Lecture 7: Fringe-fitting

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DARA Unit 4
May 2021

Further calibration

Use a skymodel of the **true visibilities** to solve for the rest of the Jones matrices:

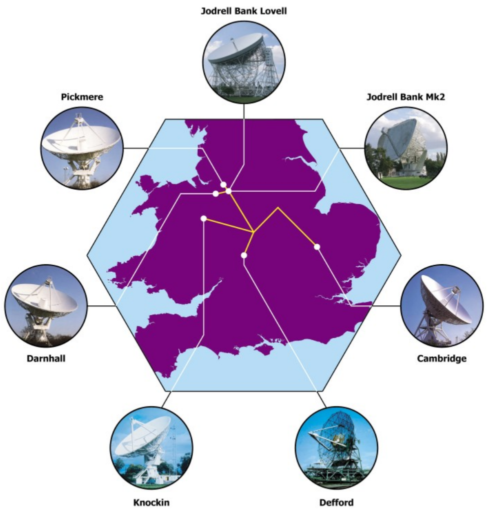
$$\vec{V}_{ij}^{\mathrm{obs}} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\mathrm{true}}$$

Remember these Jones matrices contain visibility-like information, which is represented as *complex numbers* (a+b*i*) that can be decomposed into **amplitudes** and **phases**

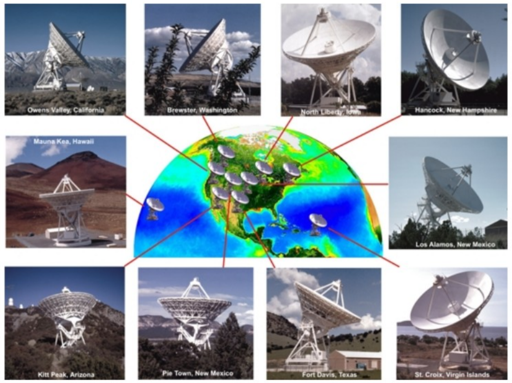
Outline

- Recap of Very Long Baseline Interferometry (VLBI)
- Fringe-fitting fundamentals
- Fringe-fitting in practice

Recap of VLBI

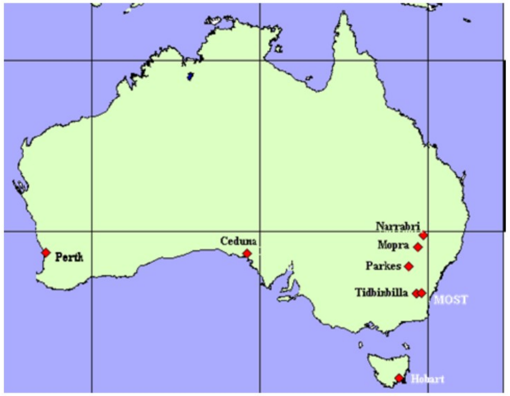


e-MERLIN



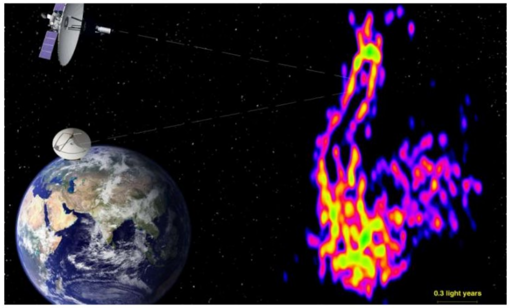
VLBA

EVN



LBA

Tanami


RadioASTRON

Recap of VLBI

- **Common element:** stations are so far apart that they require separate (non-distributed) clocks

- **This drives:**
  - Non-(near)-real time correlation
  - Clock / delay correction required
  - Lower tolerance for errors in geometric model of array
  - Having to cope with resolved sources

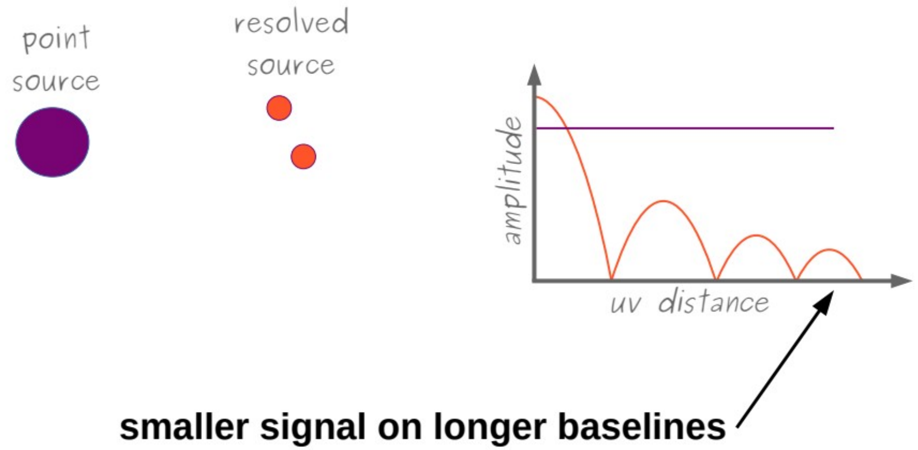
Recap of VLBI

- **What part does resolution play?**

baseline sensitivity: $S_{ij} = \sqrt{\frac{S_{sys,i}}{\sqrt{2\Delta\nu\Delta t}} \frac{S_{sys,j}}{\sqrt{2\Delta\nu\Delta t}}}$

