Wide-field VLBI Techniques: A Beginner’s Guide

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Overview

1. Wide-field VLBI
   - VLBI Sensitivity
   - Correlation
   - Imaging

2. UV Shifting
   - Transforming correlated data
   - Using the baseline vectors
   - Using correlator delay model

3. Using Wide-field VLBI

4. Future Work
   - Future Work
   - Conclusions
I would like to acknowledge useful discussions and material help from many people.

⇒ Adam Deller

⇒ Walter Brisken

Also many others including (in no particular order) Franco Mantovani, Steven Tingay, Walter Alef, Helge Rottman, Enno Middelberg, Richard Porcas
A simple ‘figure of merit’

For an interferometer with dishes of diameter $d$ separated by $D$ the primary beam $\Theta$ and resolution $\theta$ are given by

$$\theta \approx \frac{\lambda}{D}, \Theta \approx 1.22 \cdot \frac{\lambda}{d} \quad (1)$$

So the number of resolution units across the primary beam is

$$\frac{\Theta}{\theta} = \frac{D}{d} \Rightarrow n_{\text{pixel}} \sim \left(\frac{D}{d}\right)^2 \quad (2)$$

n.b. for imaging purposes the true number of pixels will be $\sim 10 \times$ bigger
### Image size of different arrays

<table>
<thead>
<tr>
<th>Array</th>
<th>$d$ (m)</th>
<th>$D$ (km)</th>
<th>$D/d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA</td>
<td>25</td>
<td>36</td>
<td>1440</td>
</tr>
<tr>
<td>MERLIN</td>
<td>32</td>
<td>217</td>
<td>8680</td>
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<tr>
<td>EVN</td>
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<td>10180</td>
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</tr>
<tr>
<td>VLBA</td>
<td>25</td>
<td>8611</td>
<td>344440</td>
</tr>
</tbody>
</table>

n.b. All arrays in longest-baseline/smallest-antenna configuration
Three Caveats

Widefield VLBI techniques are only useful if:

⇒ There are enough bright sources on the sky that more than one will fall within the primary beam

⇒ It is possible to correlate with sufficient resolution to cover the large area

⇒ There are appropriate techniques to handle the resulting large datasets
Caveat 1: Density of Detectable Sources

⇒ This depends on the sensitivity of VLBI
⇒ However even a decade ago it was possible to detect multiple sources
⇒ Sensitivity (and therefore density of detectable sources on the sky) is increasing all the time
Caveat 2: Offset source visibility phases in time/frequency

⇒ The size of the image that can be made is determined by how much averaging is done of the data
  → The number of channels
  → The integration time
How to generate the Wide-field Dataset

⇒ Generating high-resolution datasets was a problem for hardware correlators
   → It was this which limited the field of view for Wide-field VLBI until recently
⇒ With software correlators such as DiFX (Deller et al. 2007) the time penalty is acceptable.
   → Greater CPU resources required for greater number of channels
⇒ The main problem is the output data volume
   → ∼ TB for a typical VLBA observation
Caveat 3: Wide-field Imaging

Direct wide-field imaging

Very quickly becomes slow

⇒ Will quickly fill computer memory
⇒ Non-coplanar effects to handle
⇒ parallel algorithms are in development

Correlating with different phase centres

⇒ Ties up correlator (and media)

Correlating, transforming and averaging

⇒ Correlate to create one large dataset
⇒ Use this to generate several smaller datasets
Transforming correlated data

⇒ Transform one dataset into the other.
⇒ Then the data can be averaged
⇒ Repeat for every region of interest
Geometry

The correlator has already shifted the datastreams so that the two antennas are on a baseline perpendicular to the original phase centre:

Consider a phase centre offset from this position
Correlating, Transforming and Averaging

- We start with the correlated data
- Calculate a new delay for
  - each baseline
  - each time integration
- Apply a phase shift to each datum
  - time dependent
  - frequency dependent
How to calculate the delay?

