Confusion, the sky model and realistic simulations

Randall Wayth (CfA)

with

“team Greenhill” (Greenhill, Mitchell, Sault)
“team MAPS” (Doeleman, Bhat)
Ashes Update:

England all out for 350. Australia wins the ashes.
Outline

• Context:
  – What's it going to take to calibrate the MWA?
  – What do we need to test the real-time pipeline?

• Part I: Estimating Confusion
• Part II: Generating realistic simulation data
Confusion – basics

- Sources inside synthesised beam
  - Depends on size of beam
  - Flux densities add up

- Sidelobes of sources out of synthesised beam
  - $S = \text{source strength}$
  - $P = \text{pri beam power}$
  - $\sim P*S/N_{\text{ANT}}$ (snapshot)

~3 arcmin

~20 degrees
Confusion – theory

• Factors of interest:
  – Differential source count distribution: \( n(S) \)
  – Primary beam: \( P(\Omega) \)
  – Synthesised beam: \( B(\Omega) \).
  – Diffuse emission (not included yet)

• Calculate variance in pixels due to all sources in the sky:

\[
\sigma^2 = \int_{\Omega=0}^{2\pi} \int_{S=0}^{S_{\text{MAX}}} S^2 n(S) B^2(\Omega) P^2(\Omega) dS \ d\Omega
\]
Confusion – theory

• We want to set a source detection threshold, $q$, of $q$ sigma, so $S_{\text{MAX}} = q\sigma$, $q=5$ (or more)

• Sources in sidelobes of primary beam are attenuated, so $S_{\text{MAX}} = \frac{q\sigma}{|P(\Omega)|}$

• For $B(\Omega)$, assume $= 1$ in beam, $B_{\text{RMS}} = \frac{1}{N_{\text{ANT}}}$ outside

\[
\sigma^2 = \int_{\Omega=0}^{2\pi} \int_{S=0}^{q\sigma/|P(\Omega)|} S^2 n(S) B^2(\Omega) P^2(\Omega) dS d\Omega
\]
Confusion

- For \( n(S) = kS^{-\gamma} \), with \( P(\Omega) \) and \( B(\Omega) \) a "tophat" function with width \( \theta_{PB}/2 \) and \( \theta_{SB}/2 \), result is analytic:

\[
\sigma = \left( \frac{2\pi k}{3-\gamma} \left[ B_{RMS}^2 \left( 1 - \cos \theta_{PB} \right) + \left( 1 - \cos \theta_{SB} \right) \right] \right)^{\frac{1}{y-1}} q^{\frac{3-\gamma}{y-1}}
\]

Solid angle of primary beam \hspace{1cm} Solid angle of synthesised beam

- This is useful to check numerical integration and is a similar result to Condon (1974), extended to suit synthesis images
Source counts ("logN-logS")

Models for $n(S)$:

- **Power law:**
  
  \[ n(S) = kS^{-\gamma}, \quad \gamma = 1.65 \]
  
  (not realistic for large $S$)

- **Perley & Erickson:**
  piecewise linear (VLA memo 146, after Pearson, 1974)

- **Wieringa (1991)**

- **(Scaled to 150MHz)**
Primary Beam

- 150MHz
- Primary beam: 30 deg (FWHM) Airy disc (rotational symmetry)
- Synth beam: 3.4'
- $2\pi$ steradian

![Graph showing relative power vs zenith angle for Airy disc and Tile]
Results

- This table shows 5σ confusion limits for different contributors, beam models and source counts.
- 150MHz, 30 deg FWHM primary beam (PB)

