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

50 MHz → 2 GHz => Theoretical improvement: \( \sqrt{\frac{2 \text{GHz}}{50 \text{MHz}}} \approx 6 \) 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: \( \sigma_{\text{cont}} = \frac{\sigma_{\text{chan}}}{\sqrt{N_{\text{chan}}}} \propto \frac{T_{\text{sys}}}{\sqrt{N_{\text{ant}}(N_{\text{ant}}-1)} \delta \tau \delta \nu} \)

50 MHz → 2 GHz => Theoretical improvement: \( \sqrt{\frac{2 \text{GHz}}{50 \text{MHz}}} \approx 6 \) 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.....

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>( \nu_{\text{min}}, \nu_{\text{max}} )</th>
<th>(1 – 2 GHz)</th>
<th>(4 – 8 GHz)</th>
<th>(8 – 12 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>( \nu_{\text{max}} - \nu_{\text{min}} )</td>
<td>1 GHz</td>
<td>4 GHz</td>
<td>4 GHz</td>
</tr>
<tr>
<td>Bandwidth Ratio</td>
<td>( \nu_{\text{max}} : \nu_{\text{min}} )</td>
<td>2 : 1</td>
<td>2 : 1</td>
<td>1.5 : 1</td>
</tr>
<tr>
<td>Fractional Bandwidth</td>
<td>( \left( \nu_{\text{max}} - \nu_{\text{min}} \right) / \nu_{\text{mid}} )</td>
<td>66%</td>
<td>66%</td>
<td>40%</td>
</tr>
</tbody>
</table>

\( \sigma_{\text{cont}} = \sigma_{\text{chan}} \sqrt{N_{\text{chan}}} \propto T_{\text{sys}} \sqrt{N_{\text{ant}}(N_{\text{ant}}-1)} \delta \tau \delta \nu \approx 6 \)
The instrument and the sky change with frequency...

**Sky Brightness**

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

\[
I(\nu) = e^{-\nu/\nu_c} \left( \frac{\nu}{\nu_c} \right)^{1/3} \left( \frac{\nu}{\nu_c} \right)^{-\alpha}
\]

**Primary Beam**

\[
HPBW_{\nu} = \frac{\lambda}{D} = \frac{c}{\nu D}
\]
The instrument and the sky change with frequency...

UV-coverage

\[ S(u, \nu) = \frac{\vec{b}}{\lambda} = \frac{\vec{b} \nu}{c} \]

Sky Brightness

\[ \log(I_{\nu}) = \left( \frac{\nu}{\nu_c} \right)^{1/3} \left( \frac{\nu}{\nu_c} \right)^{-\alpha} e^{-\nu/\nu_c} \]

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

Vwave vs. Uwave

1.5 GHz

Vwave vs. Uwave

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 \[ \sigma_{\text{cont}} = \frac{\sigma_{\text{chan}}}{\sqrt{N_{\text{chan}}}} \]
- Increased UV-filling => better imaging-fidelity
- Larger spatial-frequency range => better angular-resolution \[ \frac{\lambda}{b_{\text{max}}} \]
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 $\nu_0$

$$V(u_\nu)$$ 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

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

Bandwidth smearing limit for HPBW field-of-view:

$$\delta \nu < \frac{\nu_0 D}{b_{\text{max}}}$$

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...

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

\[
I(\nu) = \left(\frac{\nu}{\nu_c}\right)^{1/3} \left(\frac{\nu}{\nu_c}\right)^{-\alpha} e^{-\nu/\nu_c}
\]

\[
HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}
\]
Imaging Equations

Narrow Band / Flat spectrum sky

\[ I_{\text{obs}} = I_{\text{sky}} \ast PSF \]

\[ I_{\text{wb,obs}} \approx I_{\text{sky}} \ast \left[ \sum_v PSF_v \right] \]

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

\[ I_{\text{obs}} = \sum_v \left[ I_{\text{sky}} \ast PSF_v \right] \]

Wideband Image reconstruction

= Treat each frequency separately

(Ref : Spectral Line Analysis lecture)

(or)

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

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

(Ref : Imaging and Deconvolution lecture)
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 $I_0^m, I_1^m, I_2^m, ...$

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

Interpretation:

