Wide-field VLBI Techniques: Correlation, Calibration and Imaging across the Wide Field

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Overview

Image size of different arrays

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

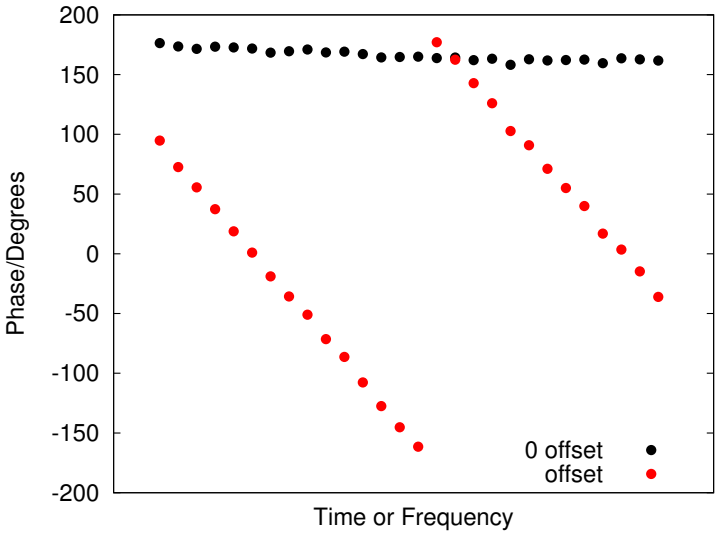
n.b. All arrays in longest-baseline/smallest-antenna configuration