<table>
<thead>
<tr>
<th>Model</th>
<th>Synth beam only</th>
<th>Tophat PB only</th>
<th>Real PB only</th>
<th>Synth beam + tophat PB</th>
<th>Synth beam + real PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-law</td>
<td>0.042</td>
<td>0.002</td>
<td>0.038</td>
<td>0.052</td>
<td>0.116</td>
</tr>
<tr>
<td>Wieringa</td>
<td>0.078</td>
<td>0.003</td>
<td>0.045</td>
<td>0.095</td>
<td>0.133</td>
</tr>
<tr>
<td>Perly + Erickson</td>
<td>0.052</td>
<td>0.005</td>
<td>0.031</td>
<td>0.061</td>
<td>0.089</td>
</tr>
</tbody>
</table>

All values in Jy
Shep's work

- **X** Wieringa total
- **X** Wieringa synth beam only

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**Figure 1:** Comparison of continuum confusion limits to thermal noise limits for the MWA. Confusion limits estimated from 327MHz source counts (Wieringa 1991) extrapolated to MWA frequencies assuming the spectral indices shown.
Conclusions – (Part I)

- The confusion limit for the MWA at 150MHz will be around 0.1Jy (with peeling)
  - Results from different approaches agree
- Confusion noise comes partly from sources in synthesised beam and partly from sources in the sidelobes of the tile beams. (does not include diffuse emission!)
  - We can (in principle) reduce the effect of the latter
- Simplified (tophat) models of the primary beam severely underestimate confusion
Part II: GSM & Simulation

• For simulations
  – We need a “real enough” sky to test the calibration and imaging software

• For the real array: GSM Visibility Predictor
  – Needed to subtract static sky from the data to reduce sidelobe confusion and look for transients
Full sky simulations

• Aim:
  – Realistic model of the sky to test the real-time system including frequency and polarisation
  – Realistic virtual telescope including antenna element (dipole) power pattern, imperfect manufacturing and imperfect gains

• Intermediate goal:
  – Data that are good enough to test the calibration systems
  – Realistic tile response (dipole pattern, gain errors, position errors)
Outline: To improve modeling of foreground emission in the MHz-GHz range.

Work from Angelica de Oliveira-Costa
Making Sims

- Ingredients: 1

```plaintext
0000-506  00  00  09.2 -50  41  31  00  02  42.5 -50  24  49  .3  4  1.28  .06  P  321.4 -64.9
0000-307  00  00  12.4 -30  45  09  00  02  45.9 -30  28  27  .2  3  1.49  .06  P  12.6 -78.8
0000-566  00  00  20.4 -56  37  45  00  02  53.5 -56  21  03  .5  5  2.07  .10  P  316.2 -59.5
0000-134  00  00  33.3 -13  24  41  00  03  06.9 -13  07  59  .3  8  .85   .08  P  81.6 -72.0
0000-149  00  00  36.3 -14  57  12  00  03  09.9 -14  40  30  .2  4  1.99  .10  P  78.4 -73.2
0000-165  00  00  36.6 -16  31  52  00  03  10.2 -16  15  10  .3  4  1.08  .05  P  74.7 -74.4
0000-550  00  00  37.5 -55  01  38  00  03  10.5 -54  44  56  .5  4  2.76  .13  P  317.3 -61.0
0000-362  00  00  39.8 -36  13  16  00  03  13.2 -35  56  34  .2  3  2.44  .08  P  349.3 -76.5
0000-593  00  00  41.1 -59  22  27  00  03  13.9 -59  05  45  .8  7  .82   .07  P  314.3 -57.0
0000-177  00  00  48.5 -17  43  53  00  03  22.1 -17  27  11  .2  4  6.51  .27  P  71.5 -75.3
0000-673  00  00  53.1 -67  18  11  00  03  25.4 -67  01  29  1   P  310.1 -49.4
0000-160  00  00  53.9 -16  03  53  00  03  27.5 -15  47  11  .3  5  1.23  .08  P  76.0 -74.1
0001+128  00  01  07.4  12  49  38  00  03  41.3  13  06  20  .3  6  3.81  .17  P  105.4 -48.1
0001-121  00  01  09.1  12  08  30  00  03  42.7  11  51  48  .3  8  1.15  .10  84.4 -71.1
0001-179  00  01  09.4  17  57  10  00  03  42.9  17  40  28  .2  4  1.59  .06  P  71.1 -75.5
0001-114  00  01  10.8 -11  25  09  00  03  44.4 -11  08  27  .3  4  .94   .04* P  85.6 -70.5
0001-237  00  01  14.6 -23  46  24  00  03  48.1  23  29  42  .2  3  1.77  .06  P  49.0 -78.6
0001-387  00  01  20.7 -38  43  46  00  03  53.9  38  27  04  .3  5  .90   .05  P  341.3 -74.9
0001-312  00  01  21.8 -31  16  29  00  03  55.1  30  59  47  .2  3  2.52  .09  P  9.7  -78.9
0001-111  00  01  22.3 -11  09  53  00  03  55.9  10  53  11  .2  3  1.02  .04  P  86.1 -70.3
0001+058  00  01  26.6  05  50  58  00  04  00.5  06  07  40  .3  7  1.28  .08  P  102.2 -54.8
0001-233  00  01  29.4  23  23  39  00  04  02.8  23  06  57  .2  4  1.23  .05  P  50.8 -78.6
0001+170  00  01  35.5  17  01  10  00  04  09.5  17  17  52  .2  6  1.61  .06  P  107.1 -44.1
0001-531  00  01  40.3  53  10  35  00  04  12.9  52  53  53  .7  17  1.25  .24  P  318.6 -62.8
0001-224  00  01  43.9 -22  29  36  00  04  17.3 -22  12  54  .4  6  .81   .06  P  55.0 -78.2
```