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

$$I_{\nu} = I_{\nu_0} \left( \frac{\nu}{\nu_0} \right)^{\alpha + \beta \log(\nu/\nu_0)}$$

$$I_0^m = I_{\nu_0} \quad I_1^m = I_{\nu_0} \alpha \quad I_2^m = I_{\nu_0} \left( \frac{\alpha (\alpha - 1)}{2} + \beta \right)$$

Sault & Wieringa, 1994
Rau & Cornwell, 2011
Dynamic-range with MS-MFS: 3C286 example: $N_t=1,2,3,4$

$NTERMS = 1$

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

\[ \alpha = +1 \]

Spectral Turn-over

\[ \alpha = -1 \]

Average Spectral Index

\[ \alpha = -2 \]

Gradient in Spectral Index

multi-scale

MFS

point-source

\[ I_0 \]

\[ \delta \alpha < 0.05 \]

\[ \alpha \approx 0.5 \]

\[ \delta \beta < 0.2 \]

\[ \delta \beta \approx 0.5 \]

=> Spectral-index error is dominated by 'division between noisy images'
   - a multi-scale model gives better spectral index and curvature maps
These examples used $n_{\text{terms}}=2$, and about 5 scales.

$\Rightarrow$ Within 1-2 GHz and 4-8 GHz, spectral-index error is $< 0.2$ for $\text{SNR}>100$.

$\Rightarrow$ Dynamic-range limit of few x 1000 $\Rightarrow$ residuals are artifact-dominated
Spectral Curvature

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

\[
\alpha = -0.52
\]

\[
\Delta \alpha \approx 0.2
\]

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 \( \beta \)
For which scales can we reconstruct the spectrum?

For high spatial frequencies, measured only at $\nu_{\text{max}}$.

For low spatial frequencies, measured only at $\nu_{\text{min}}$. 

$\nu_{\text{min}}$ UV range

$\nu_{\text{max}}$ UV range
For which scales can we reconstruct the spectrum?

Visibility function of compact emission at $\nu_{\min}$ and $\nu_{\max}$

Visibility function of extended emission at $\nu_{\min}$ and $\nu_{\max}$

Low spatial frequencies measured only at $\nu_{\min}$

High spatial frequencies measured only at $\nu_{\max}$
For which scales can we reconstruct the spectrum?

Visibility function of compact emission at $\nu_{\text{min}}$ and $\nu_{\text{max}}$

Visibility function of extended emission at $\nu_{\text{min}}$ and $\nu_{\text{max}}$

- Low spatial frequencies measured only at $\nu_{\text{min}}$
- High spatial frequencies measured only at $\nu_{\text{max}}$
Can reconstruct the spectrum at the angular resolution of the highest frequency (only high SNR)
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

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

1 – 2 GHz, 4 hr  
4 – 8 GHz, 4 hr  
1 – 2 GHz, 4 – 8 GHz, 2 hrs each

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 )

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

Dynamic range improved from ~2000 to ~4000.

Amplitudes of bandpass gain solutions

( < 5% from 1.0 )
(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
**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 \( P(\chi^2) = \int F(\phi) e^{2\pi i \phi \chi^2} d\phi \) for \( F(\phi) \)

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...

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

$$I(\nu) = e^{-\nu/\nu_c} \left( \frac{\nu}{\nu_c} \right)^{1/3} \left( \frac{\nu}{\nu_c} \right)^{-\alpha}$$

$$HPBW_{\nu} = \frac{\lambda}{D} = \frac{c}{\nu D}$$
Wide-Band Wide-Field Imaging: Primary Beams

VLA PBs

1.0 GHz

1.5 GHz

2.0 GHz

Average Primary Beam

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)

Spectral Index of PB
Wide-Band Wide-Field Imaging: Primary Beams

VLA PBs

Average Primary Beam

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...)

Spectral Index of PB

(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

\[
\frac{(I_0^m, I_1^m, I_2^m, \ldots)}{(P_0, P_1, P_2, \ldots)} = (I_{\text{sky}}^0, I_{\text{sky}}^1, I_{\text{sky}}^2, \ldots)
\]

Wideband A-Projection

-- Remove \( P(\nu) \) during gridding (before model fitting)
-- Also handles PB rotation/squint
-- Output spectral index image represents only the sky
<table>
<thead>
<tr>
<th>MT-MFS</th>
<th>MT-MFS + WB-A-Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-term MFS (wideband) Imaging</td>
<td>Multi-term MFS with wideband A-Projection to remove PB spectrum during gridding</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Absorb PB spectrum into sky model</td>
<td>Minor cycle sees only sky spectrum</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Post-deconvolution Wideband PBcor</td>
<td>Post-deconvolution PBcor of intensity only.</td>
</tr>
<tr>
<td>for intensity and alpha</td>
<td></td>
</tr>
</tbody>
</table>

