Wide-field VLBI Techniques: A Beginner's Guide

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10th EVN Symposium
Manchester
Tuesday 21st September 2010

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

Acknowledgements

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 Θ and resolution θ are given by

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

So the number of resolution units across the primary beam is

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

n.b. for imaging purposes the true number of pixels will be $\sim 10\times$ bigger

Image size of different arrays

Array	d	D	D/d
	m	km	
VLA	25	36	1440
MERLIN	32	217	8680
EVN	100	10180	101800
VLBA	25	8611	344440

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

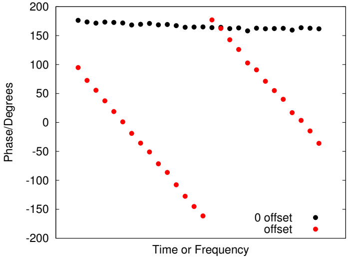
Caveat 1: Density of Detectable Sources

⇒ 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
  - → $\sim$ 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

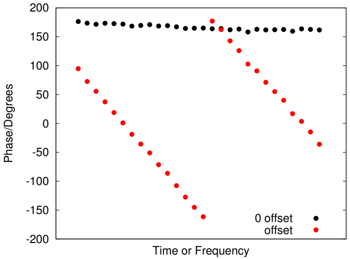
Correlating with different phase centres

- ⇒ Ties up correlator (and media)

Correlating, transforming and averaging

- ⇒ Correlate to create one large dataset
- ⇒ Use this to generate several smaller datasets

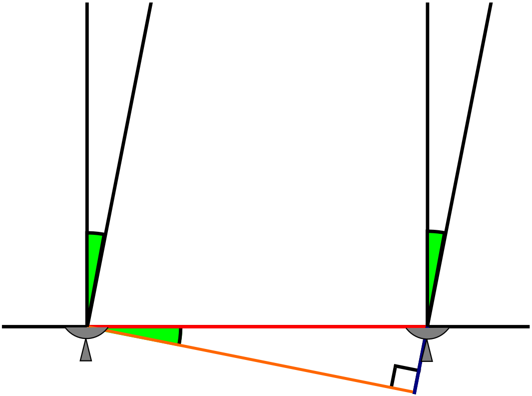
Transforming correlated data



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

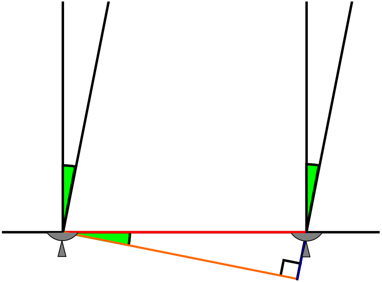
Geometry

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:

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

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:

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

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

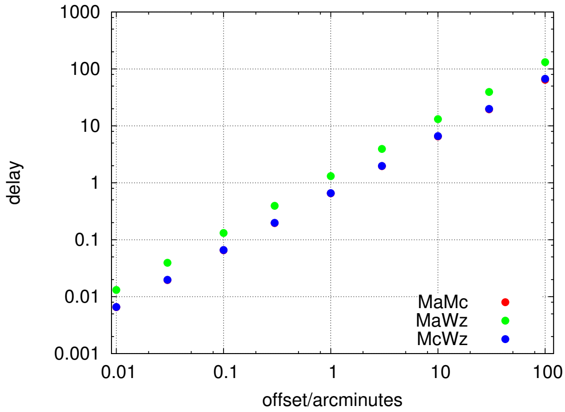
How to calculate the delay?

There is still a problem

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

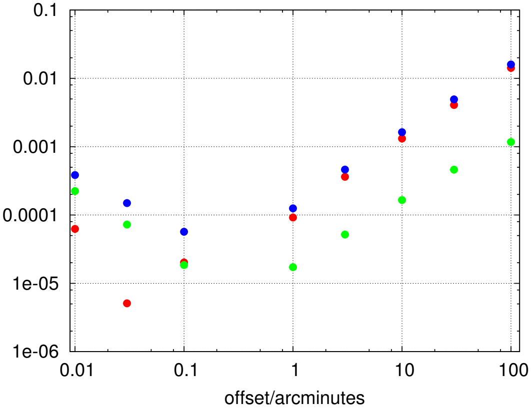
We are treating the delay across the wide field as a linear function

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 negligable for shorter shifts)

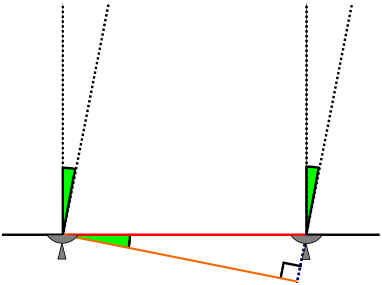
Accurate UV shifting

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

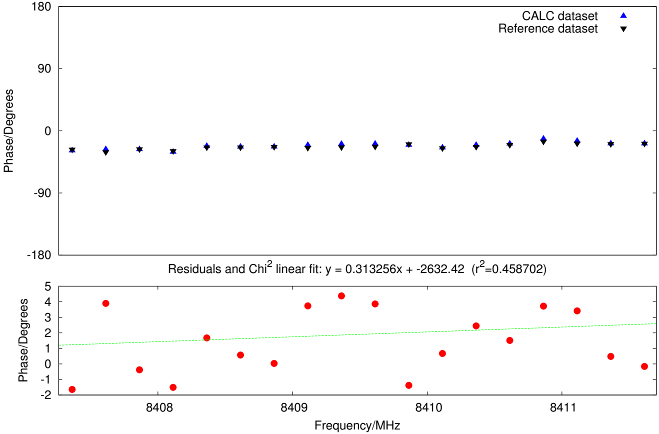


There is still an error of one part in 10^6

- ⇒ The delay is changing with time
- ⇒ Need to take into account the change in delay over the shift

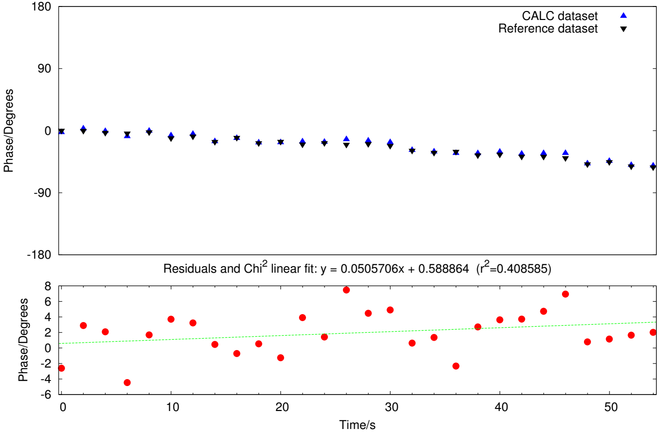
Another error which is always present but only measurable for the most extreme wide-field VLBI

Error after a phase shift of 1000000 turns



(Morgan et al. 2010)

Error after a phase shift of 1000000 turns



(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 datset for each requested phase centre

⇒ The computational efficiency is breathtaking!

(Deller et al. 2010)

Amplitude Correction and Calibration

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)

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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?

Conclusion

- ⇒ 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

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