[rwayth@play ~]$/WMA]$
```
Making Sims

• Ingredients:
  - Molonglo 408 MHz reference catalogue (MRC)
    • Point source catalogue.
    • Resolution: \(\sim\)arcmin
    • Dec: +18 to -85
    • Sources stronger than \(\sim\)0.5 Jy
Making Sims

- Ingredients: 2

This is a logarithmic scale
Making Sims

• Ingredients:
  - Molonglo 408 MHz (MRC)
  - Haslam 408MHz all-sky map
    • ~1/3 degree resolution
    • Point sources are not well represented (good)
    • Emission dominated by the Galaxy
Making Sims

- Ingredients: 3

MAPS = MIT Array Performance Simulator

visgen
Making Sims

- Ingredients: 3
  - Molonglo 408 MHz (MRC)
  - Haslam 408MHz all-sky map
  - MAPS
  - **In:** sky model, array definition, observing parameters
  - **Out:** visibilities “observed” with a simulated telescope
Making Sims

• Ingredients: 4
  - Plus:
    • CFITSIO
    • FFTW
    • SLALIB/C
Making Sims

• Ingredients: 4
  – Molonglo 408 MHz (MRC)
  – Haslam 408MHz all-sky map
  – MAPS
  – Glue

• Method:
  1) Make sky
  2) MAPS
  3) MAPS 2 UVFITS
  4) miriad

This is a log scale image
Simulation Specs...

- 250 antennas
- 1.5 km max baseline
- 10m min baseline
- $r^{-2}$ density
- 200 brightest sources from MRC (ex CenA)
- Sky from Haslam
- coplanar
- antennas consisting of 4x4 phased array of isotropic receivers
Input sky map
Dirty sky map with tile response
(tile pointing at zenith)
Dirty sky map *without* tile response
Results so far...

- Have generated simulated visibilities for
  - Single freq, single snapshot (any HA, LAT)
  - Takes ~10 mins, requires 2GB memory
  - Pipeline is in place, straightforward to generate long integrations & wide frequencies from here

- Sidelobes from extended sources (gal, Cen A) are significant
  - A few times what was expected from point sources alone
  - Caveats: 10m minimum baseline, snapshot, monochromatic

- Data essential for testing, come and get it!
Next...

- non-ideal antenna elements
- Spectral indices on sources, sky
- Polarisation on sources
- Polarisation of antenna response
Fin