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

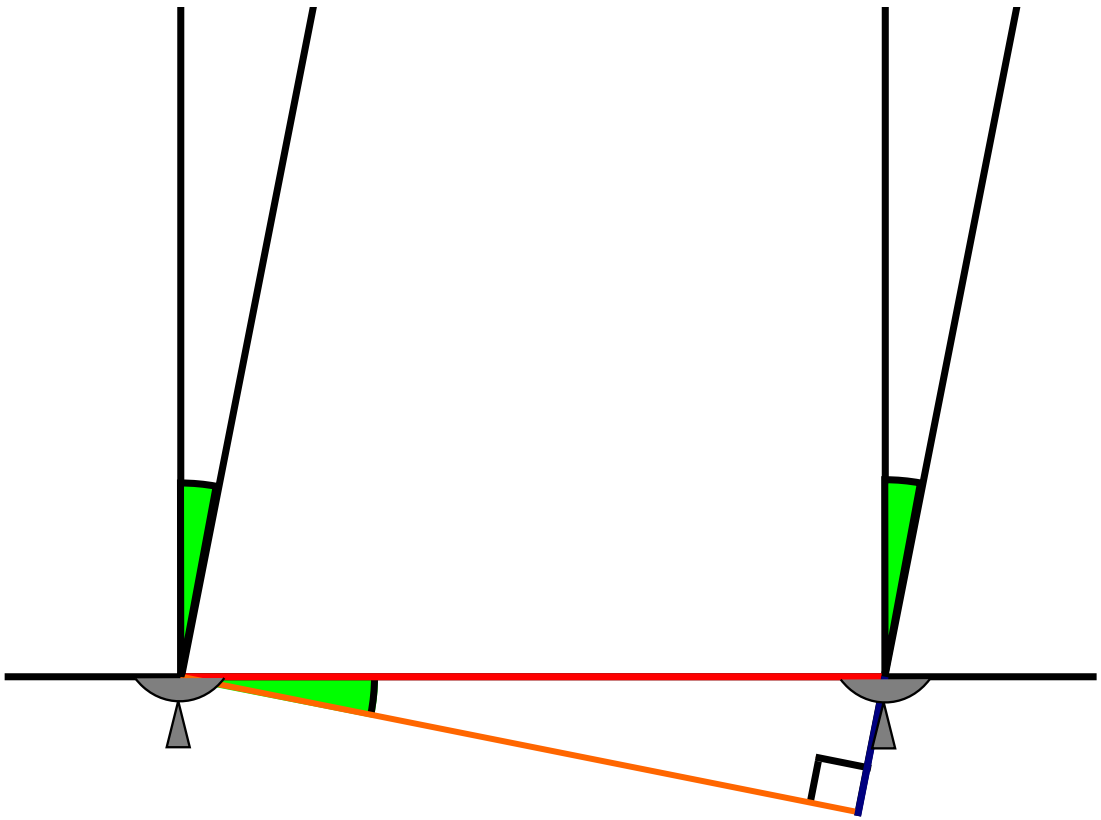
Transforming correlated data



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

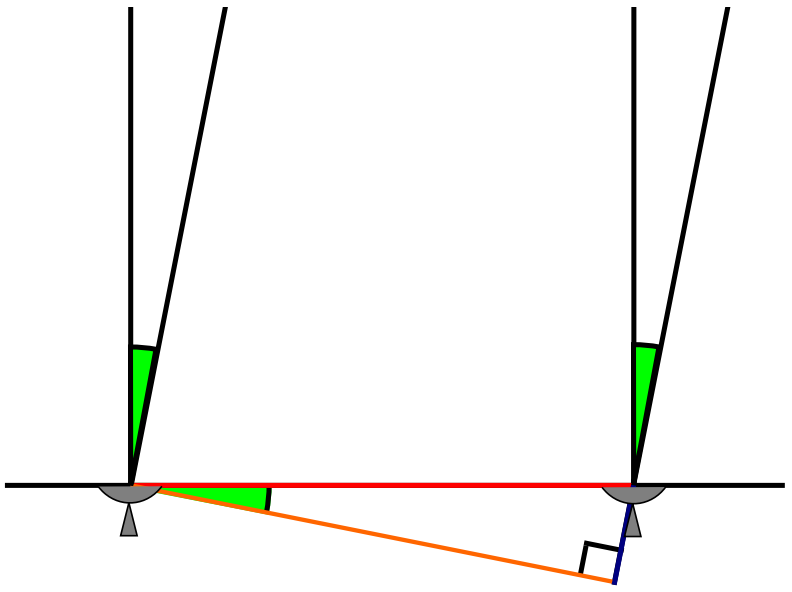
Geometry

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:

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

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:

$$(u, v, w) = c\left(\frac{\partial\tau}{\partial l}, \frac{\partial\tau}{\partial m}, \tau\right), \tag{2}$$

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

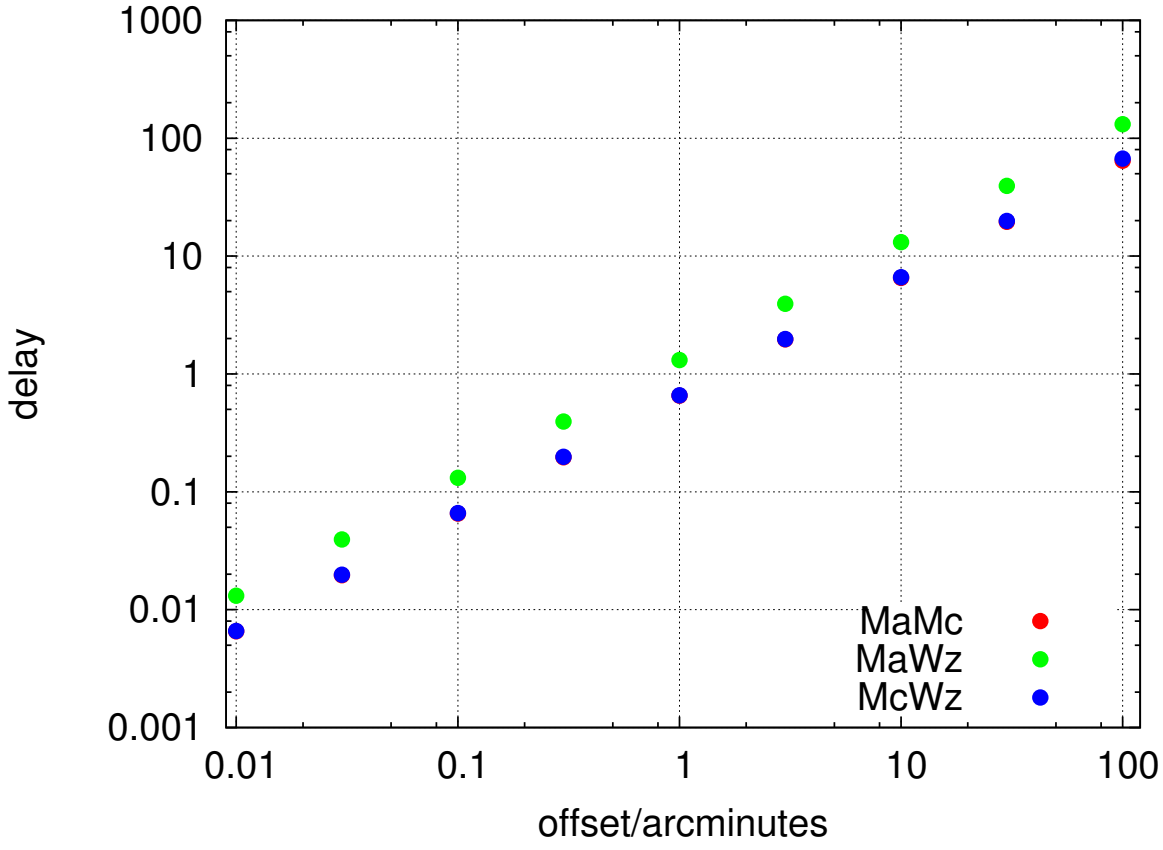
How to calculate the delay?

