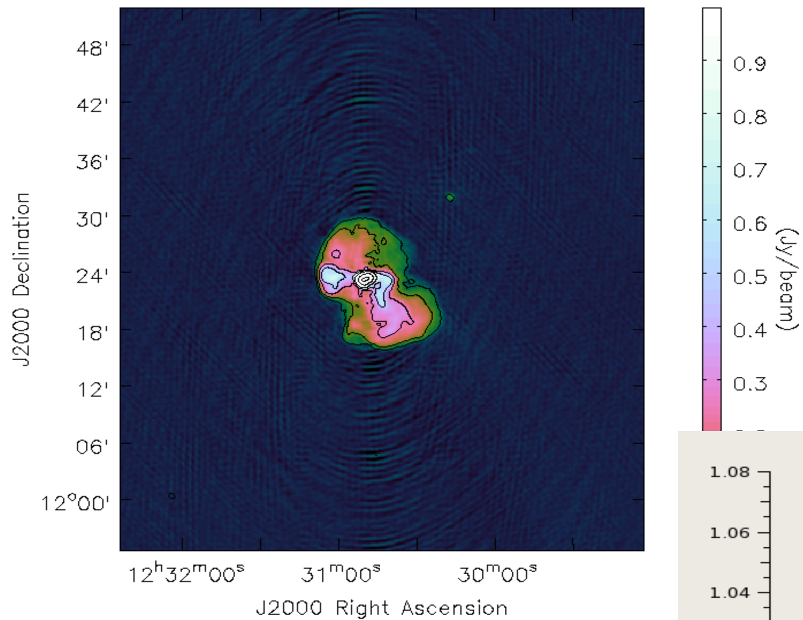
Source	Peak Flux	SNR	L alpha	C alpha	LC alpha	True
Bottom right	100 uJy	20	-0.89	-1.18	-0.75	-0.7
Bottom left	100 uJy	20	+0.11	+0.06	+0.34	+0.3
Mid	75 uJy	15	-0.86	-1.48	-0.75	-0.7
Top	50 uJy	10	-1.1	0	-0.82	-0.7

To trust spectral-index values, need SNR > 50 (within one band – 2:1)
For SNR < 50 need larger bandwidth-ratio.

Wide-band Self-Calibration (for HDR imaging)

-- First, get a wide-band sky model.
-- Follow with ‘bandpass’ calibration
-- Check amplitude solutions carefully before applying them.
(easy to impose an artificial spectrum on your data)

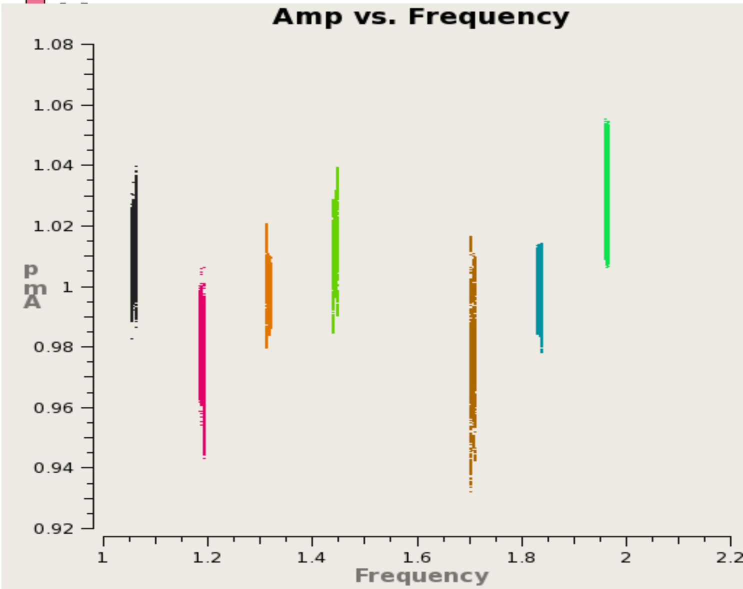




Dynamic range improved from ~2000 to ~4000.

Amplitudes of bandpass gain solutions

(< 5% from 1.0)

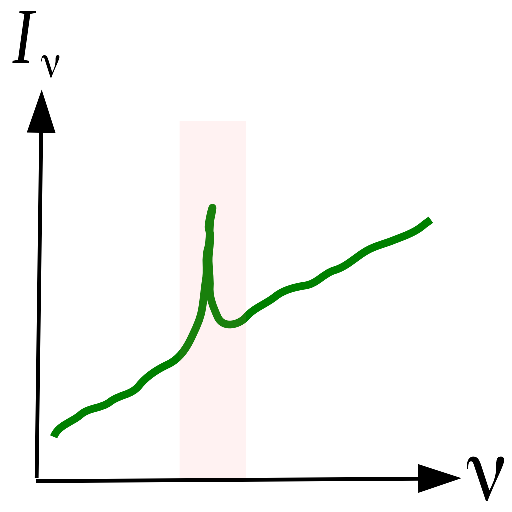


In these VLA data (of M87), each SPW had been calibrated, imaged, and phase self-cal’d separately, prior to joint MFS imaging and wide-band self-cal to smooth out the spectrum.

Using Wide-Band Models for other processing....

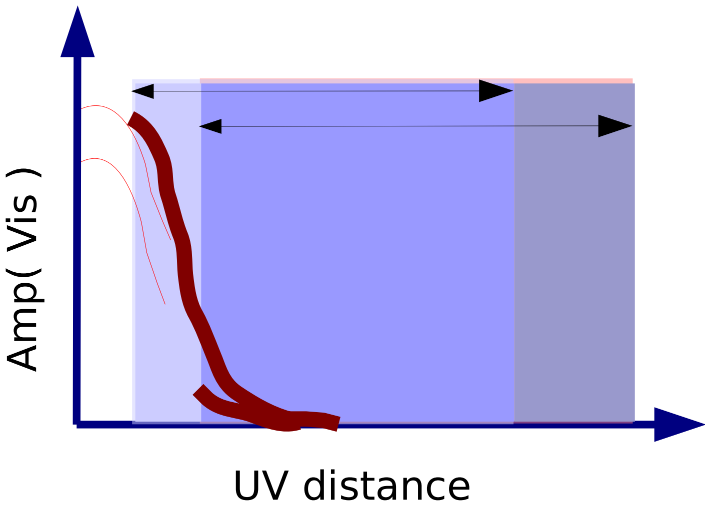
(1) Continuum Subtraction

- De-select frequency channels with spectral-lines
- Make a wide-band image model
- Predict model-visibilities over **all** channels
- Subtract these model visibilities from the data



(2) Combining with single-dish data

- Make Taylor-coefficient maps from multi-frequency single-dish images
- Use as a starting model in the MT-MFS interferometric reconstruction



Wide-Bandwidths and Polarization / Faraday-Rotation

Stokes Q,U,V can also change with frequency

- If the expected variation < ~1% of the peak, MFS (nt=1) will suffice
- If not, it is safest to make a Cube (as the spectra may not smooth)

Faraday Rotation-Measure Synthesis

Images of polarized surface-brightness at various Faraday-depths : $F(\phi)$

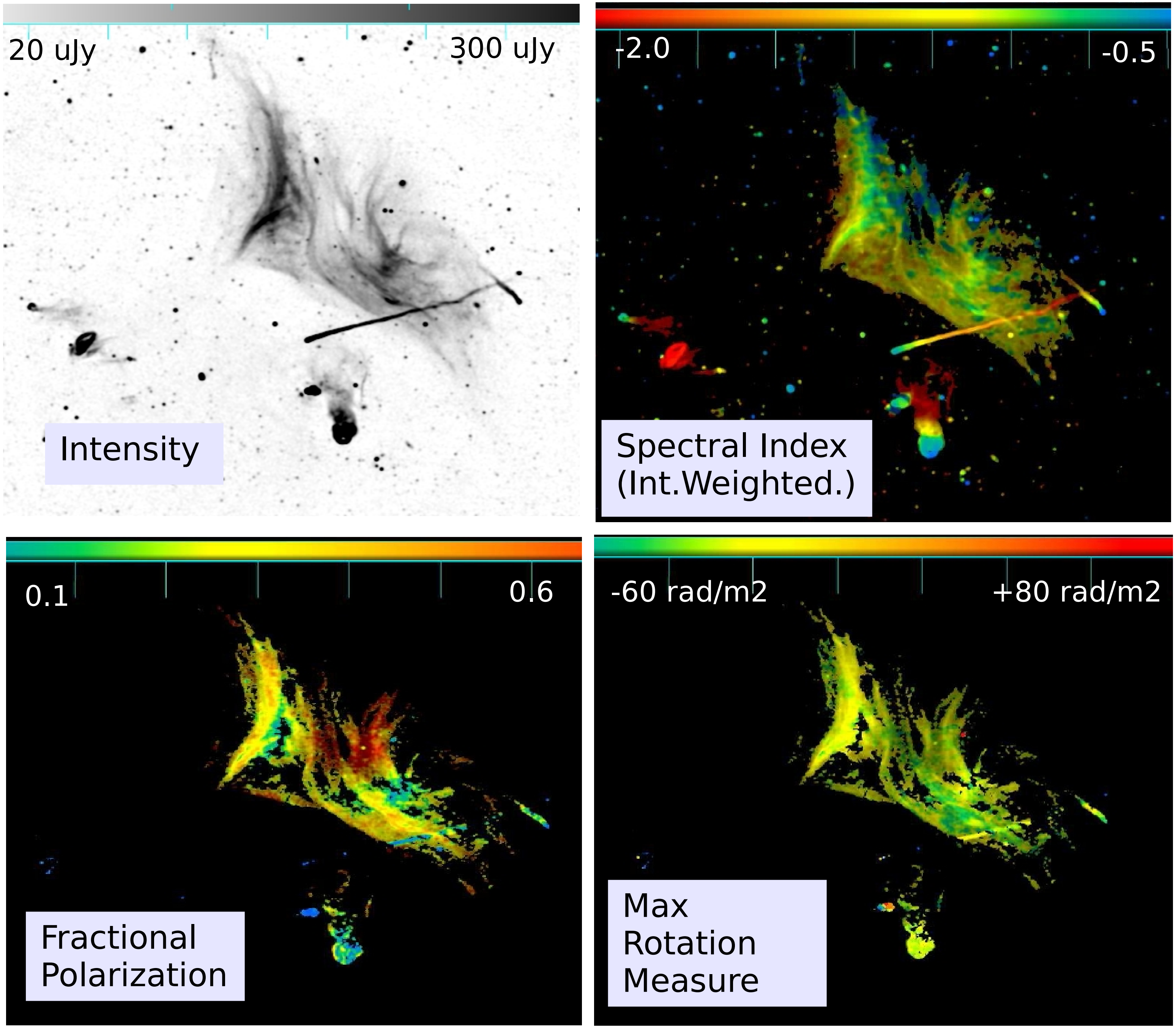
- P = Q + i U : Make spectral cubes for Q and U separately, and calculate P
- For each pixel in the P-cube, solve $P(\lambda^2) = \int F(\phi) e^{2\pi i \phi \chi^2} d\phi$ for $F(\phi)$

Brentjens, 2008, Bell et al, 2013

This calculation is currently done post-deconvolution, but it could be folded into the image reconstruction framework.

(Ref : Polarization in Interferometry" lecture)

Wideband VLA imaging of Abell 2256 *[Owen et al, 2014]*



VLA A,B,C,D at L-Band (1-2 GHz)

VLA A, at S&C bands(2-4, 4-6, 6-8 GHz)

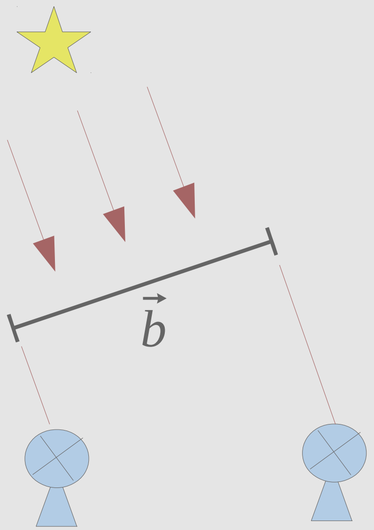
Calibration and Auto-flagging in AIPS.

Intensity and Spectral index Imaging in CASA. (with Pbcor only post-deconv.)

Polarization and Rotation Measure Imaging in AIPS.

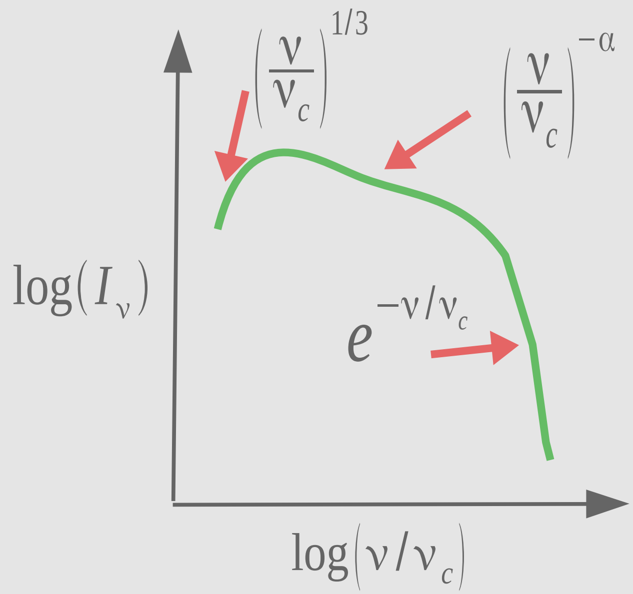
The instrument and the sky change with frequency...

