How accurately do our imaging algorithms reconstruct intensities and spectral indices of weak sources?

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Wide-band wide-field simulations: (LEFT) L-Band, C-config, 1-pointing, (RIGHT) C-band, D-config, 46 pointings
Context:

- Do we have the methods we need to do VLA mosaic deep-field science?
- Any insights on how to design an optimal wideband mosaic survey?

Analysis:

- Simulated datasets and compare reconstructed images with known 'true' sky.
- Compare different algorithms (accuracy, stability, and performance)

Stages (to ensure that simulations reflect reality):

- Narrow-band single-pointing imaging of logNlogS source distribution
  (Julia Mayeshiba's summer project)
- Wide-band single-pointing observation with wide-field spectral index recovery
- Wide-band mosaic observation with intensity and spectral index recovery
Simulation Parameters: One Pointing, L-Band, C-config

Sky: ~8000 point sources within one square degree.
Sources at pixel centers (+ compared with not)

Intensity: between 1 micro Jy and 7 mJy.
(+ one 100 mJy source for HDR test)

Spectral indices: between 0.0 and -0.8.

Observation: EVLA C-config, L-band (1-2 GHz),
16 channels/spws, One pointing

One snapshot every 20 minutes, for 4 hrs
(compare with one snapshot every 2 minutes, for 4 hrs)

Data Prediction: Visibilities were calculated using the
Wideband A-Projection de-griddor. No noise.
<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
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| **MT-MFS** | Multi-term MFS (wideband) Imaging  
+ Absorb PB spectrum into sky model  
+ Post-deconvolution Wideband PBcor for intensity and alpha |
| **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.  
| **Cube** | Per channel Hogbom/Clark/CS Clean  
+ Per channel post-deconvolution Pbcor  
+ Smooth to lowest resolution  
+ Fit spectrum per pixel, Collapse channels |
| **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 (< 10000) – compare four methods

MT-MFS
2 uJy rms

MT-MFS + WB-AWP
2 uJy rms

Cube
3 uJy rms
peak res : 9 uJy

Cube + AW-Projection
3 uJy rms
Locate sources in true image. Plot all sources >1 micro Jy. (Brighter sources are more accurate)
No source-finding uncertainty.
Very slight trend for sources near the pointing center (higher PB gain) to be more accurate.
Spectral index for brighter sources are more accurate. Degrades quickly with lower intensity. (note different numbers of sources with alpha detections)
No clear trend for spectral index accuracy as a function of distance from PB peak (within HPBW) (note different numbers of sources with alpha detections)
High dynamic range test ($>10^5$) - compare four methods

**MT-MFS**
- Brightest Source: 100 mJy
- 6 uJy rms
- Peak res: 15 uJy

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

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

**Cube + AW-Projection**
- 3 uJy rms
Need A-Projection to eliminate beam-squint errors and reach low-dyn-range accuracy
Need A-Projection to eliminate beam-squint errors and reach low dynamic range accuracy.
Other factors to check......

- **Role of masks**: Need source masks to avoid 'bias' with PSFs from sparse UV-tracks.
- **Instrumental polarization correction**: Stokes V residuals with/without WB-A-Projection.
- **Un-deconvolved weak sources with Cube clean**: A hybrid of Cube and MFS on residuals.
- **Effect of sources not at pixel centers**: Nothing significant upto dynamic ranges of 10^4.
- **Effect of baseline based averaging**: No noticeable effect with A-Projection (2xPB fov).
- **Effect of adding visibility noise**: TBD.
- **Reconstruction accuracy for diffuse emission**: TBD.
- **Numerical / implementation details**:
  - Different achieved noise levels with MosaicFT / FT / A-Projection for single pointings.
  - Non identical results between FT and the equivalent of FT from A-Projection gridders.
  - Differences due to choices of oversampling of gridding convolution functions.
  - Fake sources when simulation f-o-v is smaller than the imaging f-o-v.
  - Some uv-coverage patterns leave artifacts for multi-term runs beyond 10^5 dynamic range.
  - Algorithms react differently to bright outlier sources, depending on f-o-v.
  - Compare spectral index accuracy using same sources for all algorithms.
  - Need to automate PB-dependent mask generation.
Effect of Masks ( 'clean boxes' ) : One large circle at PB=0.1

There is a clear bias of weaker sources to lower values, with no 'boxes' on bright sources.