There is still a problem

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

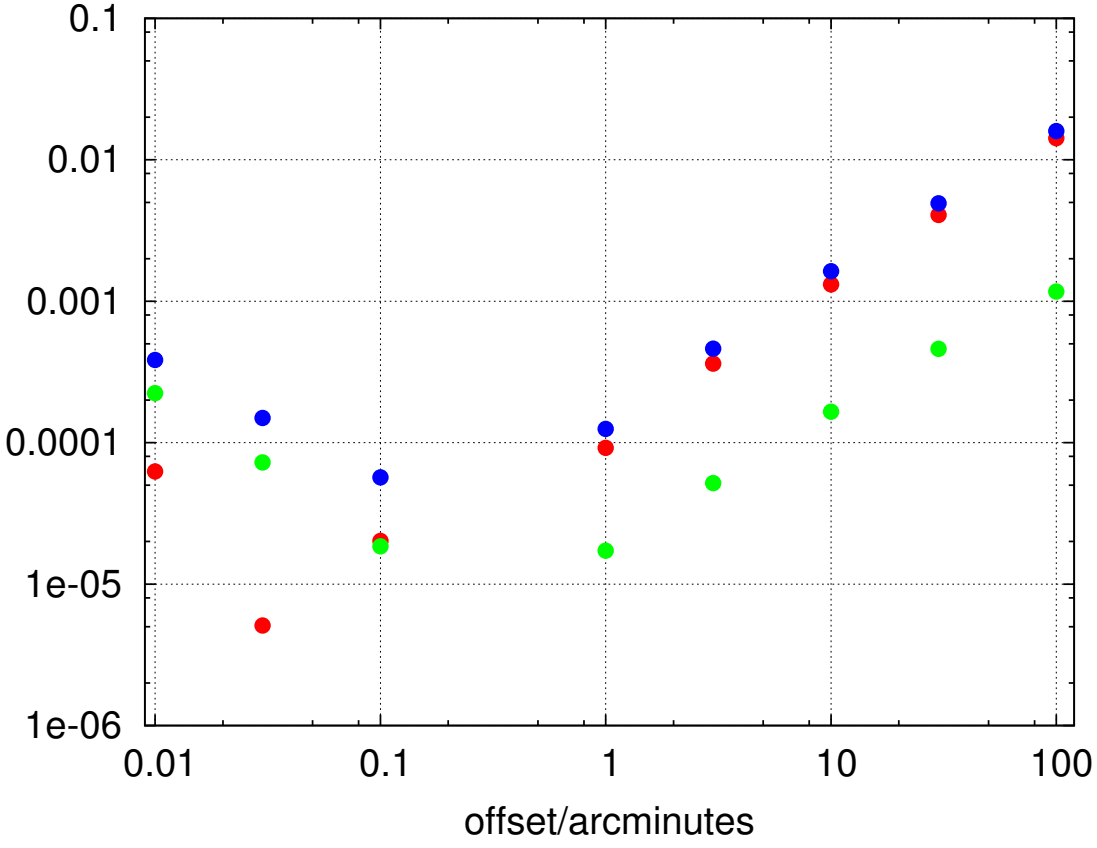
We are treating the delay across the wide field as a linear function

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)
- Plan to explore the effects of this with (Brunthaler, MPIfR)