UV-coverage



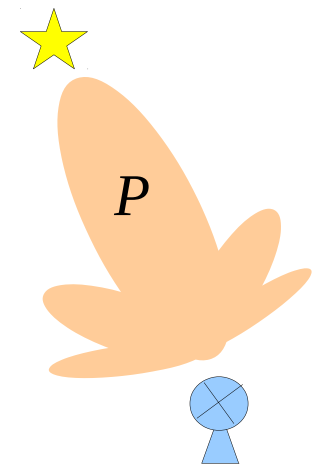
$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

Sky Brightness



$$I(\nu)$$

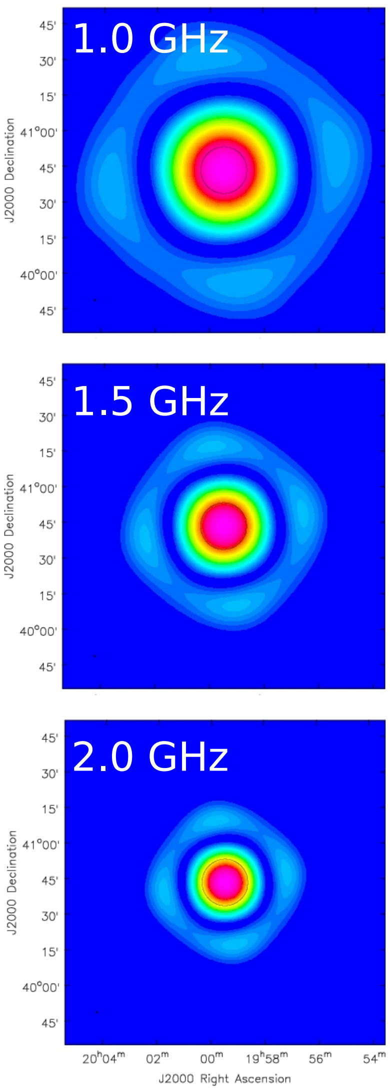
Primary Beam



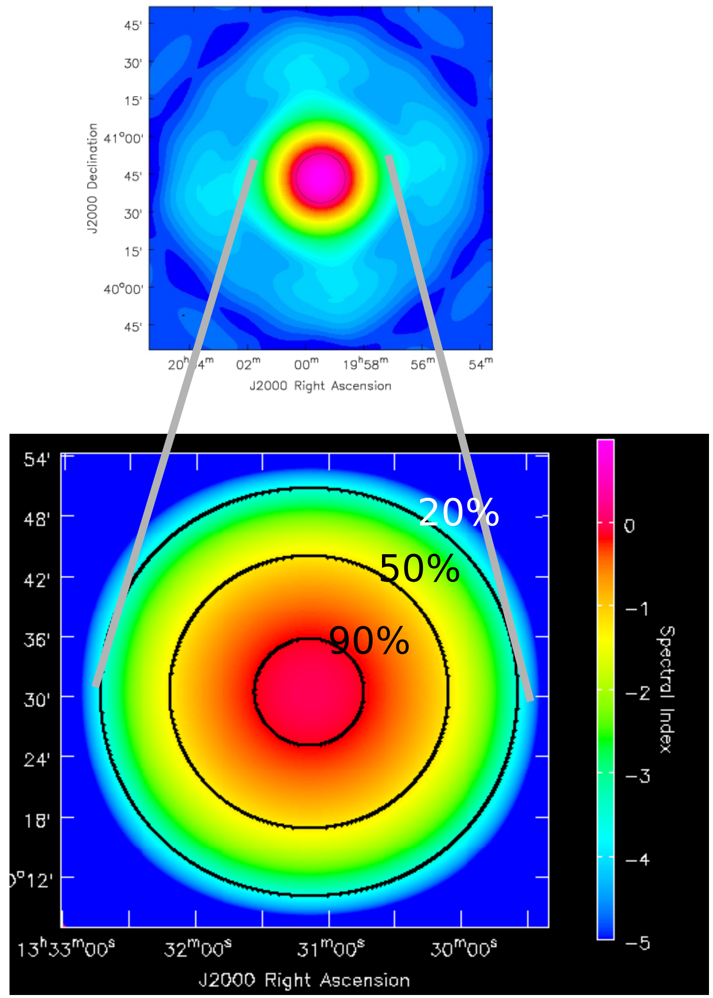
$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

Wide-Band Wide-Field Imaging : Primary Beams

VLA PBs



Average Primary Beam



Spectral Index of PB

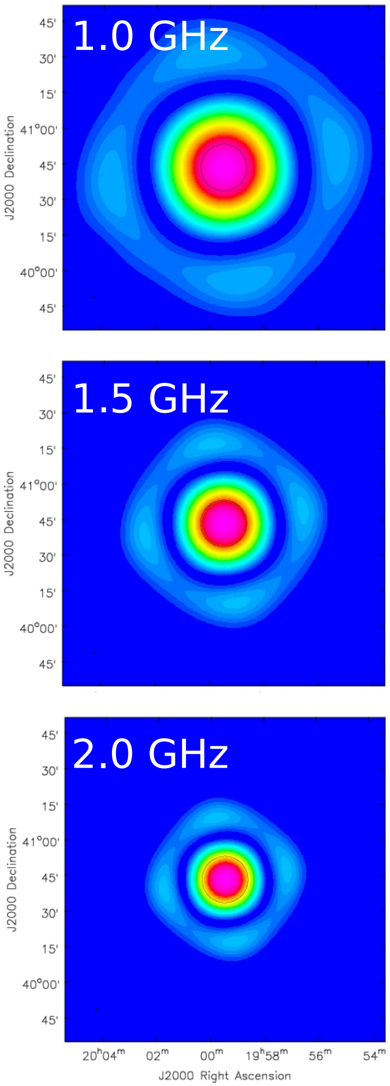
MFS : artificial 'spectral index' away from the center

For VLA L-Band (1-2 GHz)

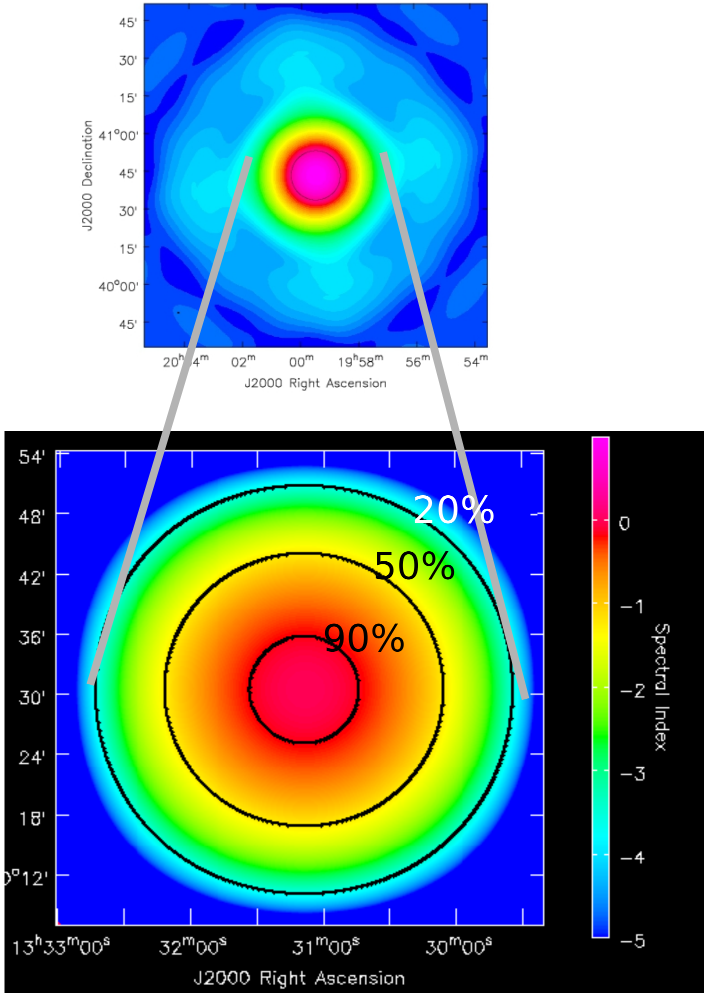
- About -0.4 at the PB=0.8
  (6 arcmin from the center)
- About -1.4 at the HPBW
  (15 arcmin from the center)

Wide-Band Wide-Field Imaging : Primary Beams

VLA PBs



Average Primary Beam



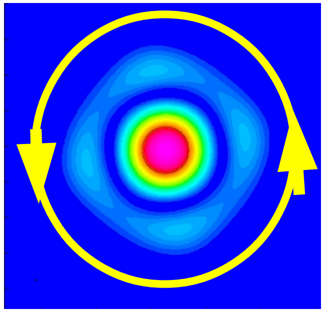
Spectral Index of PB

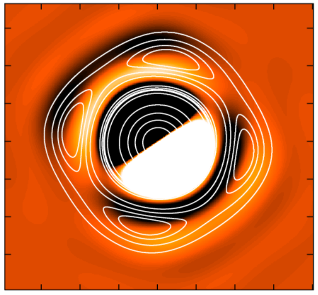
MFS : artificial 'spectral index' away from the center

For VLA L-Band (1-2 GHz)

- About -0.4 at the PB=0.8
  (6 arcmin from the center)
- About -1.4 at the HPBW
  (15 arcmin from the center)

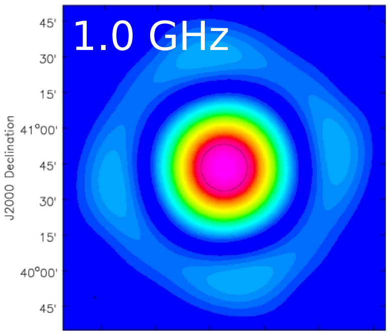
Primary beams also
- rotate with time
- have polarization structure
  (beam squint, etc...)

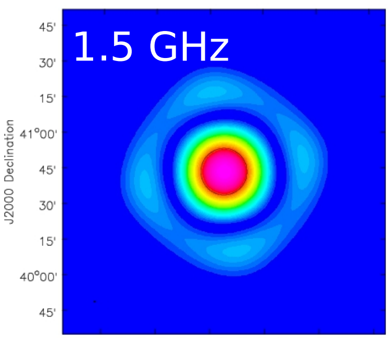


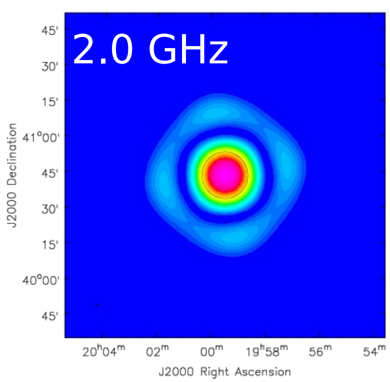


(Ref: Wide-Field Imaging – Full Beams lecture)

Wide-Band Primary Beam Correction







Cube Imaging

-- Sky model represents $I(\nu)P(\nu)$
-- Divide the output image at each frequency by $P(\nu)$

Multi-Term MFS Imaging

-- Taylor coefficients represent $I(\nu)P(\nu)$
-- Polynomial division by PB Taylor coefficients

$$\frac{\left(I_{0,}^{m} I_{1,}^{m} I_{2,}^{m} \ldots\right)}{\left(P_{0,} P_{1,} P_{2,} \ldots\right)} = \left(I_{0,}^{sky} I_{1,}^{sky} I_{2}^{sky} \ldots\right)$$

Wideband A-Projection

-- Remove $P(\nu)$ during gridding (before model fitting)
-- Also handles PB rotation/squint
-- Output spectral index image represents only the sky

Imaging Options : MT-MFS [y/n], A-Projection [y/n]

MT-MFS

Multi-term MFS (wideband) Imaging
+
Absorb PB spectrum into sky model
+
Post-deconvolution Wideband PBcor
for intensity and alpha

Sault &Wieringa 1994, Rau & Cornwell, 2011

MT-MFS + WB-A-Projection

Multi-term MFS with wideband A-Projection to remove PB spectrum during gridding
+
Minor cycle sees only sky spectrum
+
Post-deconvolution PBcor of intensity only.

