Wide-band (wide-field) imaging

Goal: Make images at the wide-band sensitivity level

Outline:
- Bandwidth and bandwidth-ratio
- Frequency-dependent sky and instrument
- Methods to reconstruct intensity and spectra
- Wide-field effects of wide-band imaging
- Wide-band self-calibration

Flagging + RFI

Goal: Discard data unusable for imaging

Outline:
- Flagging based on data-selection
- Automatic RFI identification and flagging
Bandwidth and bandwidth-ratio

Instantaneous bandwidth: \( \nu_{\text{max}} - \nu_{\text{min}} \)

VLA = 50 MHz  
EVLA = 1 GHz at L-Band, 4 GHz at C-band, upto 8 GHz at higher bands.

Currently, maximum bandwidth is 2 GHz => (x 6)

Broad-band receivers => Higher 'instantaneous' continuum sensitivity

\[
\sigma_{\text{continuum}} = \frac{\sigma_{\nu}}{\sqrt{(\nu_{\text{max}} - \nu_{\text{min}})/\delta \nu}} = \frac{\sigma_{\text{chan}}}{\sqrt{N_{\text{chan}}}}
\]

Bandwidth Ratio (\( \nu_{\text{max}} : \nu_{\text{min}} \)) or Fractional Bandwidth \( \frac{\nu_{\text{max}} - \nu_{\text{min}}}{\nu_{\text{mid}}} \)

Higher BWR (2:1 at L,S, C bands) => Stronger frequency-dependent effects within the band (sky and instrument)
Frequency-dependence of the instrument and sky

Multi-Frequency UV-coverage

Multi-Frequency Primary Beams

Average Primary Beam

- UV-coverage (angular resolution)
- Primary-beam (field-of-view)
- Sky-brightness distribution

..... all change with frequency

'Spectral Index' of PB
Wideband Imaging Options

(1) Make images for each channel / SPW separately.
   - Signal-to-noise ratio: one SPW
   - Angular resolution varies with SPW (smooth to lowest)
   - Imaging fidelity may change across SPWs

When will this suffice?
   - Sources have sufficient SNR in a single channel / SPW
   - UV-coverage per SPW gives un-ambiguous reconstructions
   - You don't need the highest-possible angular resolution for spectra

(2) Combine all frequencies during imaging (MFS: multi-frequency synthesis)
   - Signal-to-noise ratio: all SPWs
   - Angular resolution is given by the highest frequency
   - Imaging fidelity is given by the combined uv-coverage

When do you need MFS?
   - Single channel / SPW sensitivity is too low
   - Complicated fields where single-SPW uv-coverage gives non-unique solutions
   - Need high angular-resolution images (intensity and spectral index)
   (But, need to model / reconstruct spectra too...)
Comparison of single-SPW imaging with MFS - Intensity

Data: 20 VLA snapshots at 9 frequencies across L-band + wide-band self-calibration

Single SPW Imaging

Peak residual = 150 mJy
Off-source rms = 50 mJy

MS-MFS (3 terms)

Peak residual = 100 mJy
Off-source rms = 30 mJy

=> Similar results
- both methods reconstruct plausible intensity images.
- both have similar residual errors due to deconvolution.

( MS-MFS: Multi-Scale Multi-Frequency Synthesis: models intensity and spectrum (Taylor polynomial) )
Comparison of single-SPW imaging with MFS – Spectral Index

Data: 20 VLA snapshots at 9 frequencies across L-band + wide-band self-calibration

Spectral Index from single-SPW images

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

MS-MFS Spectral Index

- Shows imaging fidelity due to multi-scale deconvolution
- Shows expected structure with errors < 0.2

Two-point spectrum (1.4 – 4.8 GHz)

- Shows effect of insufficient single-frequency uv-coverage

=> It helps to use the combined uv-coverage and solve for sky spectra.

Can often extract more information from your data, compared to traditional methods, but not always.

“Multi-Scale Multi-Frequency Synthesis”

(VLA A,B,C,D Array at L and C band)
Multi-Scale MFS : as implemented in CASA

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

\[ I_{sky} = \sum_t I_t \left( \frac{\nu - \nu_0}{\nu_0} \right)^t \]

Image Reconstruction : Linear least squares + Deconvolution

User Parameters :
- Imaging mode : mode='mfs'
- Number of Taylor-polynomial coeffs. : nterms=2
- Reference frequency : reffreq = '1.5GHz'
- Set of spatial scales (in units of pixels) : multiscale=[0,6,10]

Data Products : Taylor-Coefficient images \( I_0, I_1, I_2, \ldots \)

- Interpret in terms of a power-law : spectral index and curvature

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

(Or, evaluate the spectral cube (for non power-law spectra) )
Dynamic Range (vs) NTERMS – 3C286 field (point sources)
(I=14.4 Jy/bm, alpha = -0.47, BW=1.1GHz at Lband)

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
Error estimates: Bandwidth-ratio vs 'nterms' (high SNR)

If spectra are ignored

=> larger BWR gives larger errors

If there is high SNR,

=> more terms gives smaller errors

Note: These plots are for one point-source at the phase center, with very high signal-to-noise levels.