note there is no dependence on baseline length!

what impact does source structure have?



Fringe-fitting fundamentals

take the relation between phase and delay:

$$\phi_{\nu,t} = 2\pi\nu\tau_t$$

differentiating with respect to time yields:

$$\mathrm{d}\phi_{\nu,t} = 2\pi\nu\mathrm{d}\tau_t$$

the error in is dependent on both $\boldsymbol{\nu}$ and $\boldsymbol{t}$

take the first order expansion:

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

frequency dependence

time dependence

Fringe-fitting fundamentals

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

ϕ_0 = the **phase** error at ν_0, t_0

$\frac{\delta\phi}{\delta\nu}$ = the **delay** or delay residual

$\frac{\delta\phi}{\delta t}$ = the **rate**, delay rate, or rate residual

normal phase calibration only estimates ϕ_0

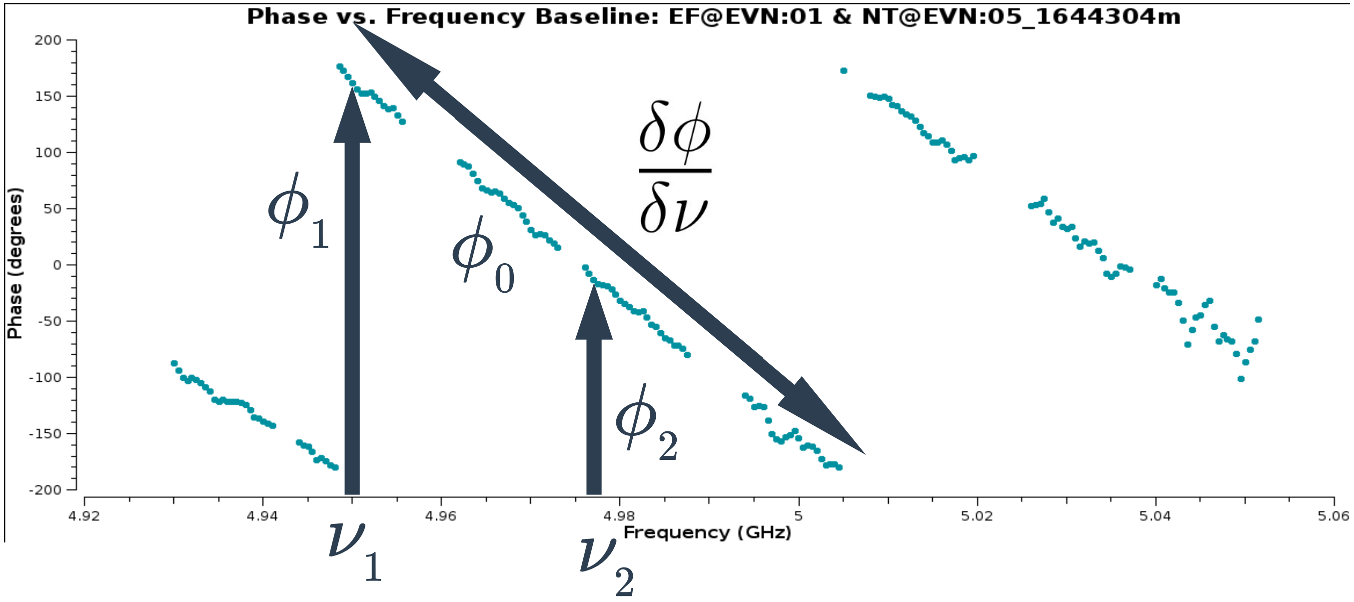
Fringe-fitting is any process that also estimates *delays* and *rates*

Effectively increases S/N by increasing solution interval

Fringe-fitting fundamentals

How does solving for delays and rates increase S/N?

a practical example of delays



ϕ_1 is only valid at ν_1 and ϕ_2 is only valid at ν_2

$\phi_0 + \frac{\delta\phi}{\delta\nu}$ is valid over a large range of $\Delta\nu$

Baseline-based fringe-fitting

The fringe-fitting equation can be written in terms of individual baselines, e.g. with antennas *i,j*:

$$\Delta\phi_{ij} = \phi_{i,0} - \phi_{j,0} + \left(\left[\frac{\delta\phi_i}{\delta\nu} - \frac{\delta\phi_j}{\delta\nu} \right] \Delta\nu + \left[\frac{\delta\phi_i}{\delta t} - \frac{\delta\phi_j}{\delta t} \right] \Delta t \right)$$

so you can construct this equation for each pair of baselines and solve for phases, delays, and rates on each baseline!