Bhatnagar, Rau, Golap, 2013

Cube

Per channel Hogbom/Clark/CS Clean
+
Per channel post-deconvolution Pbcor
+
Smooth to lowest resolution
+
Fit spectrum per pixel, collapse chans

Hogbom 1974, Clark 1980, Schwab & Cotton 1983, Schwarz, 1978

Cube + A-Projection

Same as Cube,
- with narrow-band A-Projection per channel

(A-Projection : Construct gridding convolution operators from antenna aperture illumination models. Removes beam squint and accounts for aperture rotation)

Bhatnagar, Cornwell, Golap, Uson, 2004

Low dynamic range test (< 10^4) – compare four methods

MT-MFS

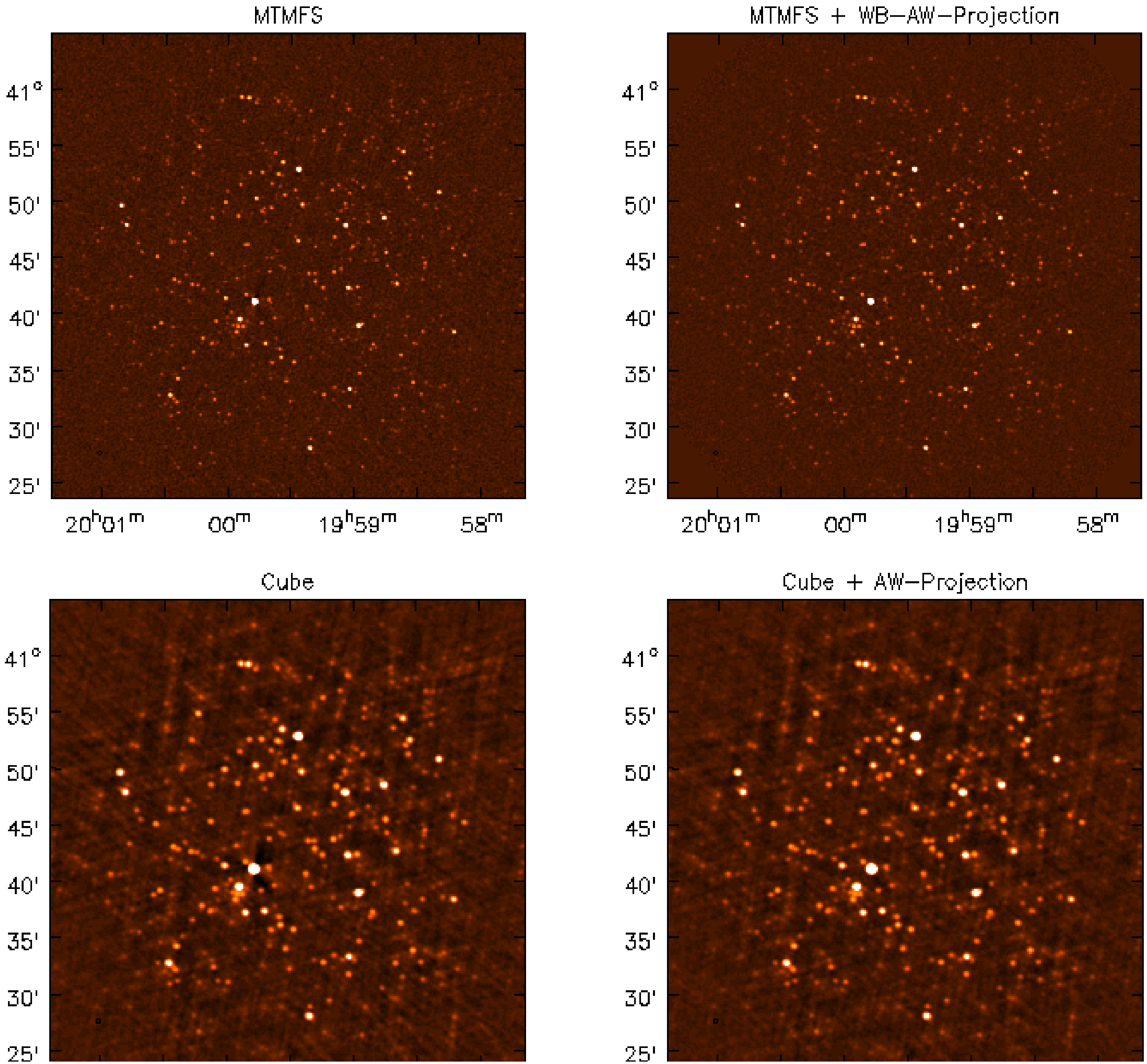
2 uJy rms

Brightest Source : 7 mJy

Cube

3 uJy rms

peak res : 9 uJy



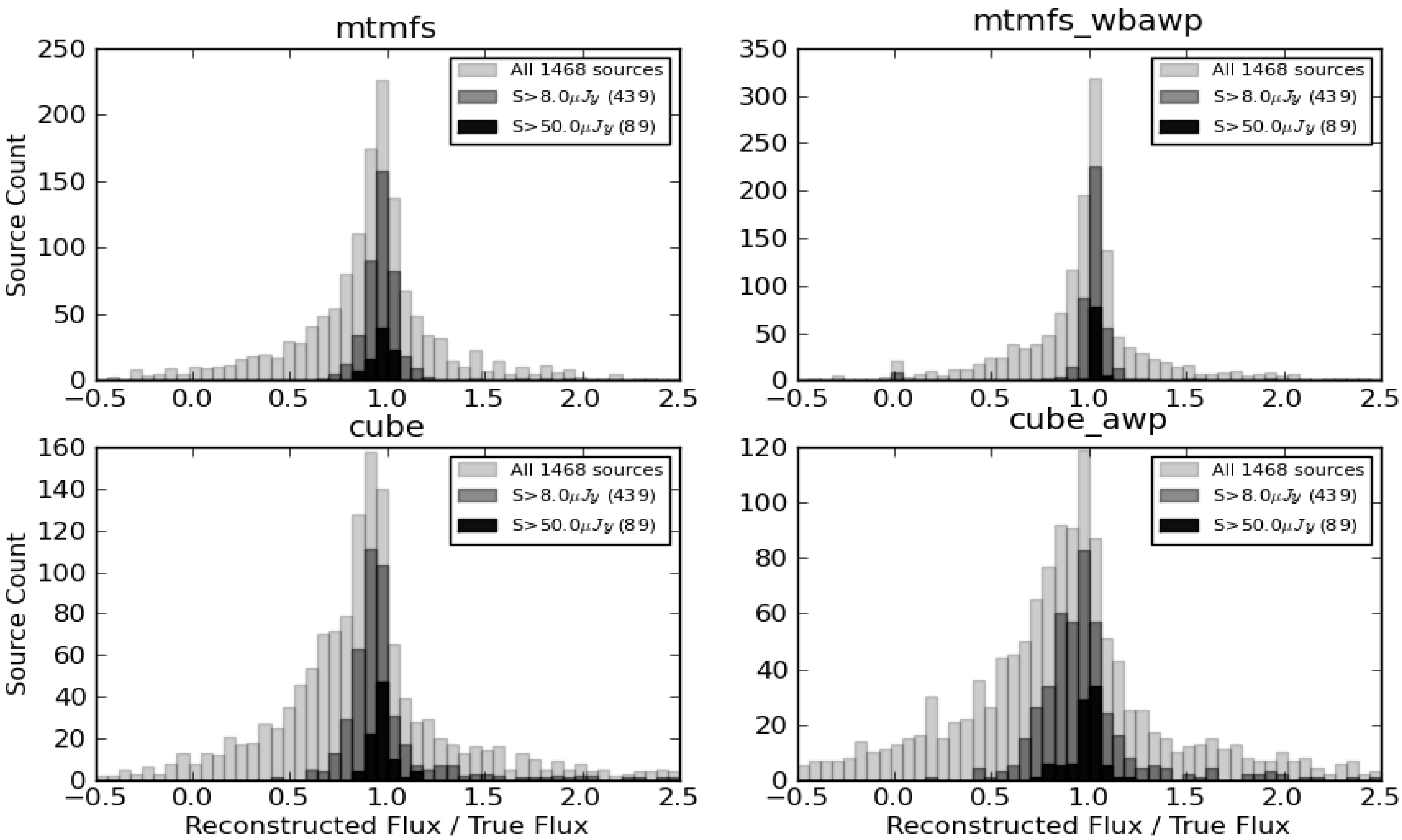
MT-MFS + WB-AWP

2 uJy rms

Cube + AWP

3 uJy rms

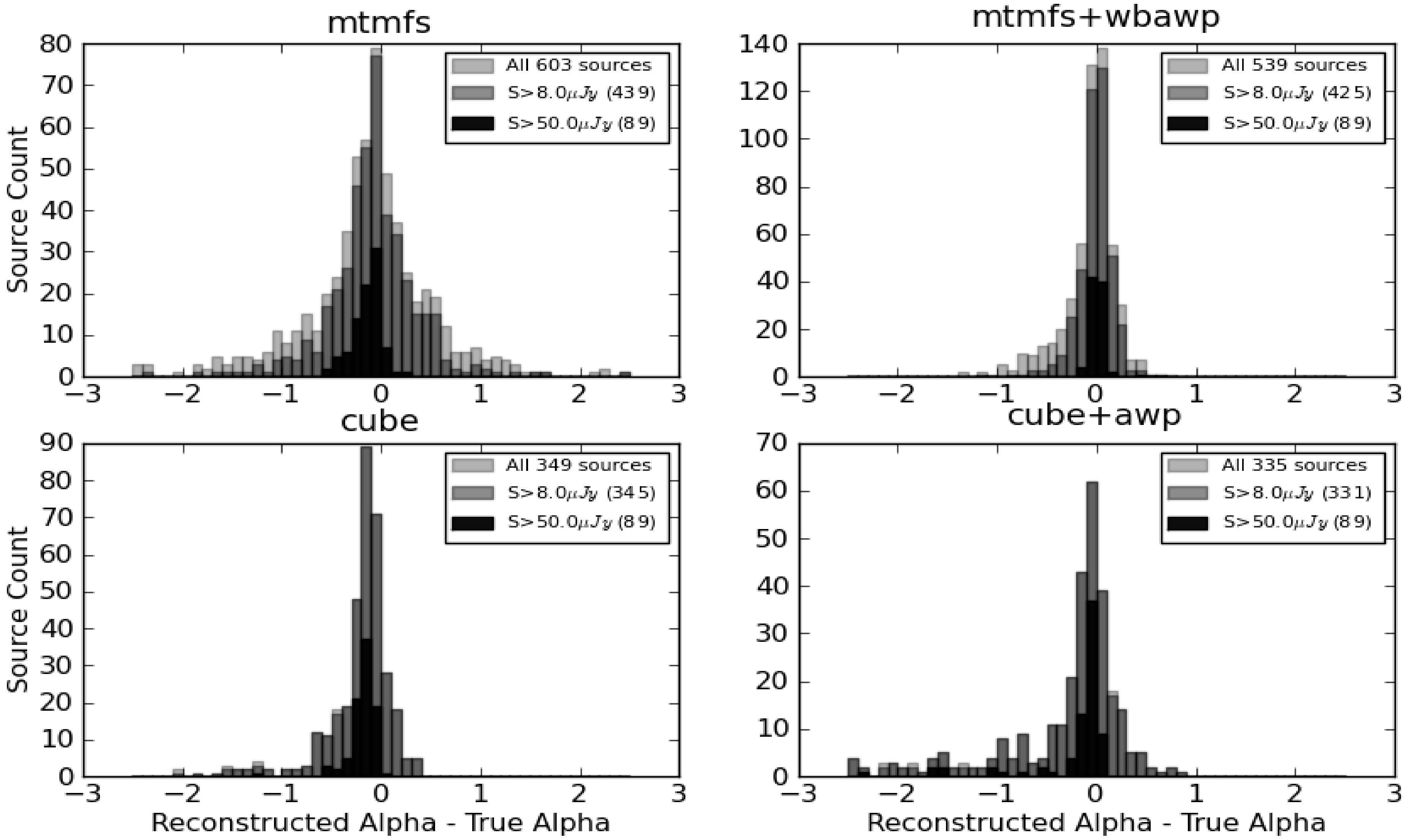
Histogram of Reconstructed / True Intensity



=> Brighter sources and MFS methods are more accurate

(Different shades in the plots indicate different source intensity ranges)

Histogram of Reconstructed – True Spectral Index



=> Spectral index accuracy degrades faster than intensity...

