Short-Spacings Correction From the Single-Dish Perspective
Snezana Stanimirovic (UC Berkeley)

VLA: FWHM=1''
Areccibo: FWHM=3''

'Black magic' for bringing the best of both worlds: short-spacings correction, or combination of single-dish and interferometer data

Outline:

- Breath and depth of combining interferometer and single-dish data ...
- A recipe for observing extended objects (with detours):
  1. the briefest possible intro to interferometry
  2. demonstration of the short-spacings problem
  3. what can we do about the short-spacings problem?
  4. different methods for data combination
- Some recent examples
- Future directions...

Single-dish and interferometer data frequently need to be combined ...

- when observing EXTENDED objects (larger than $\lambda/2_{\text{min}}$ or interferometer's primary beam) [you'll see why exactly]
- when MOSAICING: if you need to mosaic, you'll need to add single-dish data.
- especially at mm wavelengths where TOTAL POWER info is almost always needed.

A Recipe for Observing Extended Objects:

- Ingredients:
  1. an extended object (e.g. Small Magellanic Cloud)
  2. an interferometer (e.g. VLA, ATCA, BIMA, ATA)
  3. a single-dish (e.g. Arecibo, GBT, Parkes, 12m)
- Procedure:
  1. observe with an interferometer
  2. observe with a single-dish
  3. take advantage of both worlds: combine!
- This recipe makes:
  1. pretty pictures: lots of resolution elements, no image artifacts
  2. high resolution images with the TOTAL POWER information (accurate fluxes, masses etc.)
  3. images sensitive to a wide range of spatial scales.

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Step 1: 'Mosaic' with an interferometer

4.5 degrees = 4.7 kpc

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How does an interferometer actually work?

van Cittert-Zernike theorem:

$V(t) = \int_{-\infty}^{\infty} A(t) e^{-2\pi i \nu t} dt$

$V(u, v) = \int_{-\infty}^{\infty} A(t) e^{-2\pi i \nu t} dt$

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More baselines, more u-v tracks!

Australia Telescope Compact Array (ATCA), an E-W linear array.
5 antennas, 5(5-1)/2 diff. baselines

Highest spatial frequency: ~495m/0.21m
Angular resolution = 1.6'

Lowest spatial frequency: ~31m/0.21m
Can not see structure > 24'

And what is the result?
Small Magellanic Cloud at 1.4 GHz, interferometric (ATCA) observations only.

How severe the problem is?
Further away from the nucleus, the less flux is recovered.

And what is the result? WHY?
Spatial frequency domain
Image domain

What can we do about the short-spacings problem?
- How to provide missing short-spacings?
  1. Homogeneous scheme = all antennas of the same size
  2. Heterogeneous scheme = different-sized antennas
- How to combine short-spacing data with that from an interferometer?
- As few gaps in the u-v plane as possible!
  Single-dish diameter > min. interferometer baseline.
- Must match flux scales of both data sets.
Step 2: ‘Mosaic’ with a single dish

- Point to many directions & grid all spectra.
- 1540 different pointings with the Parkes (64 m) telescope!
- Go multi-beams!

Step 3: Cross-calibration of two data sets

Interferometer and single-dish data should have the same flux density scale.

Calibration scaling factor: $f_{\text{cal}} = \text{S} \text{int}/\text{S} \text{sd}$

Compare surface brightness of your object in the overlap region in the u-v plane.

Step 4: Combination of single-dish and interferometer data

- **Data combination in the Fourier domain:**
  - Miriad’s IMMERGE, Aips’ IMERG, aips++’s IMAGER
  - Bajaja & Albada (1979); Vogel et al. (1984); Sault & Killen (2003)

- **Data combination in the image domain:**
  1. ‘Linear Combination’
     - a combination of tasks, Ye & Turtle (1991); Stewart et al. (1993); Stanimirovic et al. (1999)
  2. ‘Non-linear combination’ or ‘Merging during deconvolution’
     - Miriad’s MOSMEM through either ‘default image’ capability or ‘joint deconvolution’

Single-dish as an interferometer!

Can be retrieved by scanning across your object, based on Ekers & Rots (1979).

'Phased array' → continuous range of baselines available from 0 to D.

Similar mathematical representation for both interferometers and single-dishes!

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Fourier domain combination

$V_{\text{int}}(k) = w_{\text{sd}}(k)P_{\text{sd}}(k) + f_{\text{int}}w_{\text{sd}}(k)P_{\text{int}}(k)$

$w_{\text{sd}}(k) + w_{\text{sd}}(k) = \frac{1}{g_{\text{sd}}} \exp \left( -\frac{2\pi k^2}{g_{\text{sd}}^2} \right)$

And what is the result?

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**Linear combination**

\[
I_{\text{comb}} = w_{\text{imf}} I_{\text{imf}} + w_{\text{sd}} I_{\text{sd}} \\
B_{\text{comb}} = w_{\text{imf}} B_{\text{imf}} + w_{\text{sd}} B_{\text{sd}} \\
w_{\text{imf}} = \frac{I_{\text{imf}}}{I_{\text{imf}} + I_{\text{sd}}} \\
w_{\text{sd}} = \frac{I_{\text{sd}}}{I_{\text{imf}} + I_{\text{sd}}}
\]

Wright (2004): CARMA Memo 27
Simulations show this as the best method, but it depends on quality of SD data.

**Non-Linear combination**

**Final Results:**

Small Magellanic Cloud BEFORE short-spacings correction.