<u>Disadvantages:</u>

- The source must be detected on all baselines
- Antenna-based quantities are not conserved

Global fringe-fitting

Global fringe-fitting is usually what people mean when they say *fringe-fitting*. Here we use the baseline-based equations:

$$\Delta\phi_{ij} = \phi_{i,0} - \phi_{j,0} + \left(\left[\frac{\delta\phi_i}{\delta\nu} - \frac{\delta\phi_j}{\delta\nu} \right] \Delta\nu + \left[\frac{\delta\phi_i}{\delta t} - \frac{\delta\phi_j}{\delta t} \right] \Delta t \right)$$

but now we solve for the entire system of equations *simultaneously* to find antenna-based solutions!

Major advantage:

- Even if an antenna doesn’t see the source on every baseline, the antenna-based solution can still be found!

Fringe-fitting in practice

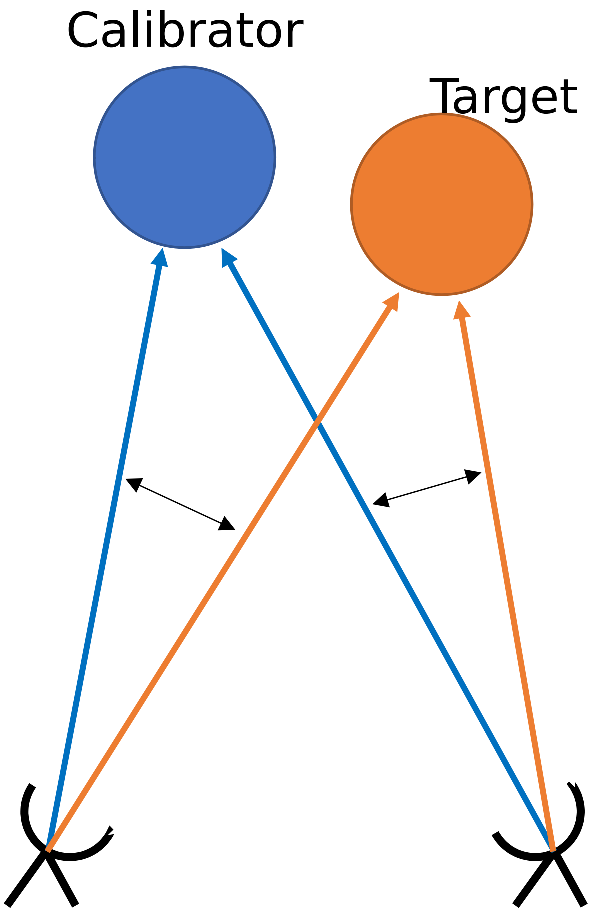
- **Global fringe-fitting** is implemented in CASA
- Sets one antenna as the reference antenna, and finds the phases, delays, and rates for all other antennas
- The solutions are therefore *relative* to the reference antenna
- **Calibrator source** is needed to find the solutions
  - Assumed to be a bright point source unless model is given
    - A point source has constant phase in the *u-v* plane
- Phase corrections only; no amplitudes!

```
--------> inp(fringefit)
#  fringefit :: Fringe fit delay and rates
vis                 =         ''        #  Name of input visibility file
caltable            =         ''        #  Name of output gain calibration table
field               =         ''        #  Select field using field id(s) or
                                        #   field name(s)
spw                 =         ''        #  Select spectral window/channels
intent              =         ''        #  Select observing intent
selectdata          =       True        #  Other data selection parameters
     timerange      =         ''        #  Select data based on time range
     uvrange        =         ''
     antenna        =         ''        #  Select data based on antenna/baseline
     scan           =         ''        #  Scan number range
     observation    =         ''        #  Select by observation ID(s)
     msselect       =         ''        #  Optional complex data selection
                                        #   (ignore for now)

solint              =      'inf'        #  Solution interval: egs. 'inf', '60s'
                                        #   (see help)
combine             =         ''        #  Data axes which to combine for solve
                                        #   (obs, scan, spw, and/or field)
refant              =         ''        #  Reference antenna name(s)
minsnr              =        3.0        #  Reject solutions below this signal-
                                        #   to-noise ratio (at the FFT stage)
zerorates           =      False        #  Zero delay-rates in solution table
globalsolve         =       True        #  Refine estimates of delay and rate
                                        #   with global least-squares solver
delaywindow         =         []        #  Constrain FFT delay search to a
                                        #   window; a two-element list, units of
                                        #   nanoseconds
ratewindow          =         []        #  Constrain FFT rate search to a
                                        #   window; a two-element list, units of
                                        #   seconds per second
append              =      False        #  Append solutions to the (existing)
                                        #   table
docallib            =      False        #  Use callib or traditional cal apply
                                        #   parameters
     gaintable      =         []        #  Gain calibration table(s) to apply on
                                        #   the fly
     gainfield      =         []        #  Select a subset of calibrators from
                                        #   gaintable(s)
     interp         =         []        #  Temporal interpolation for each
                                        #   gaintable (=linear)
     spwmap         =         []        #  Spectral windows combinations to form
                                        #   for gaintables(s)

parang              =      False        #  Apply parallactic angle correction on
                                        #   the fly
```

