Mosaicing and Single-Dish Combination

CASS Radio Astronomy School 2012

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Mosaicing with interferometers

- Nyquist sampling
- Image formation

Combining with single-dish data

- The short spacing problem
- Image v. Fourier plane combination
<table>
<thead>
<tr>
<th>SINGLE DISH ZERO SPACING</th>
<th>INTERFEROMETER</th>
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<tbody>
<tr>
<td>No</td>
<td>Single pointing</td>
</tr>
<tr>
<td>Yes</td>
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- Observation type: Interferometer
- Single pointing: Yes
- Multi-field: No
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# Example Instruments

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<td>JVLA</td>
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<td>Yes</td>
<td>Multi-field</td>
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<td>ATCA</td>
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<td>MWA+PKS</td>
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<td>ALMA</td>
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Outline

Mosaicing with interferometers
- Nyquist sampling
- Image formation

Combining with single-dish data
- The short spacing problem
- Image v. Fourier plane combination
• Ekers & Rots (1979) Image Formation, IAU Coll 49, 61.
• Sault & Killeen, miriad manual, ch.21.
• Bhatnagar, Golap & Cornwell (2005) ASPC 347, 96
• Hull et al. (2010) PASP, 122, 1510.
Mosaicing with Interferometers

Noun
mosaic (plural mosaics)

source: wiktionary

1. A piece of artwork created by placing colored squares (usually tiles) in a pattern so as to create a picture.
2. (genetics) An individual composed of two or more cell lines of different genetic or chromosomal constitution, but from the same zygote.
3. (botany) A viral disease of plants.
4. A composite picture made from overlapping photographs.
ASKAP correlator room (Photosynth by Staveley-Smith)
Galactic Centre: VLA (Yusef-Zadeh et al.)
Mosaicing is necessary to create an image larger than the field-of-view of the telescope:

ATCA primary beam
Nyquist sampling of sky

$D$ is dish diameter

Rectangular grid
$\Delta \theta = 16.5'$ at 21cm at ATCA

Hexagonal grid
$\Delta \theta = 19.0'$ at 21cm at ATCA
Super-Nyquist sampling

OTF interferometry:
- ATCA+WBCORR: AT20G (Ekers et al.)
- ATCA+CABB: CORNISH-S (Hoare, Wieringa et al.)
- IRAM Plateau de Bure interferometer

[Diagram showing primary beam, data dumped, and sky position]
Step I: observe different pointings
Step 2: make individual images
Step 3: make combined image

Mosaicing equation:

\[ I_t(x) = W(x) \frac{\sum_i P(x - x_i)I_i(x)}{\sum_i P^2(x - x_i)} \]

*P* is primary beam response; \( I_i \) are the individual images.

Also applies to PAFs.
ATCA HI mosaic

(de Blok et al.)

Mosaiced with ATCA 375,750,1.5k,6k arrays

\[ I_{\text{linear mosaic}}(l,m) = \frac{\sum P A(l - l_p, m - m_p) I_p^{\text{dirty}}(l,m)}{\sum P A^2(l - l_p, m - m_p)} \]

N6822 or Barnards Galaxy
Comparison of $u$-$v$ coverage

Individual

Extra $u$-$v$ coverage in radial and azimuthal direction

Mosaic
Background theory:
- Ekers & Rots (1979) pointed out that one can think of a single dish as a collection of sub-interferometers.
Extending this formalism to interferometers shows that an interferometer doesn’t just measure angular scales \( \theta = \frac{\lambda}{b} \) it actually measures:

\[
\frac{\lambda}{b + D} < \theta < \frac{\lambda}{b - D}
\]

“Fourier coverage”
Why is $u$-$v$ coverage improved?

interferometer beam $\times$ Primary beam = Image domain
Why is $u$-$v$ coverage improved?

Baseline sampling * illumination function = Fourier domain
Comparison of $u$-$v$ coverage

Individual

Extra $u$-$v$ coverage in radial and azimuthal direction

Mosaic
Ways to combine multiple pointings

- Combine dirty images, then deconvolve with spatially-variant beam
- Deconvolve, then combine images*
- Jointly deconvolve dirty images

* potential loss of information, but recommended for discrete sources (primary beam errors less important)
Examples (SMC)

Dirty image

Linear mosaic of deconvolved images

Joint deconvolution
Complications

Planarity

- Exact projection no problem with co-planar arrays; w-axis distortion over wide fields will occur with non-planar arrays (widefield imaging; Cornwell lecture on Fri).

Bandwidth

- Dealing with frequency-dependence of both primary beam and sky can be problematic (multi-frequency imaging; Urvashi lecture).

Primary Beam and Pointing

- Good beam model needed; high dynamic range may require pointing self-calibration; OTF interferometry produces sausage-shaped beams.

