Overview of data combination methods - II

Urvashi Rau
National Radio Astronomy Observatory, USA

Improving Image Fidelity on Astronomical Data: Radio Interferometer and Single-Dish Data Combination

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Outline

Imaging Equations

Short Spacing Problem

Combination Methods

Image Combination

Starting Model

Joint Reconstruction

Joint Reconstructions within CASA

Example: Wideband Mosaic: Feathering, StartModel, SDINT
Imaging Equations

An interferometer samples the spatial Fourier transform of the sky brightness

$$I_{INT,\nu}^{obs} = \left[I_{\nu}^{sky} \cdot P_{\nu}\right] \ast I_{INT,\nu}^{psf}$$

Angular res = wavelength / max_baseline

Sampling is incomplete and short spacings (large scales) are not measured

A single dish telescope does a raster scan of a region of sky

$$I_{SD,\nu}^{obs} = I_{\nu}^{sky} \ast I_{SD,\nu}^{psf}$$

Angular res = wavelength / aperture_size

All spatial frequencies lower than that offered by the dish size are measured.
Short-Spacing Problem

Amp(Vis) vs. UV distance

$\nu_{min}$ UV range

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

High spatial frequencies measured only at $\nu_{max}$
Short-Spacing Problem

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 $\nu_{max}$.

$\nu_{min}$ UV range

$\nu_{max}$ UV range

UV distance

Amp (Vis)
Short-Spacing Problem

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 \( \nu_{\max} \)

\( \nu_{\min} \) UV range

\( \nu_{\max} \) UV range

Amp (Vis.)

UV distance
Short-Spacing Problem

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 $\nu_{\text{max}}$
Very large 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.

Leave out shortest baselines.

No short spacings to constrain the spectra.

=> False steep spectrum reconstruction.
Very large 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.

Retain some short spacing information.

Correct reconstruction of a flat spectrum

=> So, how to add this information?
Combination Methods

Image Combination

Starting Model

Joint Reconstructions
Image Combination

Weighted average between the SD image and the reconstructed INT image

AIPS : IMERG
\[ I^{sdint} = F^{-1} \left[ F[I^{interf}]_{\text{highuv}} + F[I^{sd(mod)}]_{\text{lowuv}} + f(F[I^{interf}], F[I^{sd(mod)}])_{\text{overlap}} \right] \]

AIPS/MIRIAD have options for automatic flux scale matching within UV annulus

MIRIAD : IMMERGE
\[ I^{sdint} = F^{-1} \left[ (1 - F[B_{sd}]) F[I^{interf}] + \frac{A_{interf}}{A_{sd}} \cdot F[I^{sd}] \right] \]

CASA : Feather
\[ I^{sdint} = I^{interf} + \frac{A_{interf}}{A_{sd}} (I^{sd} - I^{interf}) \]

I^{sd}_{\text{int}} = I^{sd}_{\text{int}} \rightarrow \text{Deconvolve} \left( B_{sd} \right) \rightarrow \text{Convolve} \left( B_{\text{interf}} \right) \]

NOD3 : Immerge
\[ I^{sdint} = I^{interf} + \frac{A_{interf}}{A_{sd}} (I^{sd} - I^{interf}) + \text{others} \]

Handling INT Primary Beams : Use Flat-Sky INT image for feathering
(or) Multiply SD image with INT PB before combining
Image Combination

– Straightforward to implement and use.
  => Many successful examples in the literature

– Single step method.
  => Relies on accurate INT-only reconstructions
  => Cannot recover from all INT-only errors due to deconvolution uncertainty
    (e.g.: Artifacts in the INT-only image, divergence, etc…)

– Noise/Error levels in the SD image and INT image must be comparable
  => If not, there can be a trade-off between noise and flux accuracy.
  => Considerable care is required in designing relative UV-Weighting functions

[ For Wideband Multi-term imaging, combination is to be done on Taylor coefficient maps ]
Starting Model

Method:

Use a (deconvolved) Single Dish Image as a starting model for the INT deconvolution.

Primary Beams:

For mosaic INT data, modify the single dish image model with the INT Primary Beam.

E.g.: For a flat-noise minor cycle normalization,

multiply the Single Dish image by the INT Primary Beam.

Features:

- Requires sufficient spatial-frequency overlap between SD and INT data

  => Otherwise, it reduces to adding the SD model to the INT-only reconstruction

[ For WideBand Multi-Term imaging, a multi-term SD model must first be created ]
Joint Reconstructions

Combine constraints from SD and INT data (or images) during deconvolution

**MOSMEM :**

- Image-domain chi-square constraint with separate terms for the INT and SD images within a Maximum Entropy algorithm (narrow-band imaging only). Has auto-scaling.

**TP2VIS :**

- Construct pseudo SD visibilities by sampling the FT of the deconvolved SD image according to the UV-sensitivity envelope of the SD measurement. Match meta-data with INT observation.

- Append SD pseudo visibilities to INT dataset and reconstruct together.

**Wideband SDINT :**

- Combine SD and INT images and PSFs via feathering prior to minor cycle deconvolution, but keep the data (and major cycles) separate. Simple/flexible implementation.