**Final Results:**

Small Magellanic Cloud AFTER short-spacings correction.

**Remarks on different methods:**

- In recent years, all methods are commonly used from small 7-point to huge >1000-point mosaics.
- All methods produce comparable results in the case of high S/N data (e.g., SMC).
- ‘Feathering’ method is the fastest and the least computer intensive, great results, very robust.
- For low S/N data, as is often case at mm wavelengths, ‘linear’ method seems advantageous: no need for deconvolution by the single-dish beam nor deconvolution of int. dirty maps, it is easy to implement and automate.
- ‘MEM’ method is theoretically the best way but heavily dependant on the quality of the SD image.

**Data combination is routinely performed with a great success: examples**

<table>
<thead>
<tr>
<th>Array</th>
<th>(B_{\text{inm}})</th>
<th>SD</th>
<th>(D_{\text{inm}})</th>
<th>(v) (GHz)</th>
<th>Method</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATCA</td>
<td>25</td>
<td>Parkes</td>
<td>64</td>
<td>1.4</td>
<td>linear</td>
<td>Smirnov et al. 1999</td>
</tr>
<tr>
<td>ATCA</td>
<td>25</td>
<td>Parkes</td>
<td>64</td>
<td>1.4</td>
<td>immerge</td>
<td>McClure-Griffiths 2005</td>
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<tr>
<td>OVRO</td>
<td>15</td>
<td>IRAM</td>
<td>30</td>
<td>8.8</td>
<td>immerge</td>
<td>Lang et al. 2002</td>
</tr>
<tr>
<td>BIMA</td>
<td>8</td>
<td>FCRAO</td>
<td>14</td>
<td>115</td>
<td>linear</td>
<td>Pound et al. 2003</td>
</tr>
<tr>
<td>BIMA</td>
<td>8</td>
<td>12m</td>
<td>12</td>
<td>113</td>
<td>mosmem</td>
<td>Welch et al. 2000</td>
</tr>
<tr>
<td>BIMA</td>
<td>8</td>
<td>12m</td>
<td>12</td>
<td>115</td>
<td>linear</td>
<td>Heffer et al. 2003</td>
</tr>
<tr>
<td>VLA D</td>
<td>35</td>
<td>GBT</td>
<td>100</td>
<td>8.4</td>
<td>feathering, aips++</td>
<td>Shepherd et al. 2003</td>
</tr>
<tr>
<td>VLA D</td>
<td>35</td>
<td>AO</td>
<td>305</td>
<td>1.4</td>
<td>immerge</td>
<td>Lee et al.; Rabieh et al.</td>
</tr>
</tbody>
</table>
Recent Examples: IC443 Lee et al. (2005)

Recent Examples: SGPS = ATCA+PKS

Future Telescopes (arrays of small antennas):

<table>
<thead>
<tr>
<th>Array</th>
<th>$B_{\text{min}}$ (m)</th>
<th>SD</th>
<th>$D_{\text{min}}$</th>
<th>$v$ (GHz)</th>
<th>Method</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARMA</td>
<td>4</td>
<td>OVRO</td>
<td>10.4</td>
<td>115, 230, 345</td>
<td>provide OTF capability for OVRO</td>
<td></td>
</tr>
<tr>
<td>ALMA</td>
<td>15</td>
<td>ACA</td>
<td>7.12</td>
<td>30-950</td>
<td>short spacings high priority!</td>
<td></td>
</tr>
<tr>
<td>ATA</td>
<td>~8</td>
<td>ATA</td>
<td>6.1</td>
<td>1.4-11.12</td>
<td>homogeneous array</td>
<td></td>
</tr>
</tbody>
</table>

Future Telescopes (cont):

- Future trend: heterogeneous arrays with small dishes.
- Smaller dishes have lower systematic errors and larger field of view so are faster than large single dishes (Holdaway & Helfer 1999).
- Data combination has been the key driver for recent antenna designs and array configurations (CARMA, ALMA, ATA).
- Shadowing effects for closely packed antennas (Subrahmanyan & Deshpande 2004)
- Data combination (joint deconvolution) depends greatly on the quality of SD data (pointing errors, thermal noise, ground pick up, atmospheric fluctuations).

Particular (practical) single-dish needs:

- A large enough area must be covered with single-dish observations (edge-effect issue).
- Nyquist sampling is important to avoid aliasing during deconvolution (Vogel et al. 1984).
- S/N ratio of interferometer and single-dish data should be comparable.
- In general, and especially for the cross-calibration a very good knowledge of the single-dish beam is required (can start with a Gaussian first).
- At mm wavelengths main issues are: pointing and calibration accuracy.

Summary:

- Single-dishes have a huge role in providing information that complements interferometric observations.
- Short-spacings correction is a MUST in most of observations at mm wavelengths and may soon become a part of a general observing scheme (e.g. ALMA).
- Easy combination of single-dish and interferometer data available and frequently done for different telescopes and for sources of greatly varying sizes.
- 3 discussed methods work fine and with comparable results.
- Overlap of spatial frequencies is crucial for cross-calibration.
Bibliography:

- Stanimirovic 2002, ASP Conf. Ser. 278
- Holdaway 1999, ASP Conf. Ser. 180
- Holdaway & Helfer 1999, ASP Conf. Ser. 180
- 'Interferometry and Synthesis in Radio Astronomy' Thompson, Moran & Swenson (2001)
- Sault & Killeen 2003, Miriad Users Manual