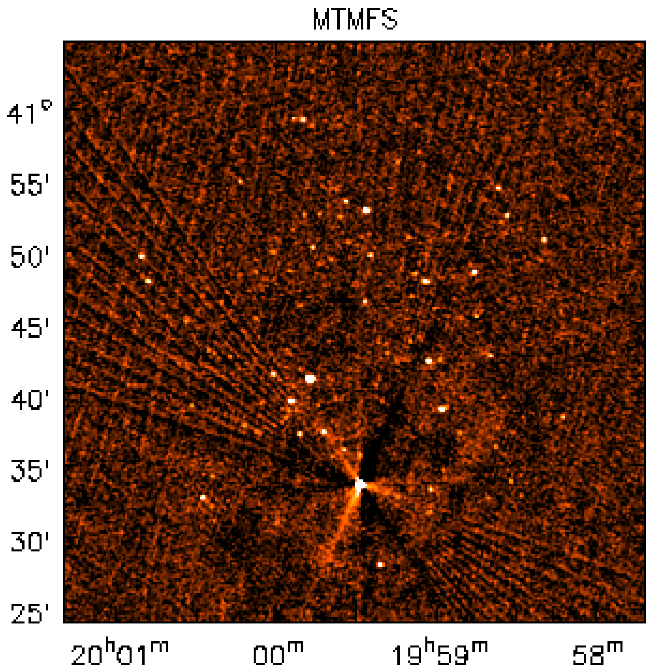
(Different algorithms produced different #s of usable spectral indices)

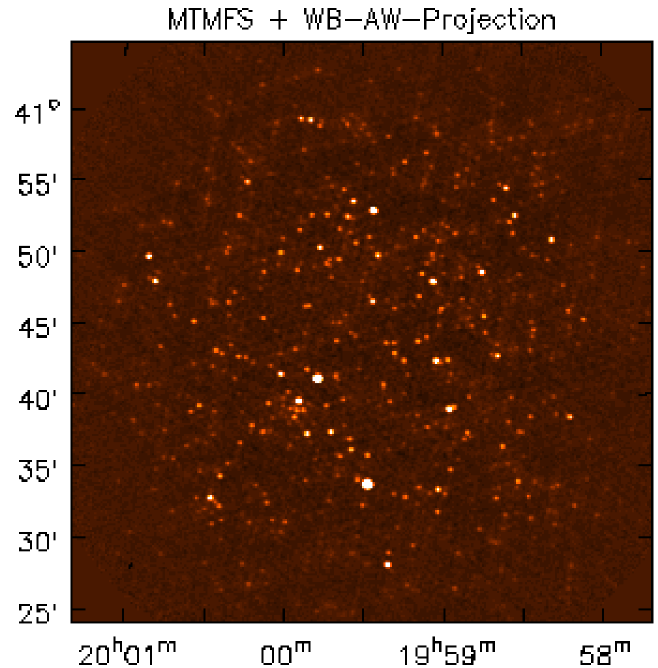
High dynamic range test (>10^4) - compare four methods

MT-MFS

6 uJy rms*

peak res :
15 uJy





MT-MFS
+
WB-AWP

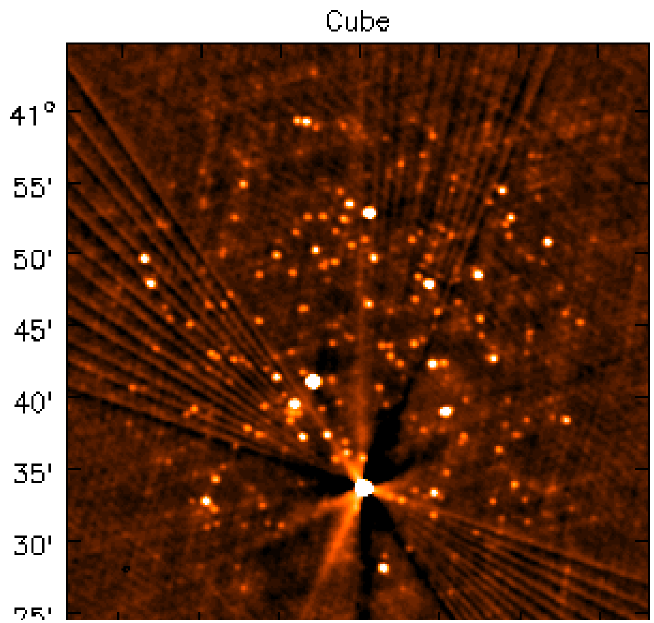
2 uJy rms

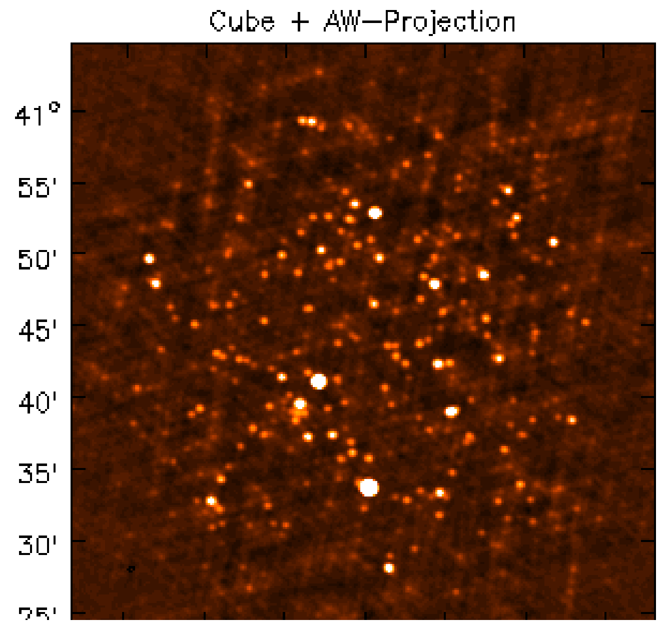
Brightest
Source :
100 mJy

Cube

4 uJy rms

peak res :
20 uJy



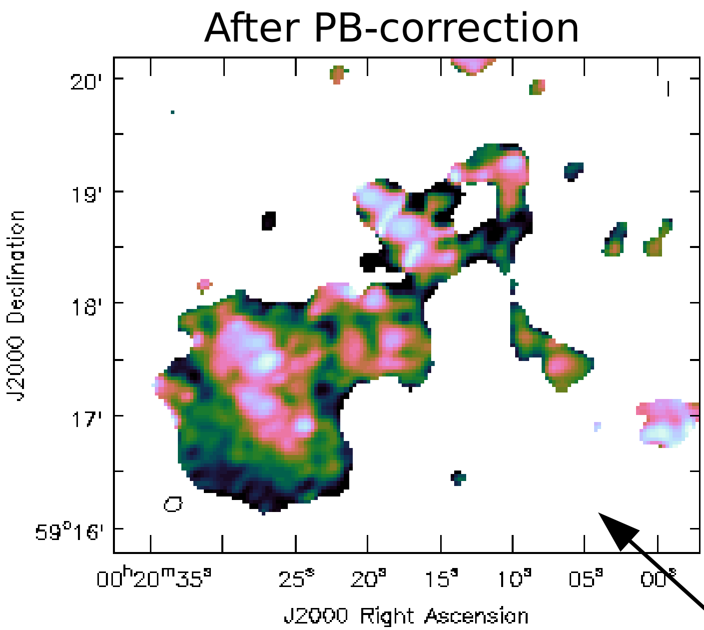


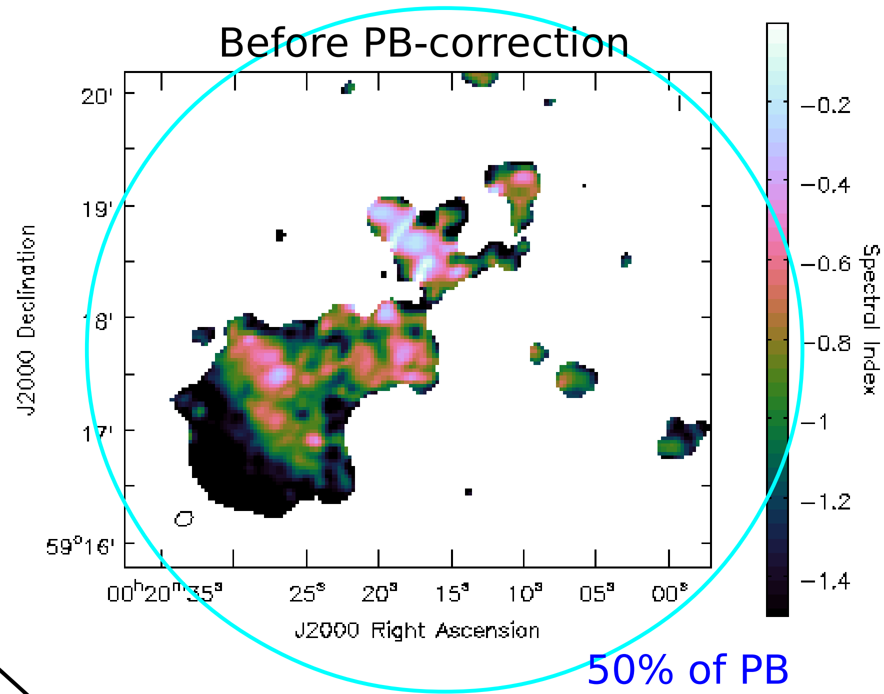
Cube
+
AW-Proj

3 uJy rms

Wideband VLA imaging of IC10 Dwarf Galaxy

[Heesen et al, 2011]

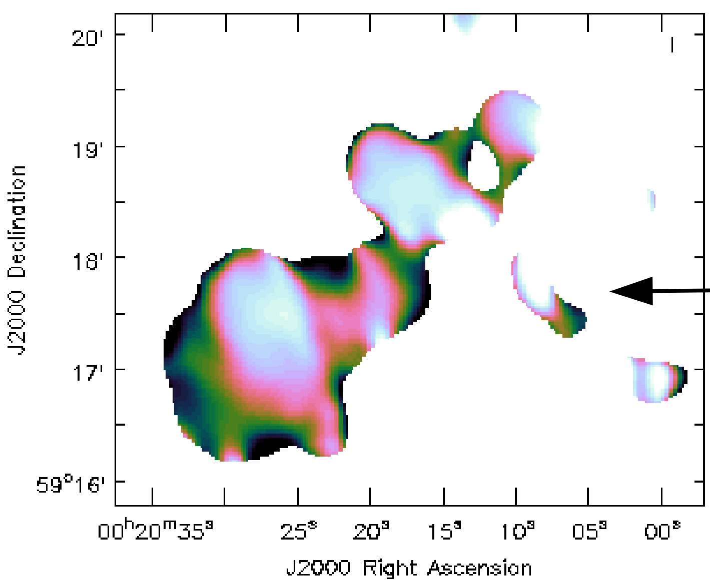




IC10 Dwarf Galaxy :

Spectral Index across C-Band.

Dynamic-range ~ 2000

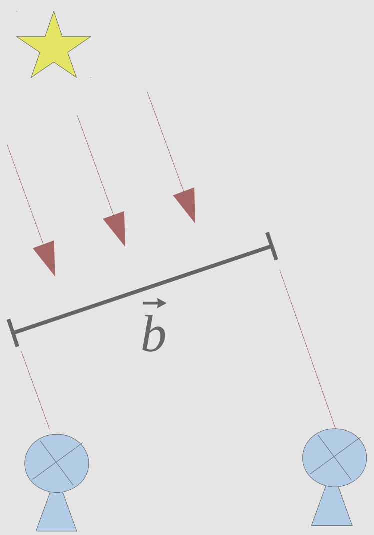


MT-MFS : Wide-band PB-correction after multi-term multi-scale MFS.

Cube : Spectral-index map made by cube imaging, smoothing to lowest resolution, and spectral fitting.

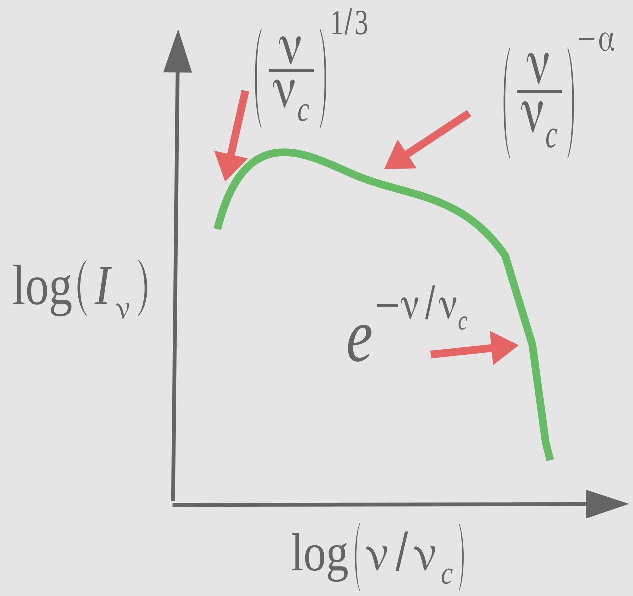
The instrument and the sky change with frequency...

UV-coverage



$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

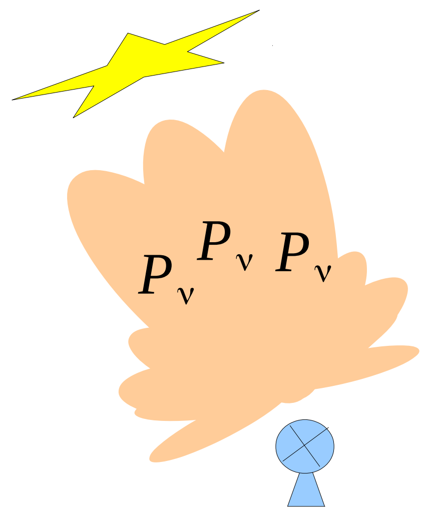
Sky Brightness



$$I(\nu)$$

Primary Beams

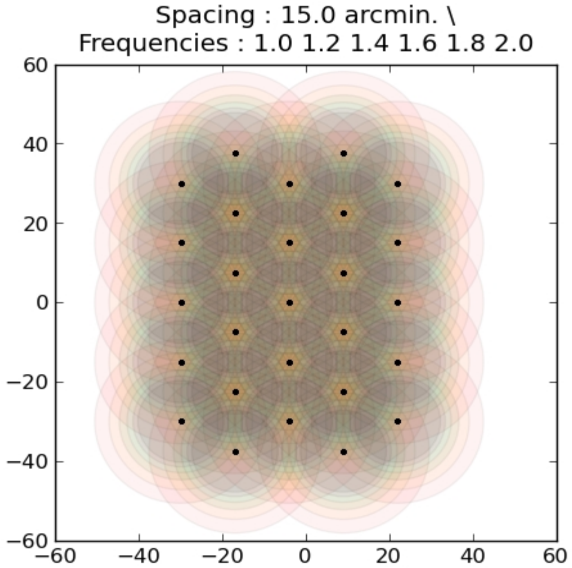
(Mosaic)