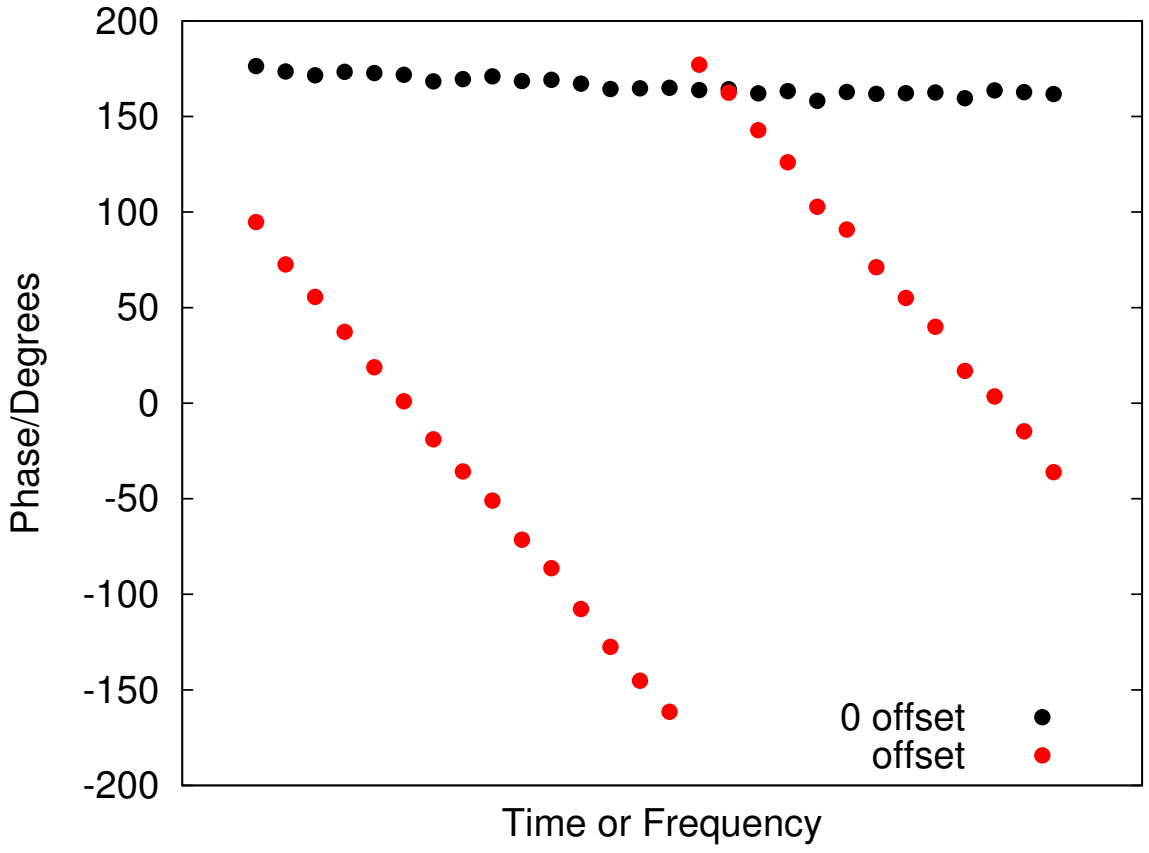
Accurate UV shifting

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

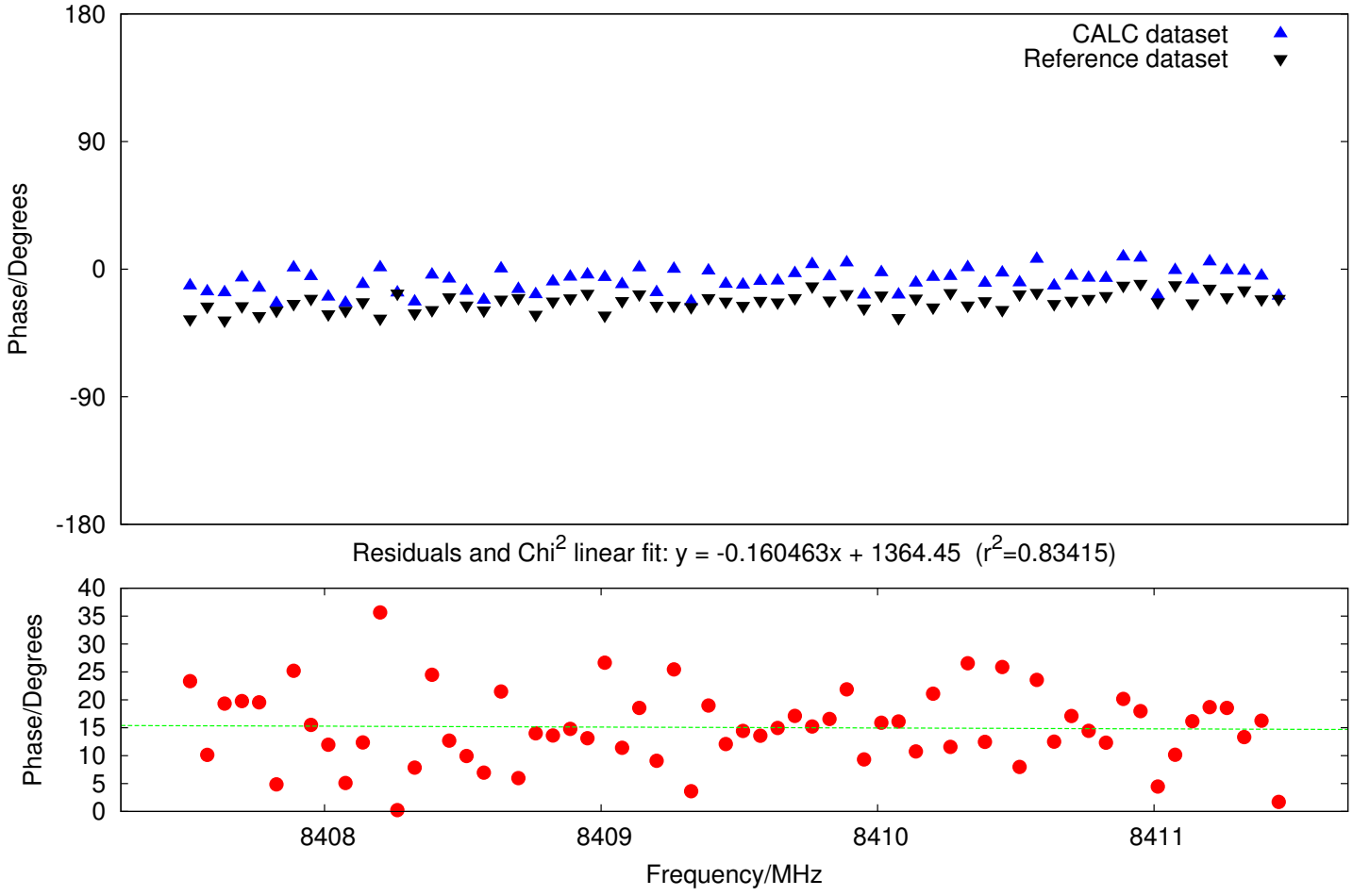
No need to recorrelate:

- 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)