This is what the baseline vectors are for!

They can be used to calculate the delay at any point in the image:

$$\Delta \phi = \frac{2\pi}{\lambda} (lu + mv)$$  \hspace{1cm} (3)

The correlator delay model takes more into account than simple geometry (Sovers et al. 1998)

DiFX actually calculates the baselines using the full accuracy of the correlator delay model:

$$(u, v, w) = c \left( \frac{\partial \tau}{\partial l}, \frac{\partial \tau}{\partial m}, \tau \right),$$  \hspace{1cm} (4)

These differ by up to 1 part in 10 000 from purely geometrical vectors. (Walter Brisken Priv. Comm.)
How to calculate the delay?

There is still a problem

⇒ There is only one value of $u$ and $v$ for each visibility

We are treating the delay across the wide field as a linear function
CALC 9 generated delays across the wide field

The delay function varies smoothly throughout the sky
No reason to think this isn’t typical
Fractional error of a linear fit

Fit forced through 0 at the origin and 0.3 arcminute point
Similar to the derivation done by DiFX
Error of using a linear fit

⇒ This is the reason for the UV shifting errors noted by others (Lenc et al. 2008; Middelberg et al. 2008)
⇒ it cannot be calibrated out
⇒ It is made whenever using UV data to look at flux away from the phase centre

(though the error may be negligible for shorter shifts)
Accurate UV shifting

By generating a second correlator model for the desired phase centre it should be possible to UV shift accurately.

No need to recorrelate:

⇒ We start with the correlated data
⇒ Replace the phase centre coordinates
⇒ Replace the baseline vectors (UVW)
⇒ Apply the phase shift to each visibility
  → difference in delay between the two models (multiplied by the frequency)
Take into account delay rate

There is still an error of one part in $10^6$

$\Rightarrow$ The delay is changing with time

$\Rightarrow$ Need to take into account the change in delay over the shift

Another error which is always present but only measurable for the most extreme wide-field VLBI
Error after a phase shift of 1000000 turns

Residuals and Chi^2 linear fit: y = 0.313256x + -2632.42  \( (r^2=0.458702) \)

(Morgan et al. 2010)
Error after a phase shift of 1000000 turns

Residuals and Chi^2 linear fit: y = 0.0505706x + 0.588864 (r^2=0.408585)

(Morgan et al. 2010)
Implementations

This is implemented with full accuracy in:

⇒ difx2fits (not in the standard release)

The latest release of DiFX (2.0) also implements the shifting algorithm with full accuracy

⇒ The extremely high resolution dataset never leaves the computer’s memory

⇒ The PI receives one standard visibility dataset for each requested phase centre

⇒ The computational efficiency is breathtaking!

(Deller et al. 2010)
Correction for smearing:

⇒ Amplitude correction can be calculated fairly accurately from the shift delay

⇒ Larger than simple smearing for DiFX due to triangular weight function (Morgan et al. 2010)

Primary Beam:

⇒ Assume that within a single image the correction is the same

⇒ Adjust the **visibilities** for the primary beam response of the **baseline**
  → time & frequency dependent

(See my poster for more details)
Amplitude Correction and Calibration

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Future Work

We can generate a model for any point on the primary beam

What would be better would be to characterise the delay across the entire primary beam

⇒ not just $u$, $v$ and $w$ but also higher terms

This would allow the calculation of the delay at any point with full accuracy.
Radio Astronomers do it in four dimensions

⇒ Accurate UV shifting at any point during correlation, calibration or imaging

⇒ This four-dimensional (antenna, $l$, $m$, $t$) could then be refined during calibration

→ Phase calibration from multiple source within and outside the primary beam
→ Synergies with low-frequency interferometry?
→ Synergies with new and future widefield interferometers?
⇒ VLBI across the primary beam is now possible
⇒ The density of sources on the sky means that many sources are detectable in an 8-hour observation at L-Band
⇒ I am interested in collaborating on Wide-field VLBI projects
References