In practice, use nterms>2 only if there is high SNR (>100), and if you can see spectral artifacts in the image with nterms=2
Multi-Scale vs Point-Source model for wideband imaging

For extended emission,
- a multi-scale model gives better spectral index and curvature maps.

\[ \alpha = +1 \quad \alpha = -1 \quad \alpha = -2 \]

Average Spectral Index

Intensity Image

Spectral Turn-over

\[ \delta \alpha < 0.05 \quad \delta \alpha \approx 0.5 \]

Gradient in Spectral Index

\[ \delta \beta < 0.2 \quad \delta \beta \approx 0.5 \]

\[ \beta \]

\[ \text{MFS (4 terms)} \]

\[ I_0 \]
Separating regions/sources based on spectral index structure

Initial results of a pilot survey (EVLA RSRO AB1345). These examples used nterms=2, and about 5 scales.

=> Within L-band and C-band, can tell-apart regions by their spectral-index ( +/- 0.2 ) if SNR>100.

=> These images have a dynamic-range limit of few x 1000
Small spatial-scales - moderately-resolved sources

Can reconstruct the spectrum at the angular resolution of the highest frequency (only high SNR)
Very large spatial scales - without short-spacing data

The spectrum at the largest spatial scales is NOT constrained by the data
Very large spatial scales – with short-spacing data

External short-spacing constraints help (visibility data, or starting image model)
Spectral Curvature : VLA data : M87 1.1-1.8 GHz

Data : 10 VLA snapshots at 16 frequencies across L-band

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

$\alpha = -0.52$  
$\Delta \alpha \approx 0.2$

$\Rightarrow$ Need SNR > 100 to fit spectral index variation $\sim 0.2$ (at the 1-sigma level ... )  
$\Rightarrow$ Be very careful about interpreting $\beta$
Wide-Field issues : Wide-band Primary-Beam

3C286 field, C-config, L-band

Verified spectral-indices by pointing directly at one background source.

→ compared $\alpha_{\text{center}}$ with 'corrected' $\alpha_{\text{off.center}}$

Obtained $\delta \alpha = 0.05$ to 0.1 for SNR or 1000 to 20

Also verified via holography observations at two frequencies

PB-correction + MS-MFS not yet available in 'clean', but approximate correction is possible with a python script.
IC10 dwarf-galaxy : spectral-index : Wideband PB correction + angular resolution offered by MS-MFS

For comparison, spectral-index map made by PB-correcting single-SPW images smoothed to the lowest resolution (AIPS).

This post-deconvolution correction assumes that the primary-beam does not vary / rotate during the observation, and that all points are weighted equally....
Choices that effect errors during wide-band imaging

- Artifacts in the continuum image due to too few Taylor-terms.
  Very high signal-to-noise, point-sources: use a higher-order polynomial. Otherwise, use 2 or 3 terms to prevent over-fitting.

- Error in spectral index/curvature due to too many Taylor-terms.
  Low signal-to-noise: use a linear approximation. Again, nterms=2 or 3 is safer for low signal-to-noise extended emission.

- Error propagation during the division of one noisy image by another.
  Extended emission: use multiple spatial scales to minimize this error (see output error map)
  Choice of scale sizes: by eye, and verifying that the total-flux converges

- Flux-models that are ill-constrained by the measurements
  Choose scales/nterms appropriately. For very large scales, add short-spacing information.

- Wide-field errors: Time and Frequency-variability of the Primary Beam
  Use W-projection, A-projection along with MS-MFS (software in progress)

Remember: Increased imaging sensitivity (over wide fields), high-fidelity high dynamic-range reconstructions of both spatial and spectral structure.
Choices that effect performance (current MS-MFS implementation)

- Major Cycle runtime \( x \ N_{\text{taylor}} \) (and size of dataset)
  - \( N_{\text{Taylor}} \) residual images are gridded separately; \( N_{\text{Taylor}} \) model images are 'predicted'.
  - Wide-field corrections are applied during gridding (A-W-Projection, mosaicing).

- Minor Cycle runtime \( x \ N_{\text{taylor}} N_{\text{scales}} N_{\text{pixels}} \)

- Minor Cycle memory \( x \left[ 0.5 \left( N_{\text{taylor}} N_{\text{scales}} \right)^2 + N_{\text{taylor}} + N_{\text{taylor}} N_{\text{scales}} \right] N_{\text{pixels}} \)

Rate of convergence: Typical of steepest-descent-style optimization algorithms: logarithmic. Can control 'loop gain', 'cleaning depth'

Some source structures will handle loop-gains of 0.3 to 0.5 or more (0.3 is safe).