Transforming correlated data



Error after a phase shift of 100000 turns



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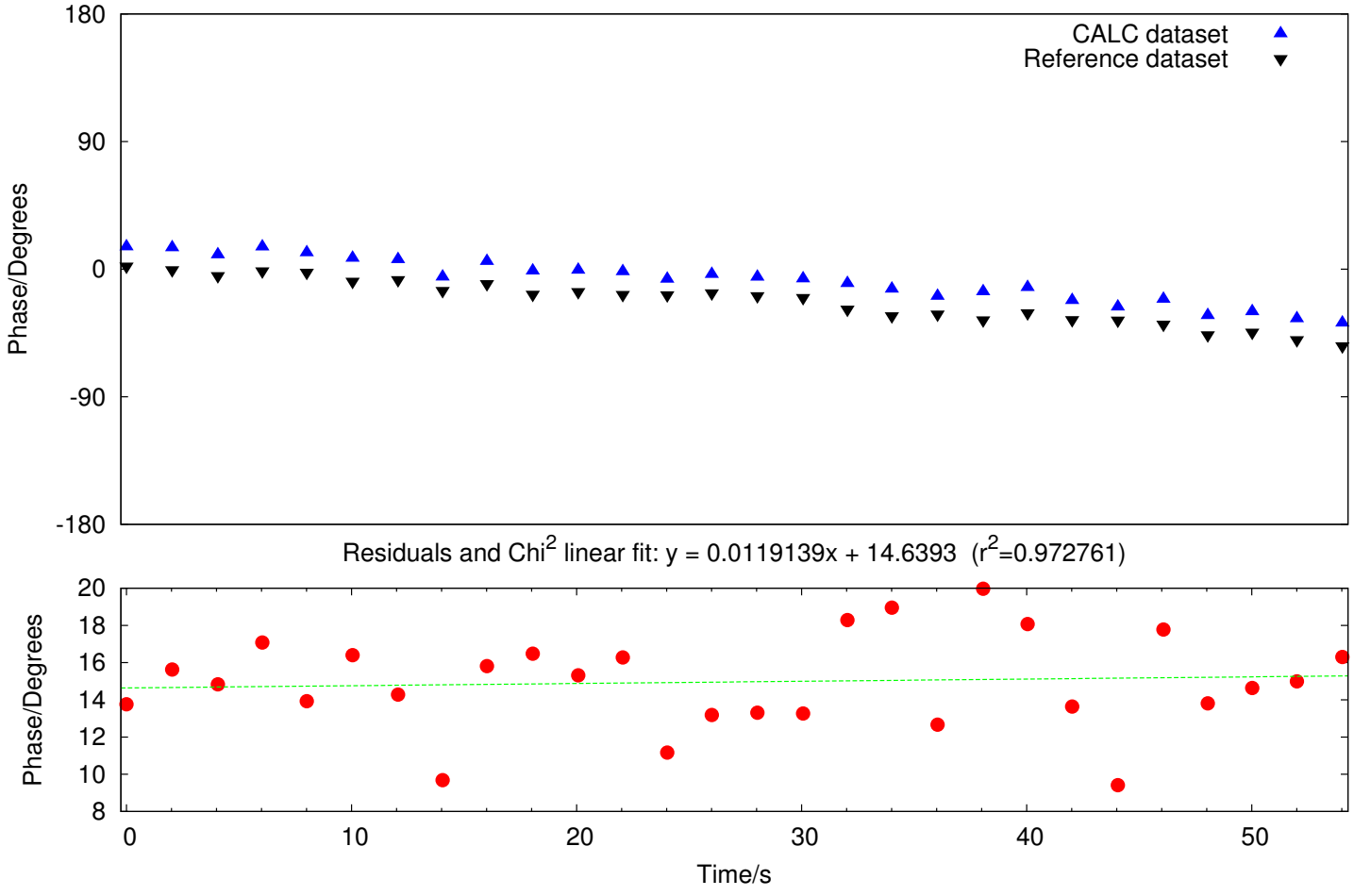
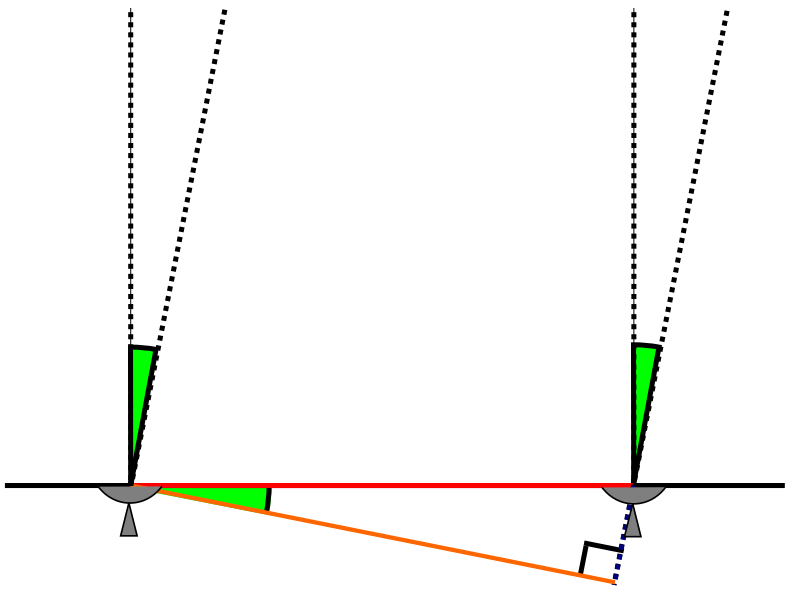