+ others
Joint Reconstructions

– A joint sky model is constructed using information from all scales at once
  => Errors from INT-only reconstructions are not burnt in at any stage.

– The SD beam is also deconvolved from the SD observed image
  => Better resolution than just the SD observed image

– Merge Images and PSFs (feathering as a weighting scheme for deconvolution)
  => Robust to a wide range of choices of scale factors and UV-weighting functions.

– Potentially better handling of high relative error in SD data
  => Less of a trade-off between noise suppression and flux accuracy.

– Watch out for position-dependent PSFs in CLEAN-based wideband mosaics (natural and artificial)
  – e.g. RFI-affected frequencies may differ across the field-of-view and telescopes, but algorithms may assume that measurement properties are invariant.
Joint Reconstructions within CASA

TP2VIS (Tuesday talk)
- Make SD pseudo-visibilitys and use with CASA tclean

SDINT
- Uses PySynthesisImager scripting interface
- Modular design for generic data combination
- Scripts and examples: https://github.com/urvashirau/WidebandSDINT
- A CASA task is being designed and evaluated
  (Suggestions for features and validation tests are welcome)
CASA: Spectral Line (Cube) Imaging: INT only

**INT Residual Visibilities**

Gridding + iFT

(Data - Model)

FT + De-Gridding

**Major Cycle (Imaging)**

**Minor Cycle (Deconvolution)**

Residual Image Cube

Model Image Cube
CASA: Spectral Line (Cube) Imaging: Joint INT + SD

Major Cycle (Imaging)
- INT Residual Image Cube
- Gridding + iFT
- SD Residual Image Cube
- (Data - Model)
- FT + De-Gridding

Minor Cycle (Deconvolution)
- Residual Image Cube
- Feathering (Image & PSF Cubes)
- Model Image Cube

(Observe Image - Smoothed model)
CASAJ : Wideband Multi-Term Imaging : Joint INT + SD

**Major Cycle (Imaging)**

1. **Gridding** + iFT → INT Residual Image Cube
2. INT Residual Visibilities
3. **FT** + De-Gridding

**Minor Cycle (Multi-Term MFS Deconvolution)**

1. RESIDUAL IMAGE CUBE
2. RESIDUAL IMAGE CUBE (OBSERVED IMAGE - SMOOTHED MODEL)
3. FEATHERING (IMAGE & PSF CUBES)
4. MULTI-TERM RESIDUAL IMAGES
5. MODEL IMAGE CUBE
6. MULTI-TERM MODEL IMAGES
CASA : Wideband Multi-Term Imaging : Joint INT + SD

Data-to-Image transforms can differ across instruments.
Example: Simulation

Sky Brightness:

Extended: 10 – 20 arcmin Gaussians, Alpha = 0.0
(Max INT scale at 1.5 GHz: 20 arcmin)

Compact: 3 point sources
Alpha of -1.0, -1.0, and 0.0 from left to right.

VLA D-config + GBT: 1.0, 1.5, 2.0 GHz

(1) Single Pointing Simulation
- No Primary Beams
- Wideband Short Spacing Problem

(2) Mosaic Simulation
- 25 Pointings
- Frequency dependent Primary Beams
Wideband Imaging – INT, SD, SDINT

Intensity and Spectral Index (deconvolver='mtmfs', nterms=2)

INT only

SD only

INT-only reconstruction has errors at mid and large scales

SDINT spectral index is accurate to within 0.15 (typical of any multi-scale result).
Wideband Imaging – Feathering, Startmodel, SDINT

Intensity and Spectral Index (deconvolver='mtmfs', nterms=2)

Multi-term Feather

Wideband SDINT

Multi-term StartModel

Feathering did not fully recover from INT-only errors on spectral index.

StartModel did not provide sufficient constraints on the INT-reconstruction
Mosaic Cube

INT

SD

Feather

SDINT
Wideband Mosaic - INT, Feather and SDINT

INT-only Multi-term Mosaic

Feathered Multi-term Mosaic

Wideband Mosaic SDINT

With a mosaic, the INT-only spectral index is better but still too steep (-0.5)

Feathering gets close (err: +/- 0.3)

SDINT gets alpha accurate within +/- 0.15
High relative Single Dish noise

Added random noise to the true sky before convolution with the SD beam.
~ Proxy for pointing errors?

Lower the SD gain by a factor required to match image noise with IN image, but not too much to incur bias in reconstructed flux.

Bias due to weighting is less than due to direct scaling.

Intensity: Flux is accurate. Noise is down.

Alpha: Minor improvement
Summary of Data Combination Methods

– **Image Combination** : When INT and SD images are both well-behaved
  – Effective and simple
  – Errors arise from trade-offs between flux accuracy and error control.

– **Start Model** : When INT and SD data overlap well in UV-space
  – Easy to use with existing image reconstruction solvers

– **Joint Reconstructions** : When deconvolution just needs more constraints from the data
  – SD+INT, joint mosaics, multi-frequency-synthesis before reconstruction.
  – More robust to relative weighting schemes than a single-step approach
  – Faster convergence, less divergence, less need for masks, more accurate model
  – Instability can occur when the data do not match a uniform instrument model