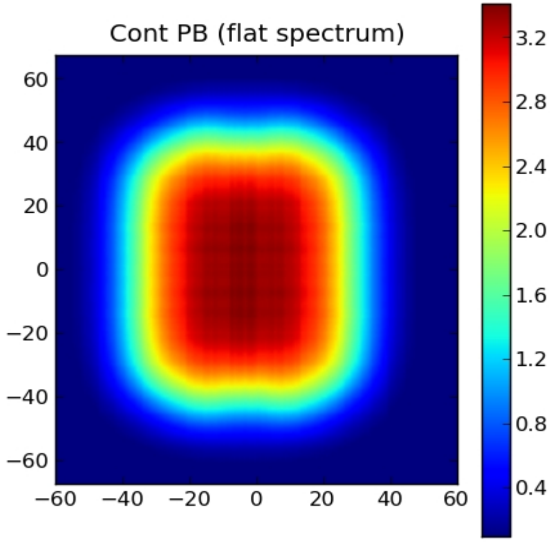


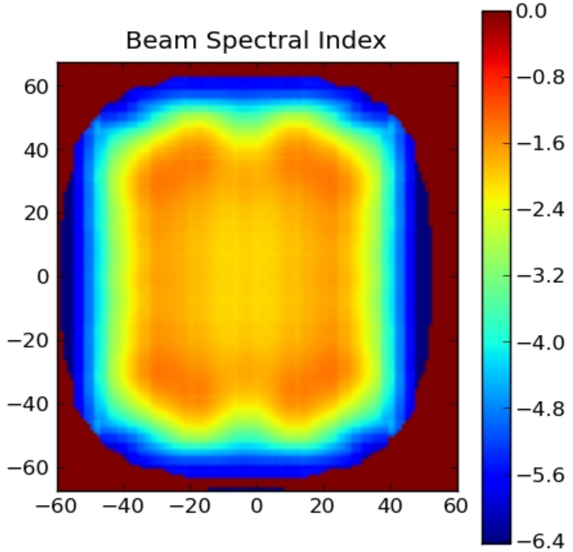
$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

Wide-Band Wide-Field Imaging : Mosaics

The mosaic primary beam has an artificial spectral index all over the FOV

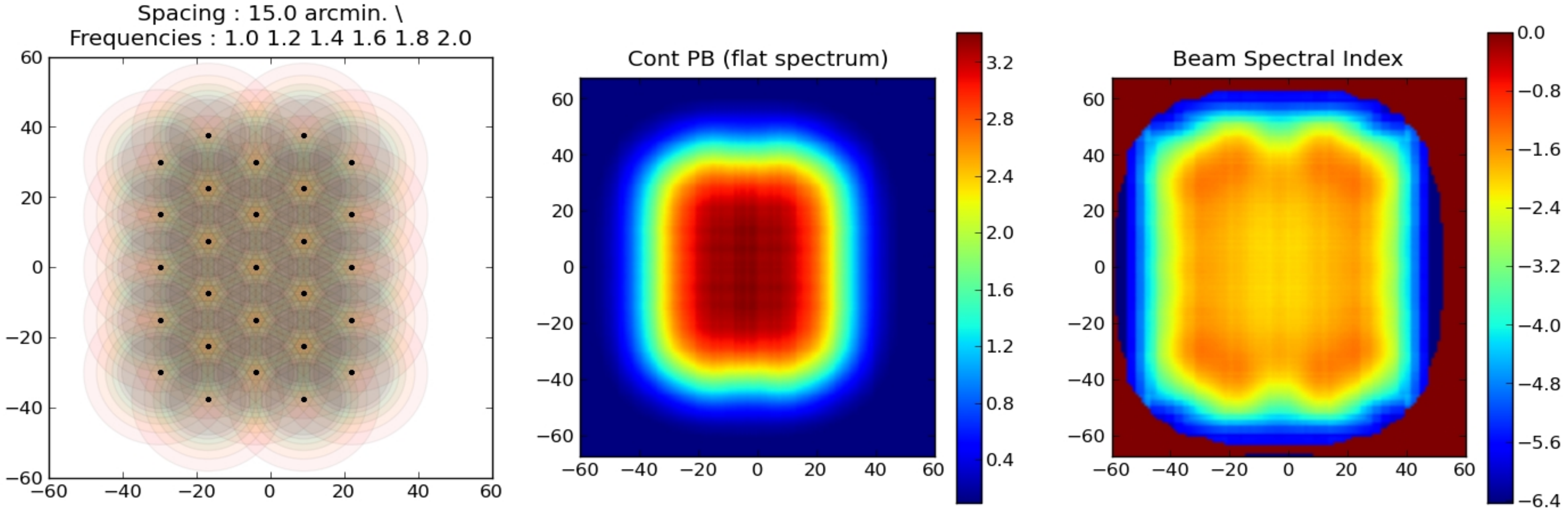






Wide-Band Wide-Field Imaging : Mosaics

The mosaic primary beam has an artificial spectral index all over the FOV



Algorithms :

- Deconvolve Pointings separately or together (Stitched vs Joint Mosaic)
  - Impacts image fidelity, especially of common sources.

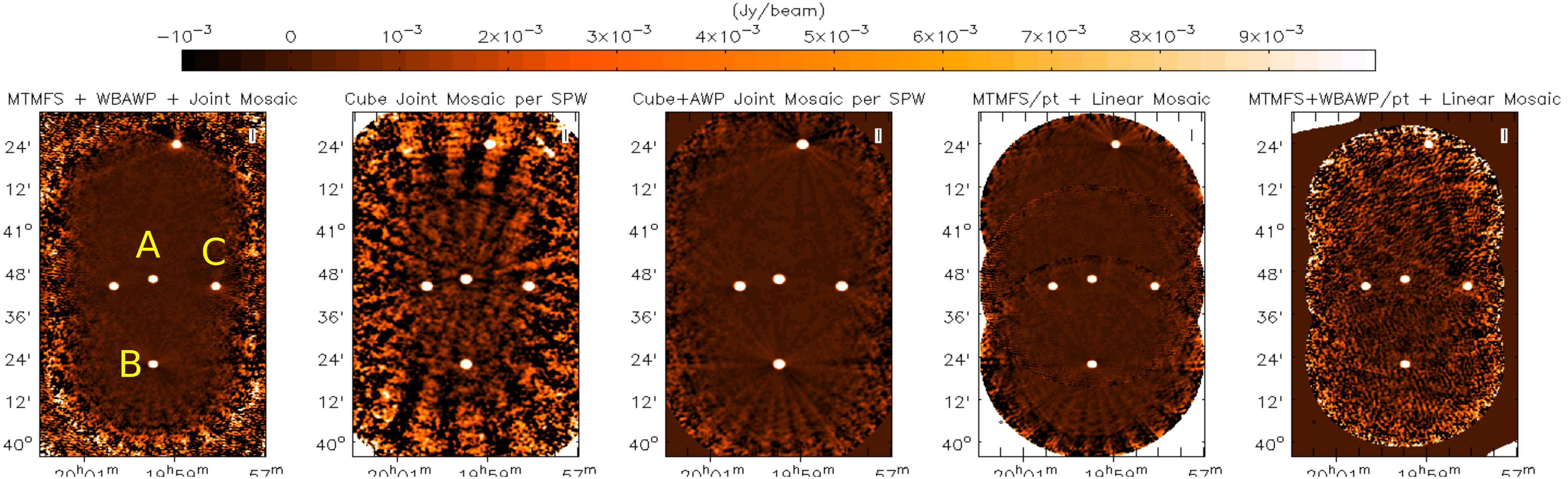
(Ref: Wide-Field Imaging – Mosaicing lecture)

- Deconvolve Channels separately or together (Cube vs MFS)
  - Impacts imaging fidelity and sensitivity, dynamic range

- Use A-Projection or not (Accurate vs Approximate PB correction)
  - Impacts dynamic range and spectral index accuracy

Comparison of several wideband mosaic methods

Dataset : L-Band D-config, 3 pointings, 5 sources (intensity = 1 Jy, alpha= -0.5)



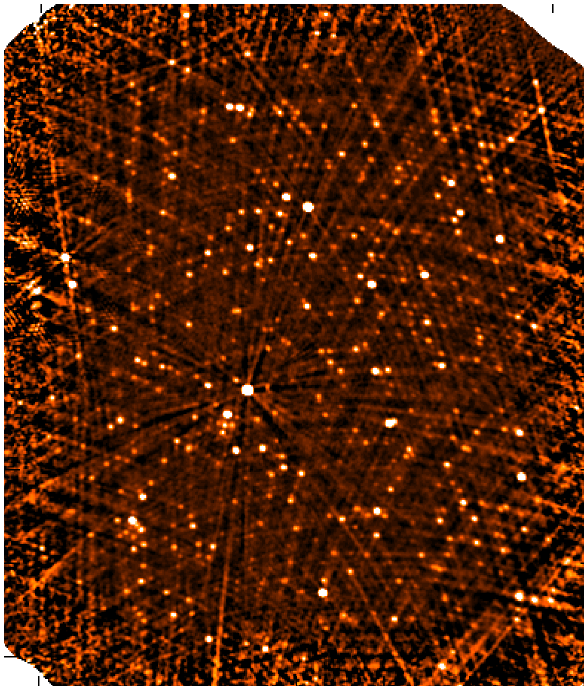
	Joint Mosaic Wideband-AP	Joint Mosaic Cube	Joint Mosaic Cube-AP	Stitched Mosaic Wideband	Stitched Mosaic Wideband-AP
A	1.0002	0.98	1.011	0.88	1.01
	-0.508	-0.52	-0.51	-0.87	-0.48
B	1.0004	0.99	1.012	0.90	0.99
	-0.502	-0.47	-0.48	-0.80	-0.50
C	1.0005	0.887	1.04	0.73	1.007
	-0.507	-0.62	-0.53	-1.6	-0.7

Wideband Mosaic Imaging Accuracy

[U.Rau et al, (in prep) 2014]

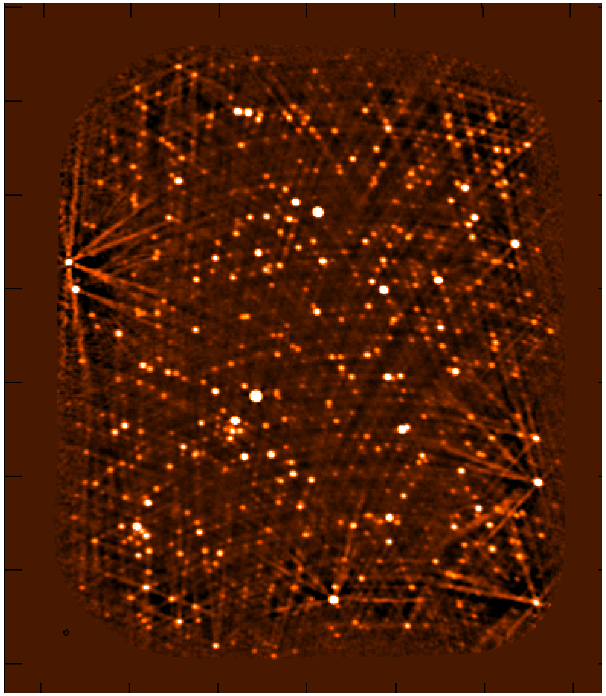
Cube + Joint Mosaic
(with static Primary Beams)

Dyn.Range = 5000:1

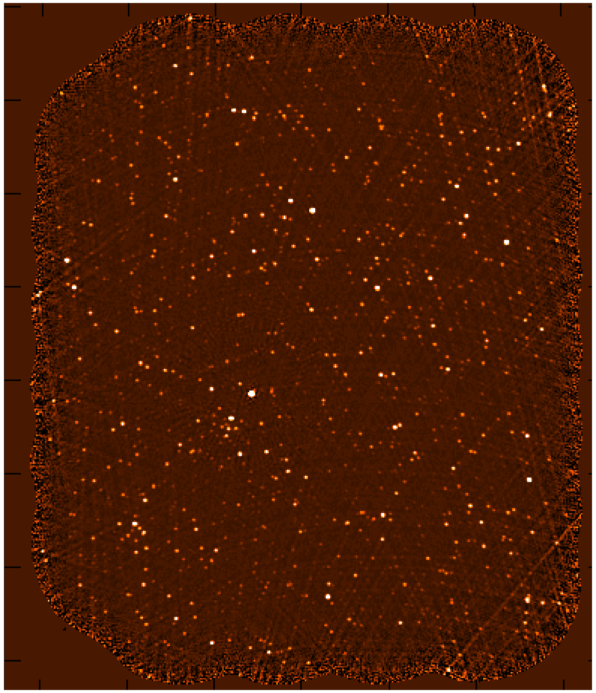


Cube + A-Projection + Joint Mosaic

Dyn.Range = 10000:1



Wideband A-Proj + Joint Mosaic + Multi-term MFS
Dyn.Range = 40000:1

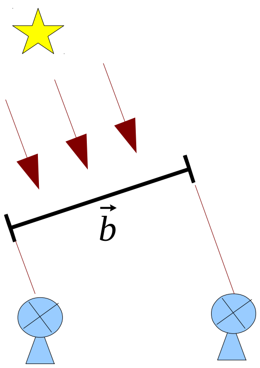


Method Intensity Range	I/I_{true} $> 20\mu Jy$	I/I_{true} $5 - 20\mu Jy$	I/I_{true} $< 5\mu Jy$	$\alpha - \alpha_{true}$ $> 50\mu Jy$	$\alpha - \alpha_{true}$ $10 - 50\mu Jy$
Cube	0.9 ± 0.1	0.9 ± 0.3	0.9 ± 0.5	-0.5 ± 0.2	-0.6 ± 0.5
Cube + AWP	1.0 ± 0.05	1.0 ± 0.2	1.0 ± 0.3	-0.15 ± 0.1	-0.1 ± 0.25
MTMFS + WB-AWP	1.0 ± 0.02	1.0 ± 0.04	1.0 ± 0.15	-0.05 ± 0.05	-0.1 ± 0.2

So far, none of our methods produced accurate spectral indices below 10 micro Jy.