Non-linearity of correlator lags

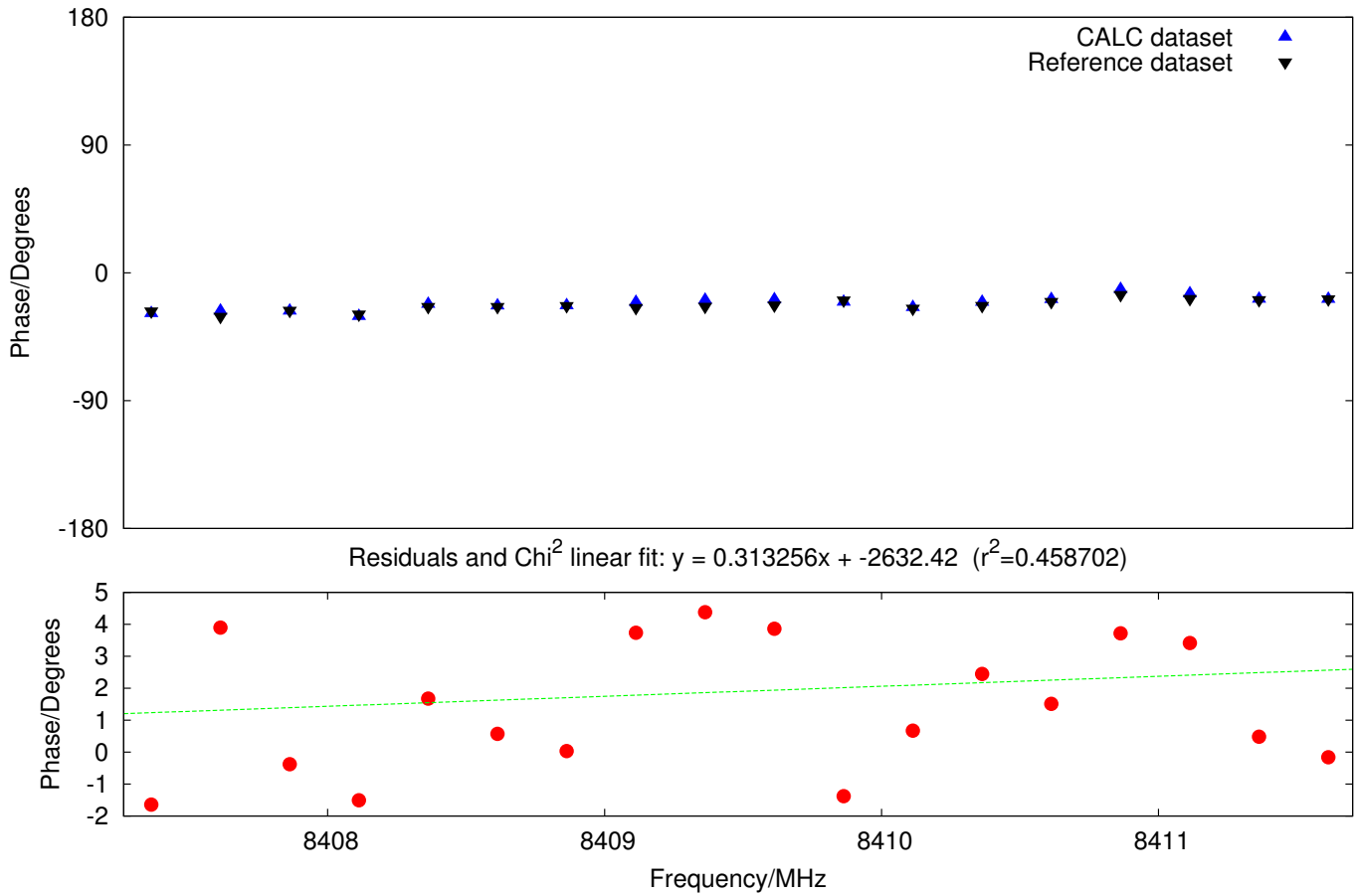


There is still an error of one part in 10^6

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

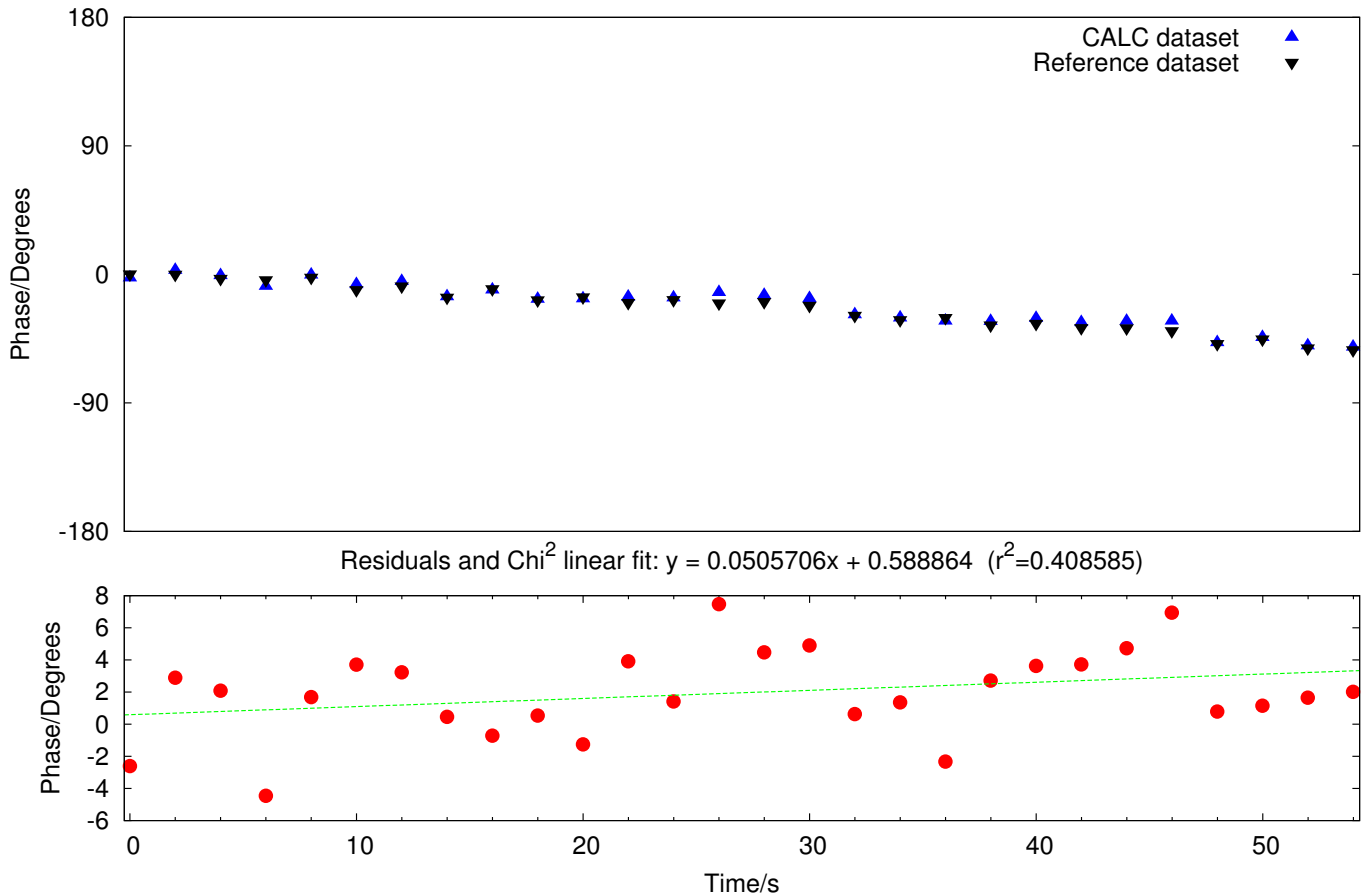
Another error which is always present but only measurable for the most extreme wide-field VLBI

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

Amplitude correction can be calculated fairly accurately from the shift delay

Larger than simple smearing for DiFX due to triangular weight function

A first search for detections is very simple

- Most calibration can be applied across all datasets
- pipelining tools (such as ParselTongue) are invaluable

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Primary beam correction