**Cube**

<table>
<thead>
<tr>
<th>Cube + A-Projection</th>
<th>Cube + A-Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per channel Hogbom/Clark/CS Clean</td>
<td>Same as Cube,</td>
</tr>
<tr>
<td>+</td>
<td>- with narrow-band A-Projection</td>
</tr>
<tr>
<td>Per channel post-deconvolution Pbcor</td>
<td>per channel</td>
</tr>
<tr>
<td>+</td>
<td>( A-Projection : Construct gridding convolution operators from antenna aperture illumination models. Removes beam squint and accounts for aperture rotation )</td>
</tr>
<tr>
<td>Smooth to lowest resolution</td>
<td>Bhatnagar, Cornwell, Golap, 2004</td>
</tr>
<tr>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Fit spectrum per pixel, collapse chans</td>
<td></td>
</tr>
</tbody>
</table>

---


Bhatnagar, Rau, Golap, 2013

Bhatnagar, Cornwell, Golap, Uson, 2004

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

- MT-MFS
  - 2 uJy rms

- MT-MFS + WB-AWP
  - 2 uJy rms

- Cube
  - 3 uJy rms
  - Brightest Source: 7 mJy
  - peak res: 9 uJy

- Cube + AW-Projection
  - Cube
    - 3 uJy rms
  - 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
- Brightest Source: 100 mJy

**Cube**
- 4 uJy rms
- Peak res.: 20 uJy

**MT-MFS + WB-AWP**
- 2 uJy rms

**Cube + AW-Proj**
- 3 uJy rms
Wideband VLA imaging of IC10 Dwarf Galaxy

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.

50% of PB

[Heesen et al, 2011]
The instrument and the sky change with frequency...

\[ S(u, v) = \frac{\vec{b} \cdot \vec{b} v}{\lambda} = \frac{\vec{b} \cdot v}{c} \]

\[ \log(I_\nu) = \log \left( \frac{\nu}{\nu_c} \right)^{1/3} \]

\[ e^{-\nu/\nu_c} \]

\[ I(\nu) \]

Primary Beams (Mosaic)

\[ HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D} \]
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)
Wideband Mosaic Imaging Accuracy

**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

---

<table>
<thead>
<tr>
<th>Method</th>
<th>$I/I_{true}$ &gt; 20μJy</th>
<th>$I/I_{true}$ 5 – 20μJy</th>
<th>$I/I_{true}$ &lt; 5μJy</th>
<th>$\alpha - \alpha_{true}$ &gt; 50μJy</th>
<th>$\alpha - \alpha_{true}$ 10 – 50μJy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube</td>
<td>0.9 ± 0.1</td>
<td>0.9 ± 0.3</td>
<td>0.9 ± 0.5</td>
<td>-0.5 ± 0.2</td>
<td>-0.6 ± 0.5</td>
</tr>
<tr>
<td>Cube + AWP</td>
<td>1.0 ± 0.05</td>
<td>1.0 ± 0.2</td>
<td>1.0 ± 0.3</td>
<td>-0.15 ± 0.1</td>
<td>-0.1 ± 0.25</td>
</tr>
<tr>
<td>MTMFS + WB-AWP</td>
<td>1.0 ± 0.02</td>
<td>1.0 ± 0.04</td>
<td>1.0 ± 0.15</td>
<td>-0.05 ± 0.05</td>
<td>-0.1 ± 0.2</td>
</tr>
</tbody>
</table>

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

\( n_{\text{terms}}=2, \text{multiscale}=[0, 6, 10, 18, 26, 40, 60, 80] \)

Peak Brightness : 6.8 mJy
Extended Emission : \( \sim 500 \) micro Jy
Peak residual : 65 micro Jy
Off-source RMS : 10 micro Jy (theoretical = 6 micro Jy)
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
Spectral Indices are artificially-steepened by the Primary Beam

\[ \alpha = -1.1 \]

\[ \alpha = -2.7 \]

\[ \alpha \approx -2.9 \]

\[ \alpha \approx -3.2 \]
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