Wide-Band (wide-field) Imaging - Summary

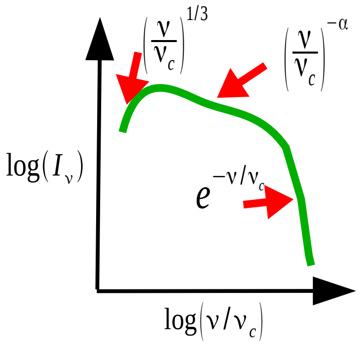
– UV coverage changes with frequency



-- Avoid bandwidth-smearing
-- Use multi-frequency-synthesis

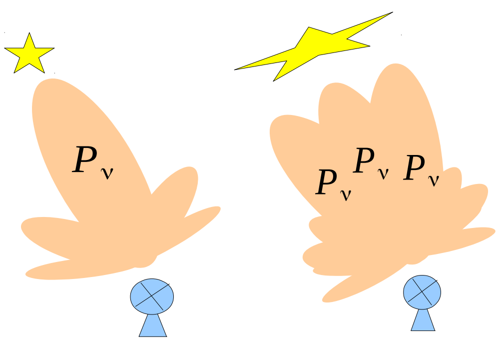
-- to increase the uv-coverage and image-fidelity
-- to make images at high angular-resolution

– Sky brightness changes with frequency



-- reconstruct intensity and spectrum together (MT-MFS)
-- (or) make a Cube of images

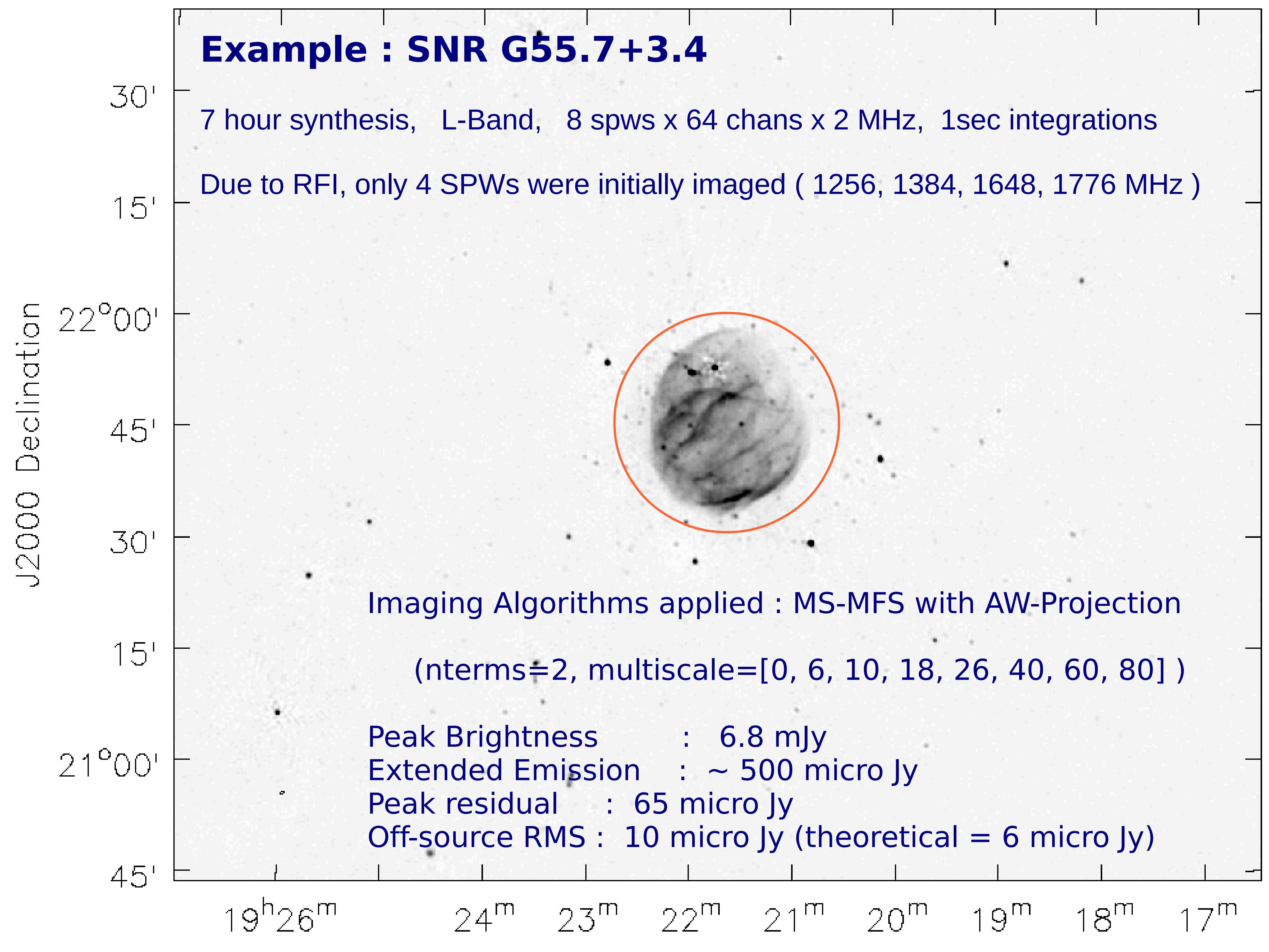
– Instrumental primary beam changes with frequency



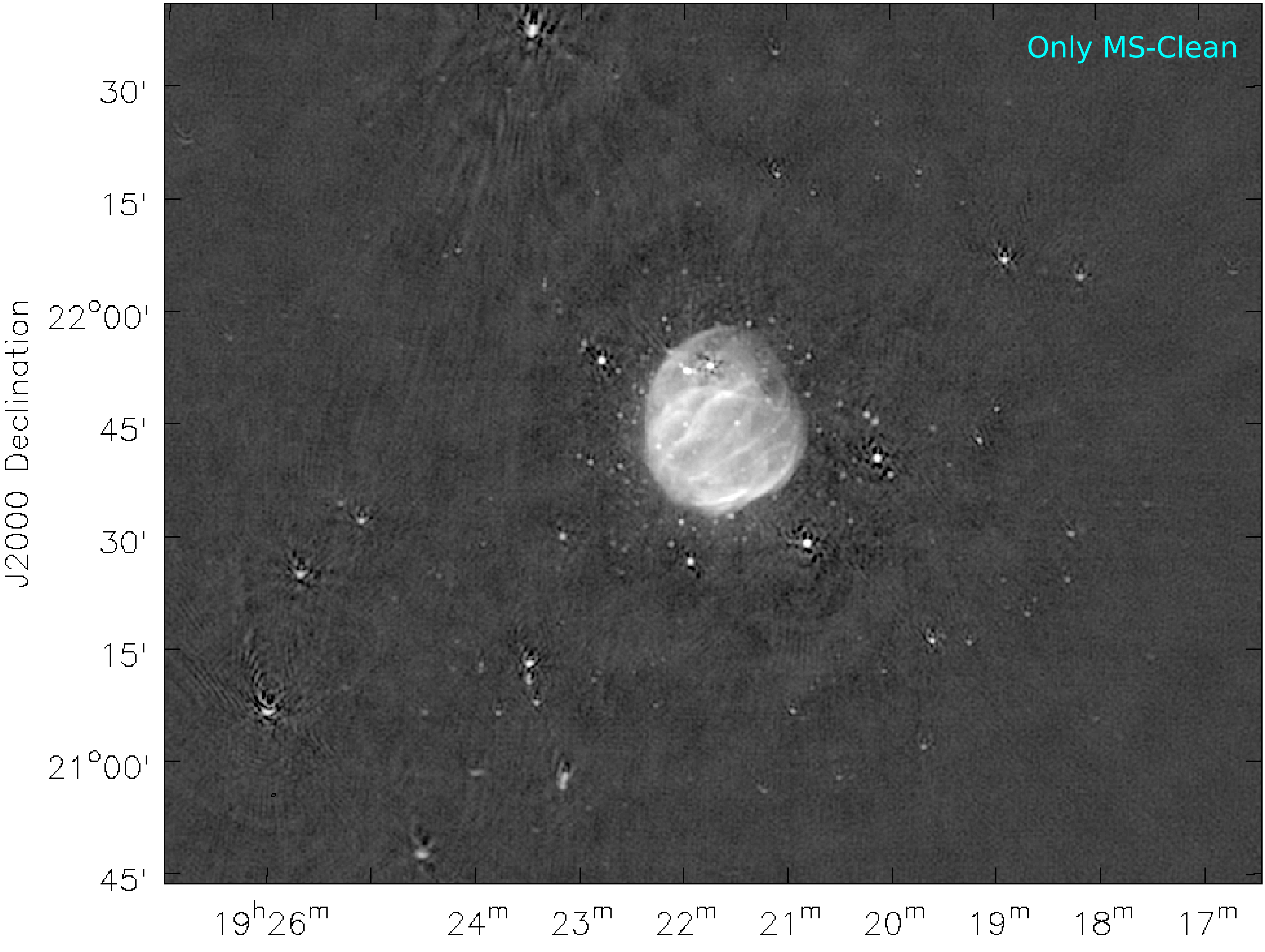
-- divide PB-spectrum from observed sky-spectrum.
-- apply wide-field imaging techniques to eliminate
the PB frequency dependence during imaging.
-- Stitched vs Joint mosaics

Wide Band (wide field) Imaging – some guidelines

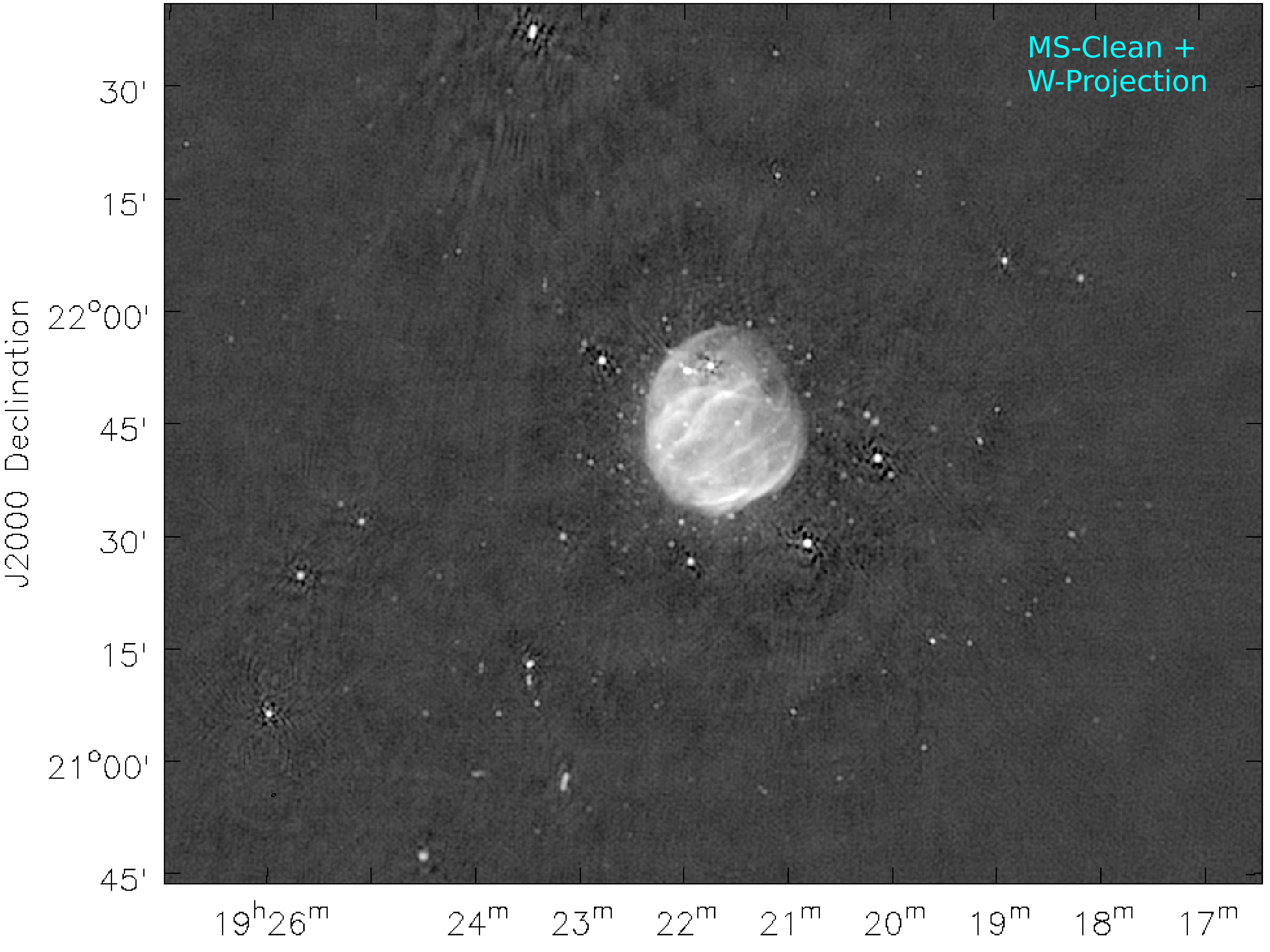
- MFS has better imaging fidelity, resolution and sensitivity than Cube
- For 2:1 bandwidth, the dynamic range limit with standard MFS (no spectral model) is few 100 to 1000 for a spectral index of -1.0
- For point sources,
  MT-MFS spectral index errors < 0.1 for SNR > 50 (2:1 bwr)
  for SNR > 10 (4:1 bwr)
- For extended emission
  MT(MS)-MFS spectral index errors < 0.2 for SNR > 100
- For 2:1 bwr, the PB's artificial spectral index at the HPBW is -1.4
- VLA beam squint and rotation effects appear at the few x 10^4 DR.
- Joint mosaics have better imaging fidelity than stitched mosaics.
- The current most practical approach to wideband mosaicing is cube joint mosaicing using A-Projection (accuracy vs cost vs software)