- Assume that within a single image the correction is the same
- Adjust the visibilities for the primary beam response of the baseline

A full treatment will be

- time dependent
- frequency dependent

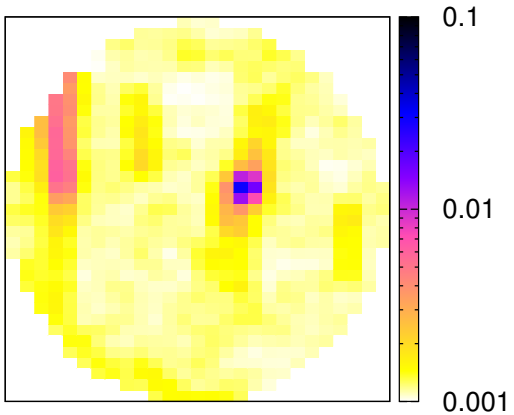
In-beam calibration

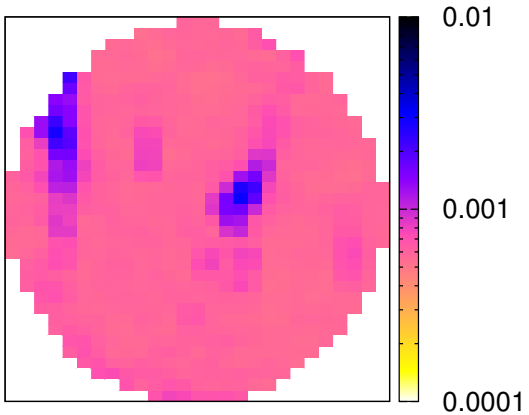
The blessing and curse of an in-beam calibrator:

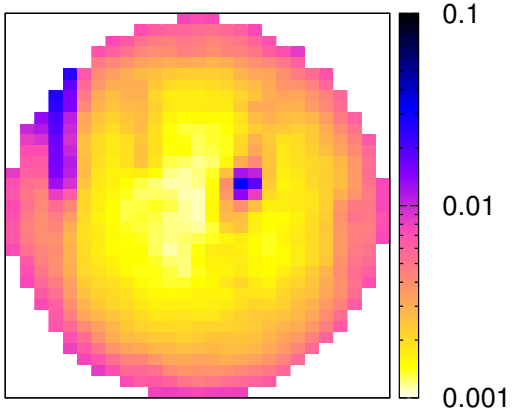
- If one source is detected strongly[1] it can be used to improve the delay solutions
  - compared to a nodding calibrator
- A source strong enough source can be fringe fitted even when very distant from the phase centre
  - This necessitates the subtraction of a model of the source from nearby datasets (peeling)