Doppler

- Doppler corrections are dependent on time and position, so not strictly applicable in visibility domain.

Off-axis

- Off-axis calibration and polarimetry poor for some radio telescopes.
Mosaicing with interferometers
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  - Image formation
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  - Image v. Fourier plane combination
Merging Interferometer and Single-Dish Data
Ekers & Rots (1979) pointed out that one can think of a single dish as a collection of sub-interferometers.
Interferometer:
Asymmetric cross-correlations
$C_{ij}(\tau) \neq C_{ij}(-\tau)$
\[\Leftrightarrow\]
Complex visibilities $V(\nu)$

Single dish:
Symmetric auto-correlations
\[\Leftrightarrow\]
Real visibilities
Holdaway (1999) ASP Conf. Series 180
The short (zero)-spacing problem

UV plane

PSF

ideal

Central hole

Typical interferometer

Braun & Walterbos (1985)

Negative ‘bowl’
HI in the E-arm of the LMC (ATCA 4x750 m)
(post-MEM deconvolution)

Negative 'bowl'
HIPASS2 1.4 GHz map (Calabretta et al. 2012)
Several ways to combine...

- Combine data in IMAGE plane
  - add dirty images (and beams), then deconvolve
  - joint deconvolution*

- Combine data in FOURIER plane
  - combine interferometer uv data and single-dish pseudo-visibilities
  - add transform of deconvolved interferometer and single-dish images*

*good for mosaics
Merging interferometer and single-dish data

The Fourier (UV) plane

Interferometer data

Single dish data

Overlapping region
Combination in Image Plane
(Stanimirovic et al. 1999)

Combined image:

\[ I_{\text{tot}} = w_{\text{int}} I_{\text{int}} + w_{\text{sd}} f_{\text{sd}} I_{\text{sd}} \]

Weights:

\[ w_{\text{int}} = \frac{\Omega_{\text{sd}}}{\Omega_{\text{int}} + \Omega_{\text{sd}}} \]
\[ w_{\text{sd}} = \frac{\Omega_{\text{int}}}{\Omega_{\text{int}} + \Omega_{\text{sd}}} \]
Combining dirty images (Stanimirovic 1999, 2002)
Joint deconvolution

Maximize “entropy”:

\[ \mathcal{H} = - \sum_i I_i \ln \left( \frac{I_i}{M_i e} \right) \]

Subject to

1. \[ \sum_i \left( I_{\text{int}}^D - B_{\text{int}} \ast I \right)^2 < N \sigma^2_{\text{int}} \]
2. \[ \sum_i \left( I_{\text{sd}}^D - \frac{B_{\text{sd}} \ast I}{f_{\text{sd}}} \right)^2 < M \sigma^2_{\text{sd}} \]

This may be the best approach for ALMA or Mopra+ATCA data
Joint deconvolution (Stanimirovic 1999, 2002)
Combination in Fourier plane

1. Appropriately weight data in overlap region
   - E.g. taper interferometer Fourier-plane data with transform of SD beam
   - Multiply SD Fourier-plane data with transform of interferometer beam

2. Adjust flux density scales (relative calibration)

3. Add in Fourier plane!
Weighting function in Fourier plane (Sault & Killeen)
Example of Fourier plane combination: McClure-Griffiths et al.
Comparing different methods using the SMC in HI at 169 km/s (Stanimirovic 2002)

immerge (Fourier)  linear combination (image)
mosmem default image=Parkes  joint deconvolution
MWA 32T (Hurley-Walker) Parkes 408 MHz, scaled to 150 MHz
(Haslam)
Hurley-Walker
Check you understand your calibration

Relative scaling of data in overlap region from immerge (120-170 km/s HI in SMC)
Complications

**Single dishes:**
- Flux density and beam determination may be tricky
- Frequency-dependent beam properties
- Beam size may depend on elevation
- Flux density scale may depend on angular scale (e.g. HIPASS)
- Significant far-out sidelobes (main beam efficiency ~70%)

**Interferometers**
- uv-coverage scales with frequency, especially if data flagged
- Pre-deconvolution PSF depends on position (mosaic)
- Post-deconvolution PSF varies with S/N ratio and angular scale
- Fourier plane coverage may be poor
- S/N may be low in overlap region
Cen A: 406 ATCA fields+ HIPASS2 (Feain et al 2011)
LMC: 1344 ATCA fields+PKS (Kim et al. (2003))
Mosaicing essential for wide fields; *modus operandi* for ASKAP.

Single-dish data essential if your image has large-scale structure approaching the interferometer primary beam size.

Parkes+ATCA: excellent 1-20 GHz; ALMA: excellent 100-900 GHz.

For mosaicing and single dish combination, linear Fourier plane combination mostly works well

miriad and casa tasks (e.g. invert, image, immerge, feather) work well.