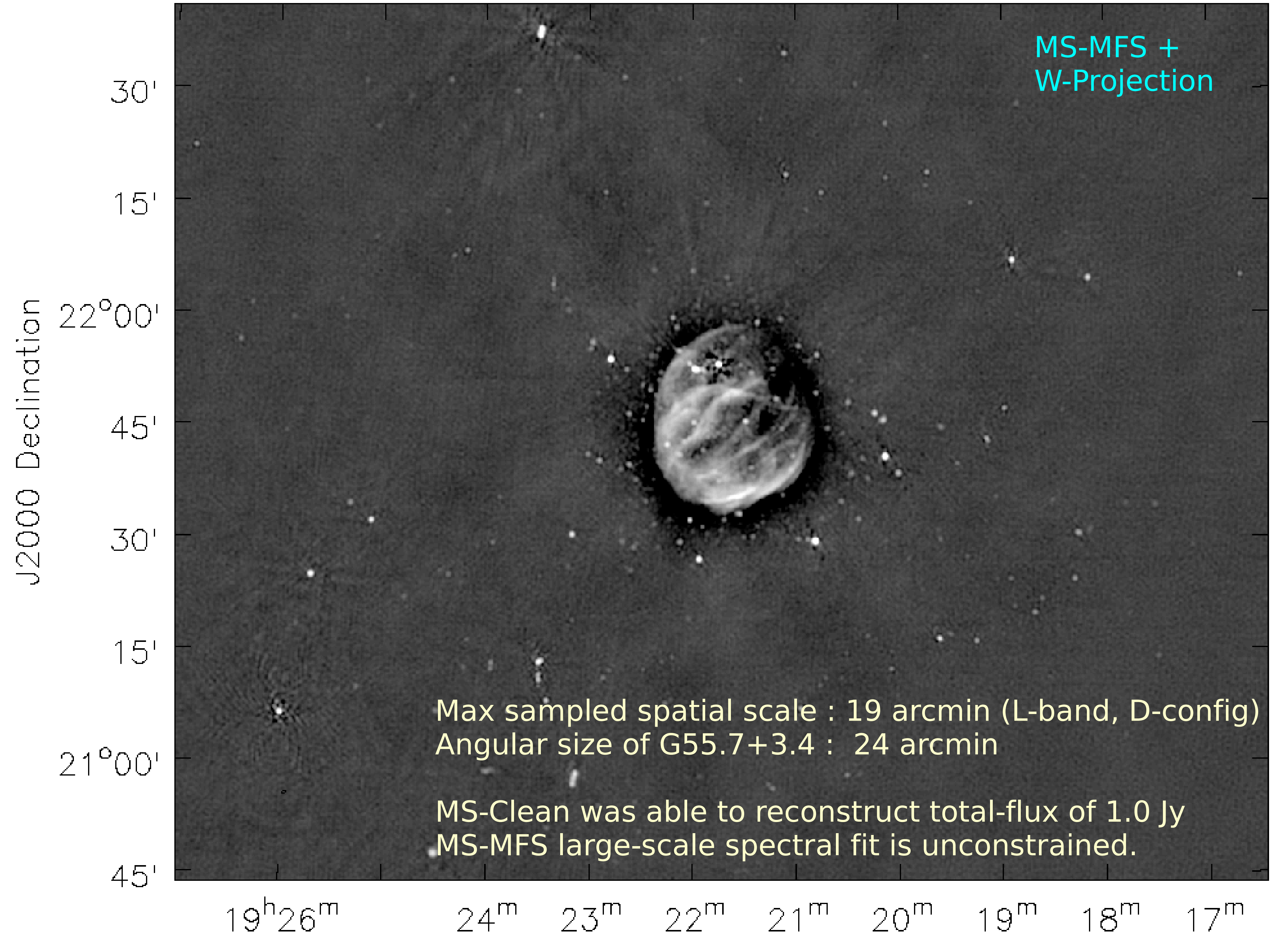


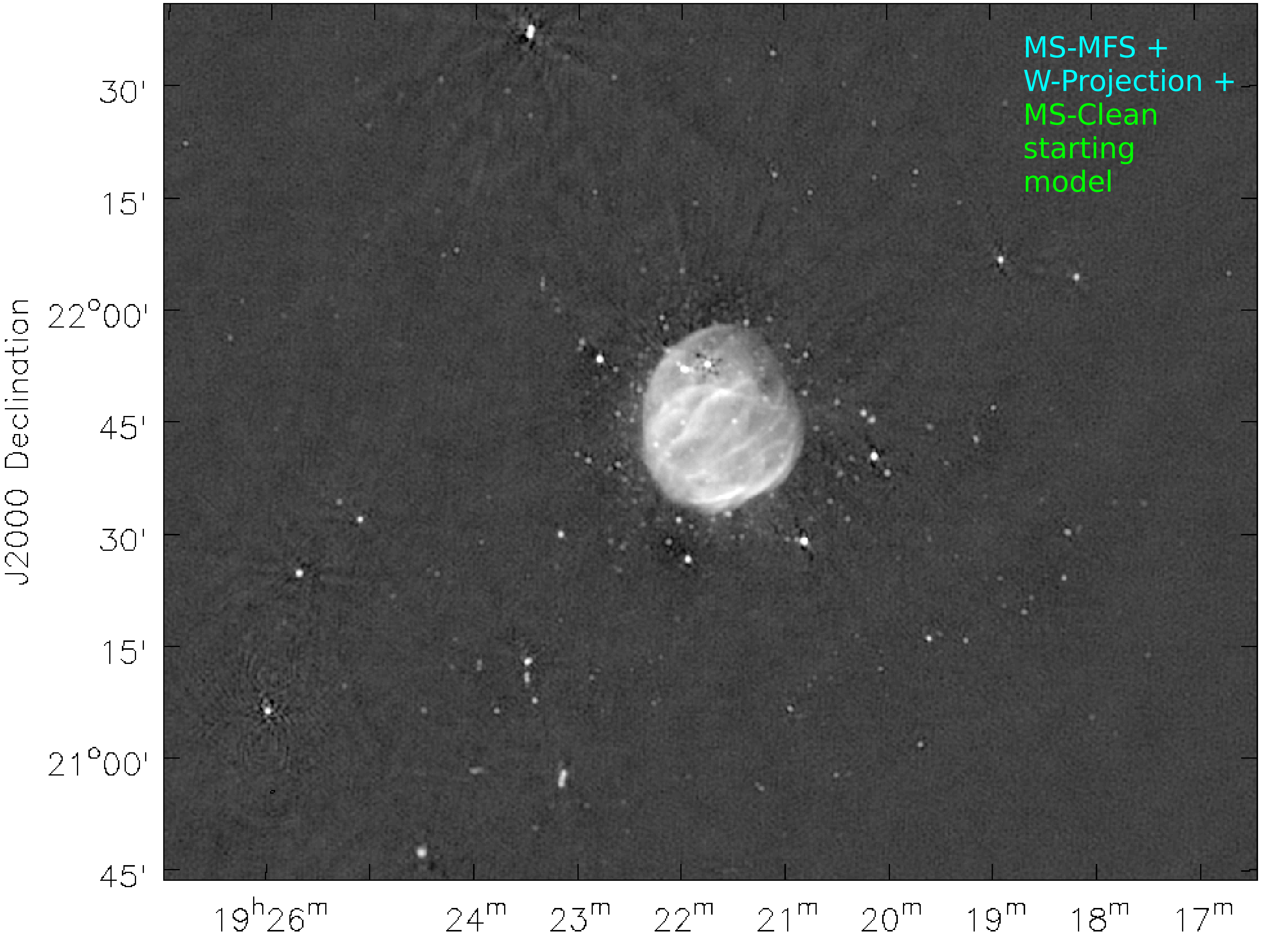
Example : SNR G55.7+3.4
7 hour synthesis, L-Band, 8 spws x 64 chans x 2 MHz, 1sec integrations
Due to RFI, only 4 SPWs were initially imaged (1256, 1384, 1648, 1776 MHz)
Imaging Algorithms applied : MS-MFS with AW-Projection
(nterms=2, multiscale=[0, 6, 10, 18, 26, 40, 60, 80])
Peak Brightness : 6.8 mJy
Extended Emission : ~ 500 micro Jy
Peak residual : 65 micro Jy
Off-source RMS : 10 micro Jy (theoretical = 6 micro Jy)
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m



Only MS-Clean
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m


MS-Clean +
W-Projection
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

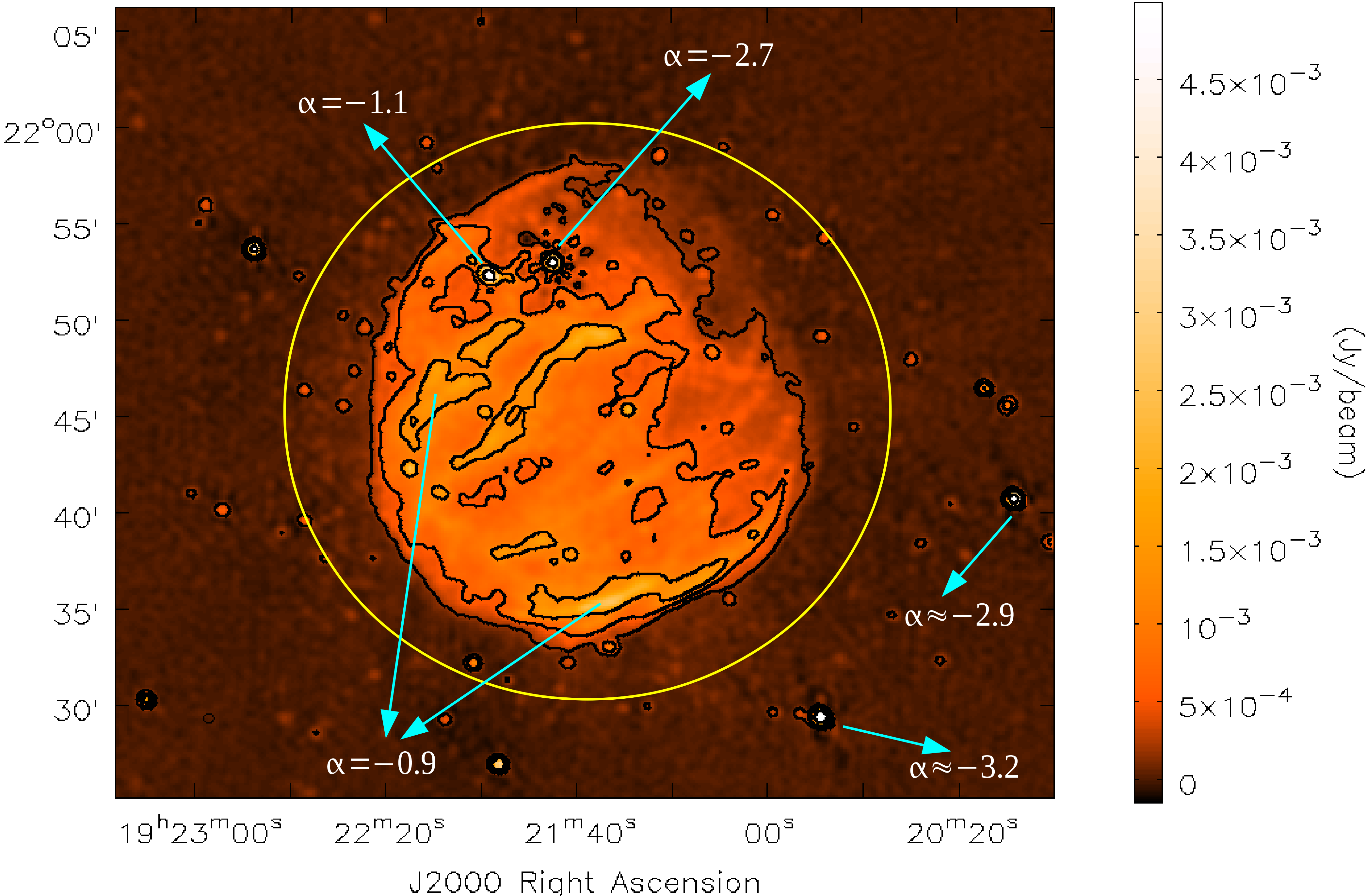

MS-MFS +
W-Projection
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m
Max sampled spatial scale : 19 arcmin (L-band, D-config)
Angular size of G55.7+3.4 : 24 arcmin
MS-Clean was able to reconstruct total-flux of 1.0 Jy
MS-MFS large-scale spectral fit is unconstrained.