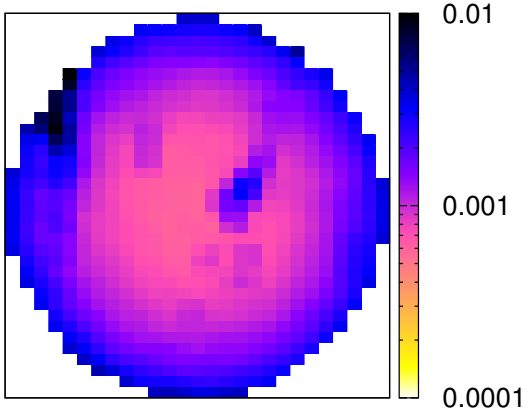
[1] use calibrator scans to detect for transients

Results

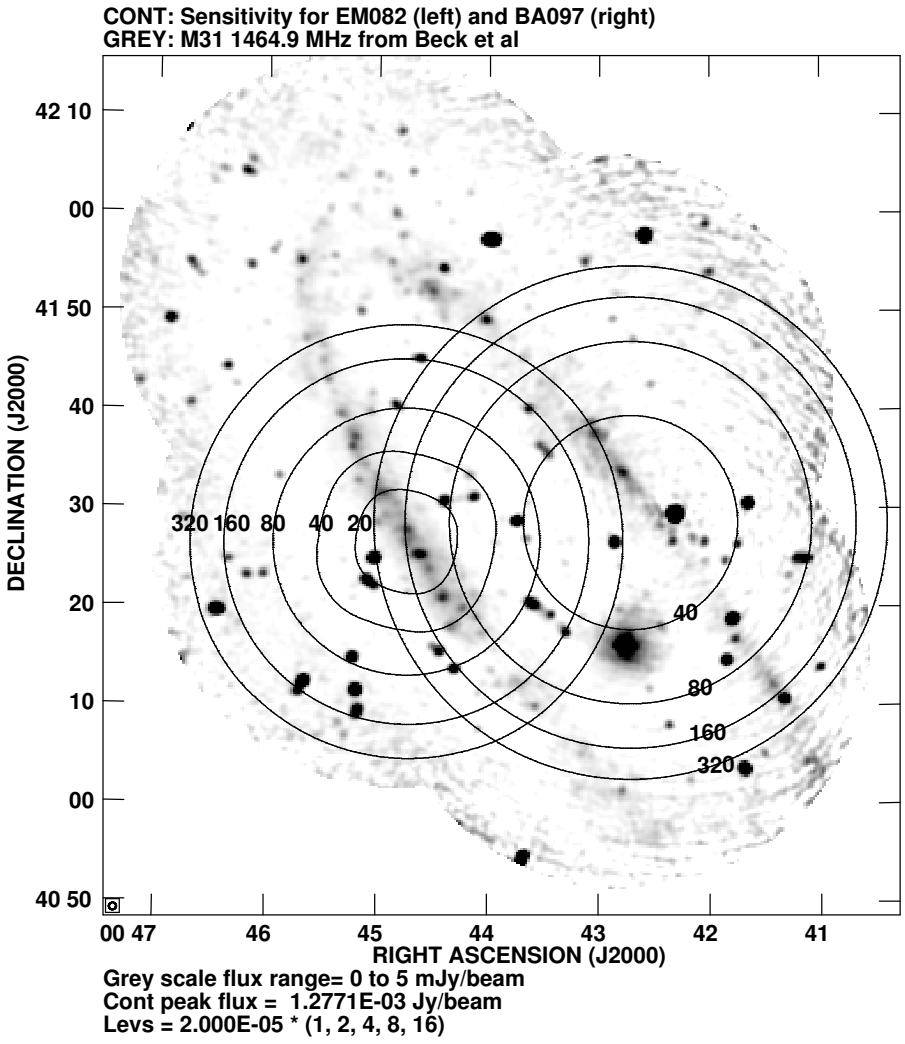








Two Widefield Observations Done



Heterogeneous Arrays

Dominated by primary beams of larger antennas[2]

- Even beyond the primary beam, baselines with large antennas are brighter than baselines without
- Properly characterising the primary beams of the larger arrays improves "survey speed"
  - May also be necessary for peeling of bright sources
- We are bound to discover other problems
  - Many problems cancel out across baselines of identical antennas
  - Different PB correction for each polarisation???

[2] Don't phase up Wb!!

Calibration across the primary beam

It may be possible to sum multiple weak sources across the primary beam to create a single in-beam calibrator

- image all detected sources
- uv-shift to the phase centre, divide through by model
- vector-add visibilities together
- fringe fit this summed source

Calibration across the primary beam

Next use this (hopefully improved) delay calibration

- re-image all detected sources
- fringe fit all sources at once making a best fit to some model of the delay across the wide field
  - simple gradiant
  - something more complicated

Delay across the wide field

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?

Imaging the entire primary beam

Phase calibration is now folded in with UV shifting:

- UV shift using new delay model

Image the entire primary beam using shift and average scheme (Wucknitz in prep.)

- This could be done automatically (without phase calibration) in parallel with every low frequency VLBI observation (similar to commensal transient detection)
- Correlation reduction factor ~ 20
- May well be possible on a single machine (with high speed storage attached)

Conclusion

- VLBI across the primary beam is now possible
  - and becoming mainstream
- 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

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