(note - MT-MFS+WBAWP needed a mask on the brightest source, to not diverge)
Effect of Masks: Few bright-source boxes + PB=0.1 circle

With a two-stage mask (interactive), the bias disappears, but there is still considerable spread.
Effect of Masks: Boxes around bright sources

With tight boxes on more bright sources, there is even less bias, and less intensity spread.

........... so far, all results have been for snapshots every 20 min, for 4 hours.....
PSF quality: Compare snapshot series vs continuous tracks

Snapshots every 20 min → every 2 min => Improvement consistent with SNR increase.

=> NO need for tight boxes ('bias' is a symptom of a PSF with high sidelobes and non-sparse sky)
Wideband Mosaics – Simulation + Algorithms

Same field as with C-config L-band single pointing

EVLA D-config, C-band (4-8 GHz), 16 spws/chans

46 pointings at 5 arcmin spacing, 2 loops
- One snapshot every 6 min => 8.8 hr observation

Algorithms

- Deconvolve Pointings separately or together
- Deconvolve Channels separately or together
- Use A-Projection or not

(1) Joint Mosaic with Wideband AW-Projection with MT-MFS (nterms=2)

(2,3) Cube Imaging with Joint Mosaic per SPW – With/Without rotating, squinted PBs

(4,5) MT-MFS per pointing with wideband PBCOR and post-deconvolution linear mosaic.
- With/Without rotating, squinted PBs.
Wideband Mosaic Sensitivity Patterns

“Bandpass Calibration” normalizes primary beam peaks to 1.0 for each frequency and pointing.

- For Cube Joint Mosaics, need to compute a weighted average of frequency-dependent beams.
- For Wideband Linear Mosaics, need to compute a weighted average across pointings.

Points to be careful of:
- Accumulate with PB or PB^2 as weights?
- When to normalize PBs to peak 1?
- Flat-noise or flat-sky?
- PB-correction before or after accumulation?
Algorithm Test: L-Band D-config, 3 pointings, 5 sources (1 Jy, a=-0.5)

<table>
<thead>
<tr>
<th></th>
<th>Joint Mosaic Wideband-AP</th>
<th>Joint Mosaic Cube</th>
<th>Joint Mosaic Cube-AP</th>
<th>Linear Mosaic Wideband</th>
<th>Linear Mosaic Wideband-AP</th>
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<tbody>
<tr>
<td>A</td>
<td>1.0002</td>
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<tr>
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<td>-0.62</td>
<td>-0.53</td>
<td>-1.6</td>
<td>-0.7</td>
</tr>
</tbody>
</table>
Cube Imaging with Joint Mosaic (Ap=F) and PBCOR per SPW

RMS : 0.9 microJy

Intensity : Reconstructed / True

Alpha : Reconstructed - True
Cube Imaging with a Joint Mosaic (Ap=T) and PBCOR per SPW

RMS : 0.7 microJy

Intensity : Reconstructed / True

Alpha : Reconstructed - True
Joint Mosaic with Wideband AW-Projection and MT-MFS (nt=2)

RMS : 0.3 microJy

Intensity : Reconstructed / True

Alpha : Reconstructed - True
Summary + Next Steps

1. **Single Pointing**: Mostly OK. Several numerical effects to resolve.
   Repeat for HDR and with noise and diffuse emission.

2. **Mosaic**: Basics are OK. Need to check normalizations, HDR tests, noise, mask heuristics.
   Analyse achievable continuum sensitivity and observing strategy...

3. **Submit paper(s)**

4. **CTB80 wideband mosaic data**: Pilot project for a wideband Galactic plane survey.
   (Part of RSRO project: S.Bhatnagar, D.Green, M.Rupen, etc...)

5. **Other projects**: M87 (F.Owen), Plaeides (S.White et.al.), Cen-A (S.Neff et.al.).
   M31 (Adam Leroy et.al.)...

6. **More simulations**:
   - Add calibration errors, and antenna-dependent PB perturbations
     (Kara Kundert: ALMA single pointing, narrow-band, few bright sources)
   - Add source polarization and test wideband IQUV and rotation-measure recovery
     (Preshanth Jeganathan: part of PhD thesis project + RSRO project (R.Taylor et.al.))