MS-MFS +
W-Projection +
MS-Clean
starting
model
30'
15'
22°00'
45'
30'
15'
21°00'
45'
J2000 Declination
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

G55.7+3.4 : Supernova-Remnant + Pulsar

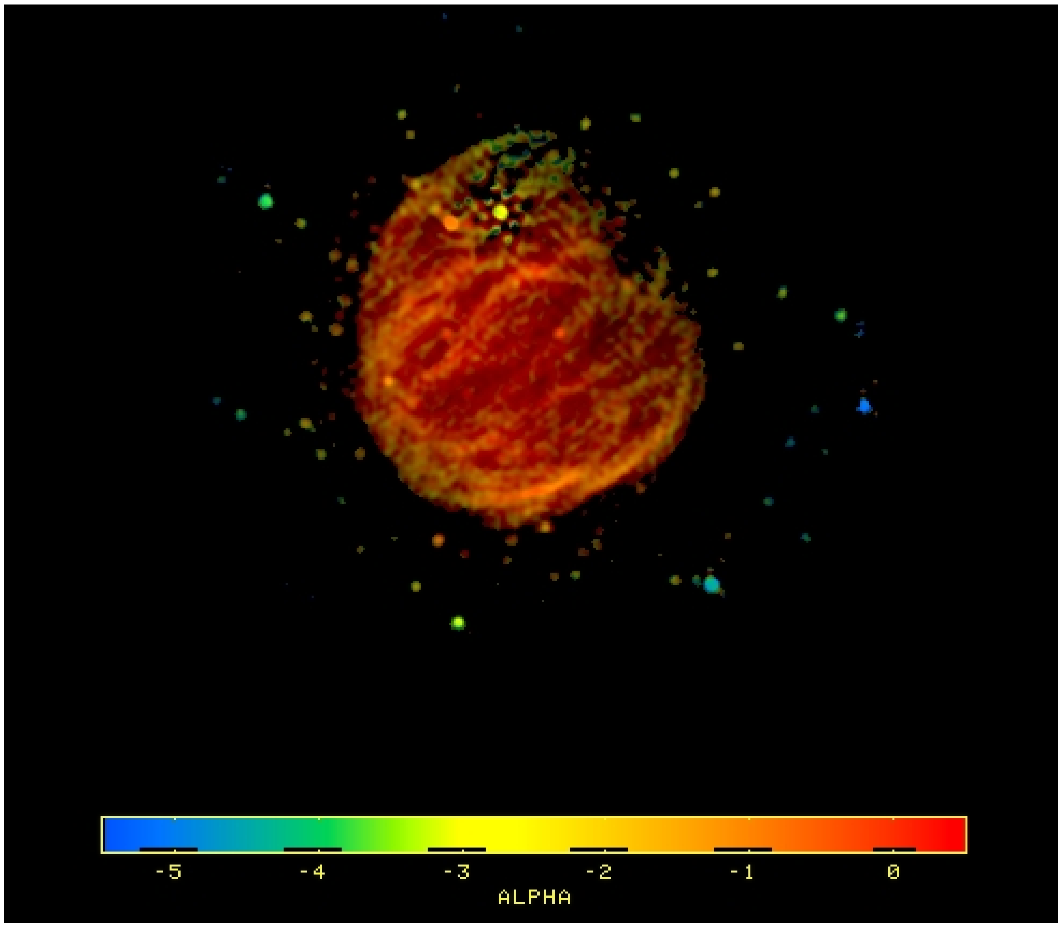
Spectral Indices are artificially-steepened by the Primary Beam

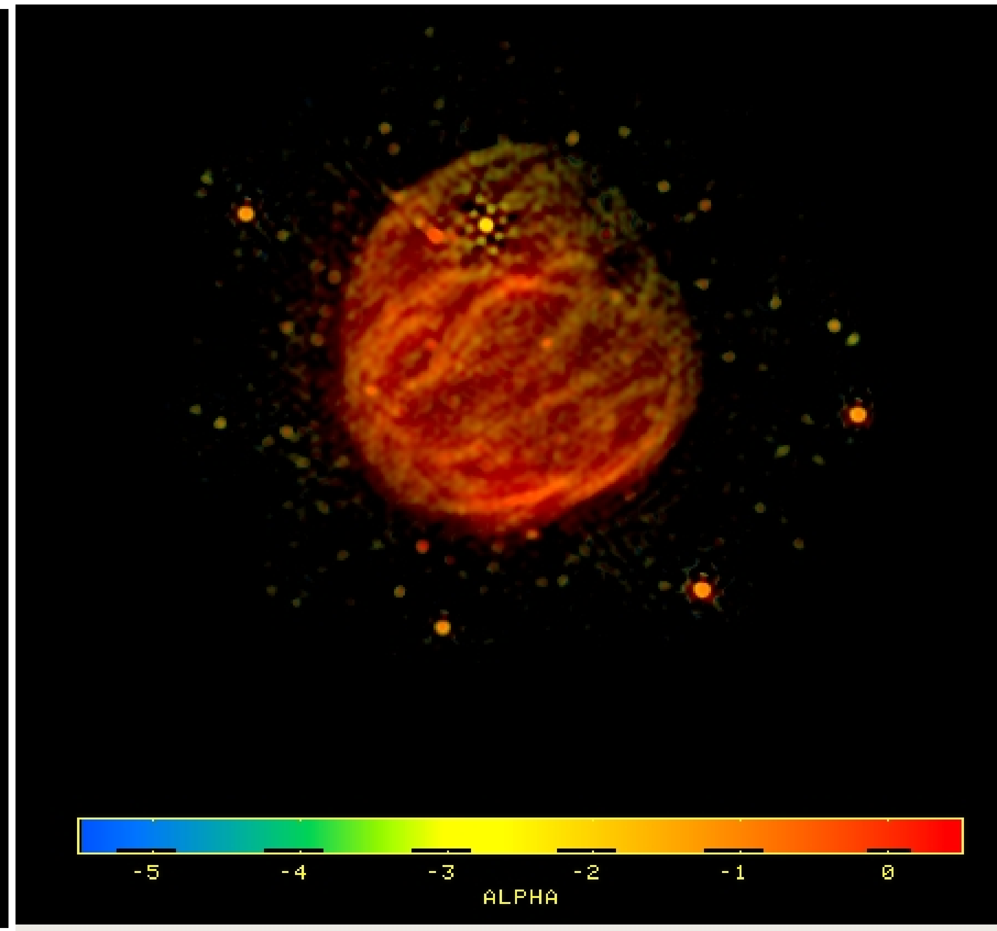


Spectral Indices before and after WB-A-Projection

Without PB correction
Outer sources are artificially steep

With PB correction (via WB-AWP)
Outer sources have correct spectra





Intensity-weighted spectral index maps (color = spectral index from -5.0 to +0.2)

Wide-field sensitivity because of wide-bandwidths

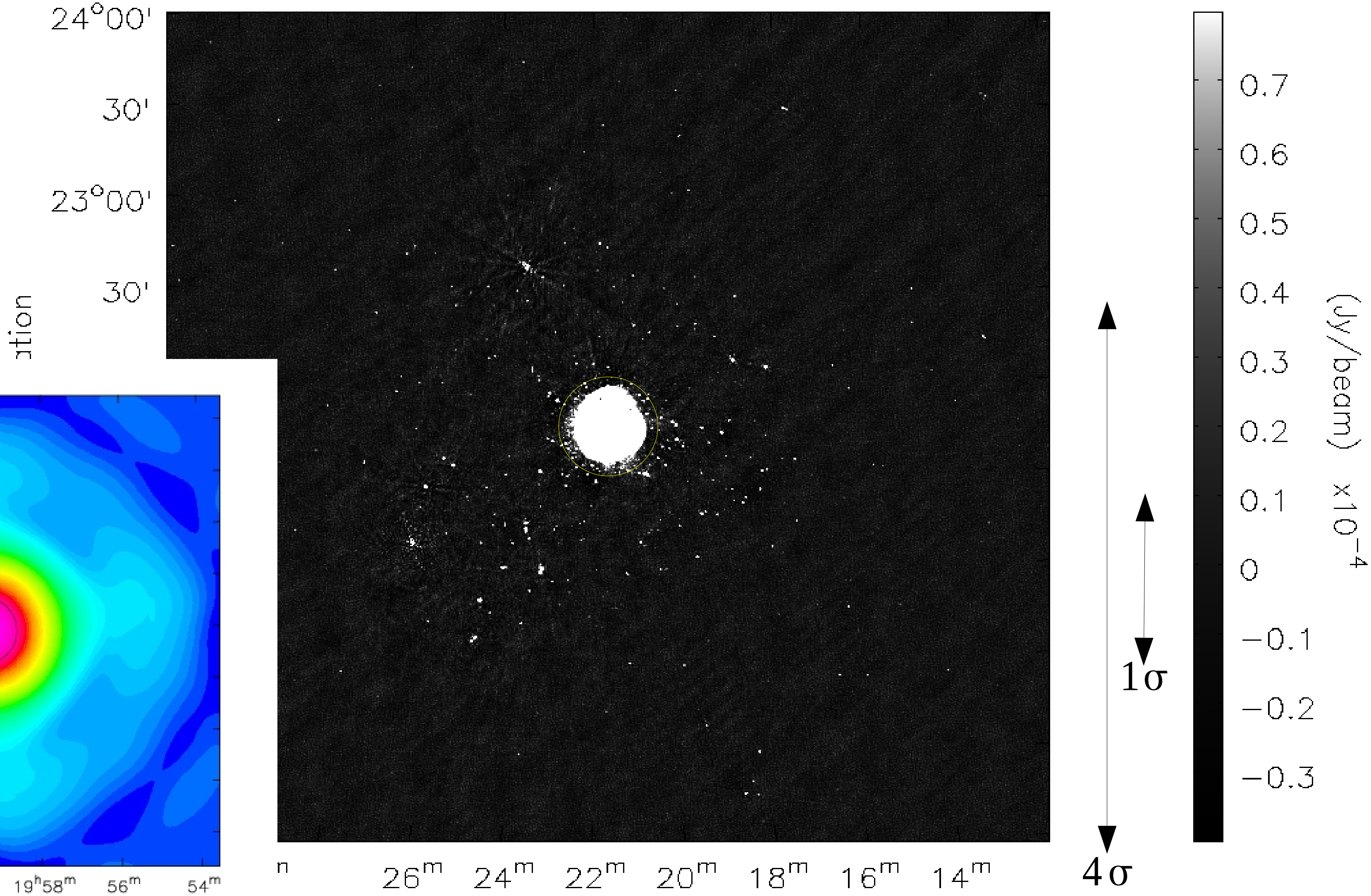
G55.7+3.4 : 4 x 4 degree field-of-view from one EVLA pointing

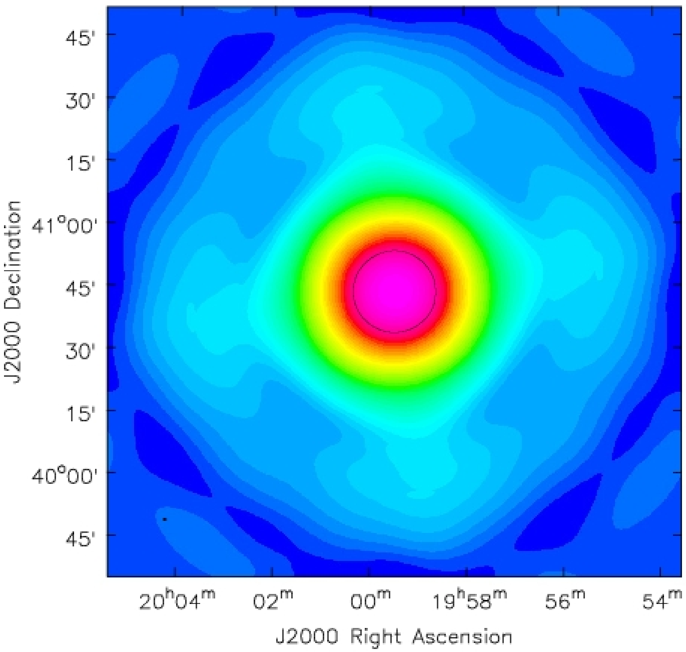
1 Jy total flux

24 arcmin

(PB: 30 arcmin)

10 micro Jy RMS





=> Wideband Imaging implies wide-field imaging

Summary

Broad-band receivers provide increased instantaneous sensitivity

↓

Cube-imaging will suffice for a quick-look, and bright simple targets

↓

For deep imaging, do wideband MFS (intensity and spectrum)

↓

Apply appropriate wideband primary beam correction

↓

Choose your algorithms based on desired accuracy and computing cost

↓

Pay attention to the **many** sources of error in this whole process.

↳ New astrophysics made possible by new instruments !

→ High dynamic range, wideband, full-polarization, mosaic imaging
--> An ACTIVE area of research for VLA and other new telescopes