Runtimes reported by different people have ranged from 1 hr to several days.

\[ N_{\text{taylor}} N_{\text{scales}} N_{\text{pixels}} \]

\[ 0.5 \left( N_{\text{taylor}} N_{\text{scales}} \right)^2 + N_{\text{taylor}} + N_{\text{taylor}} N_{\text{scales}} \]
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 used for initial imaging (1256, 1384, 1648, 1776 MHz)

(All flagging and calibration done by D.Green)

Imaging Algorithms applied: MS-MFS with W-Projection

(terms=2, multiscale=[0, 6, 10, 18, 26, 40, 60, 80])

Peak Flux: 6.8 mJy
Extended flux: ~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 model
Wide-field effects of wide-band imaging
G55.7+3.4 : within the main lobe of the PB

\[ \alpha = -1.1 \]
\[ \alpha = -2.7 \]
\[ \alpha \approx -2.9 \]
\[ \alpha \approx -3.2 \]
Wide-band Self-calibration (using MS-MFS wideband model)

In CASA, 'clean' saved a wide-band model (calready=True). Or, use 'ft'.

- Can use MS-MFS on your calibrators too, if you don't know their spectra.
- Can also use this wide-band model for continuum subtraction.
Flagging + Examining your data for RFI

Flagging Modes:
- operator logs of known bad antennas and time-ranges / online flags
- shadowing between antennas (elevation-dependent)
- elevation-dependent flags
- known frequency ranges with bad RFI
- exact zeros (from the correlator), clip very high points, 'automatic flagging'

At L-Band, can use ~500 MHz with very rough flagging, ~800 MHz if done carefully.

One way to examine your data, is to run 'autoflag' and look at flag counts

- Inspect uncalibrated data to identify 'clean' regions
- Get an estimate of the fraction of total bandwidth usable for imaging.
- Obtain a flagversion to use as a starting point (first calibration/imaging pass).
- Run it on RFI monitoring data – feed-back information about un-documented RFI
Automatic RFI identification and flagging

TFCrop: Detect outliers on the 2D time-freq plane.

- Average visibility amplitudes along one dimension
- Fit a piece-wise polynomial to the base of RFI spikes
  - calculate 'sigma' of data - fit.
- Flag points deviating from the fit by more than N-sigma
- Repeat along the second dimension.
- Grow/extend flags along time, frequency, polarization

Can operate on un-calibrated data + one pass through MS 'testautoflag' in CASA 3.3. 'tflagdata' in CASA 3.4

RFLAG: Detect outliers using a sliding-window rms in time

- For each channel,
  - Calculate rms of real and imag parts of visibilities across a sliding time window.
  - Calculate the mean-rms across time, and deviations of these rmss from the mean.
- Search for outliers
  - (local rms > N x (median-rms + median-deviation)
  - For each timestep,
  - Calculate a median-rms across channels, and flag points deviating from this median.
- Grow/extend flags (pol, time, freq, baselines)

Needs calibrated data + two passes through data.
“RFLAG” in AIPS. 'tflagdata' in CASA 3.4
Visualize Data/Flags at run-time (testautoflag in CASA 3.3, tflagdata in CASA 3.4)
Example 1 (with extension along frequency, and statistics-based flagging)
Example 2  (an example where it is better to flag more than less..)
Example 3 (with broad-band RFI)
RFI identification strategies

– RFI is in-general frequency and direction-dependent (satellites / local/ … )

  => Inspect and decide flagging strategies separately per SPW / IF and Field.
  => Inspect baseline groups (short, mid, long... ), especially at higher frequencies

– Choose which correlations to operate on (extend flags to others)

  => RL, LR have higher RFI signal-to-noise, and RR and LL have stronger band-
    shape information (depends on what you're looking for)

– Operate on bandpass-corrected data

  => Do a bandpass calibration in a separate step, or use methods that account for
    uneven bandpass levels.

– Hanning Smoothing

  => when there is very strong RFI with ringing in nearby channels.
    ( for weak RFI, this can spread the RFI to more channels )
Summary

Broad-band receivers
  => better sensitivity

To achieve this sensitivity
  => Careful RFI removal
  => Spatial and spectral image reconstructions along with corrections for wide-field instrumental effects.

User choices (start simple):

- Will single-SPW imaging suffice?

- If not, then use MS-MFS:
  N-terms (is there enough SNR?)
  Multi-scales (measured vs desired)

- Wide Field-of-view?
  W-term, Primary-beam

Imaging results so far (high SNR):

- Point sources: OK
- Extended emission: DR of few 1000,
- Spectral-index accuracy: 0.02 ~ 0.2
- Wideband PB-correction: Upto HPBW
- RFI at L-Band: Lose 200 ~ 500 MHz

Ongoing work: HPC methods + more software integration + more efficient minor-cycle algorithms + uncertainty estimates, improving autoflag......