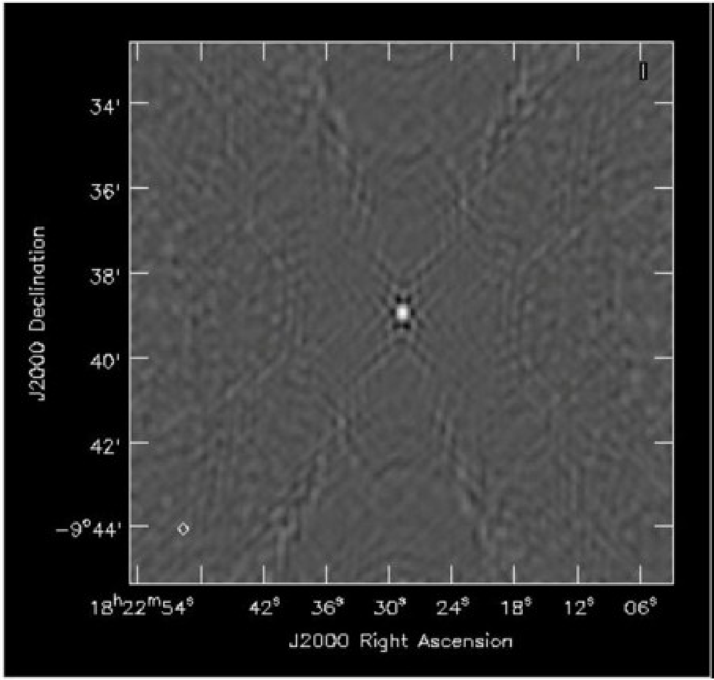
Phase referencing

- Use **Global fringe-fitting** to find phases on calibrator source near target
  - Calibrator structure is known (target unknown)
- Interpolate phase solutions to target

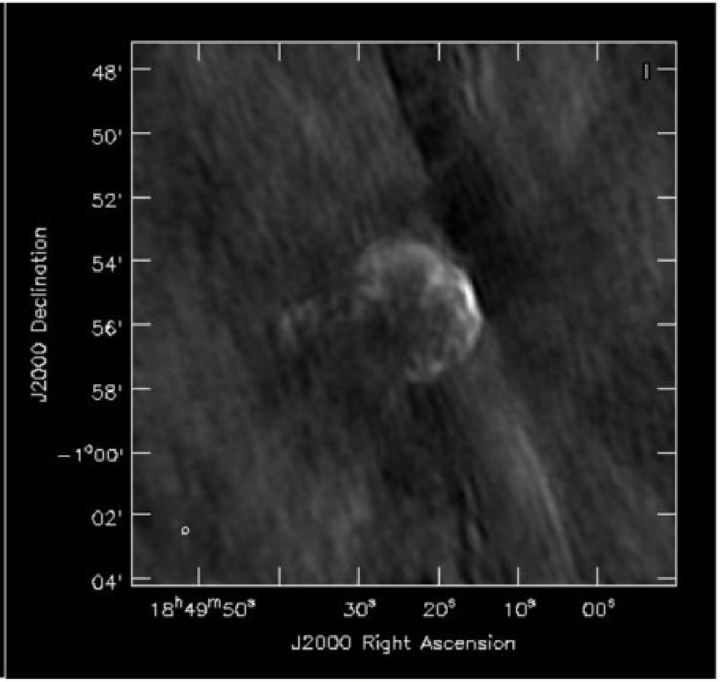
- Typically observations will "nod" between the calibrator and target, with a cycle time set by the timescale of atmospheric fluctuations
  - ~ 10 min at 5 GHz ; ~ 5 min at 1.6 GHz
- Calibrator and target must be close!
  - Typically within ~1 deg
- Biggest problem is the atmosphere
  - Troposphere at high freqs, ionosphere at low



Phase referencing



J1822-0938
(calibrator)

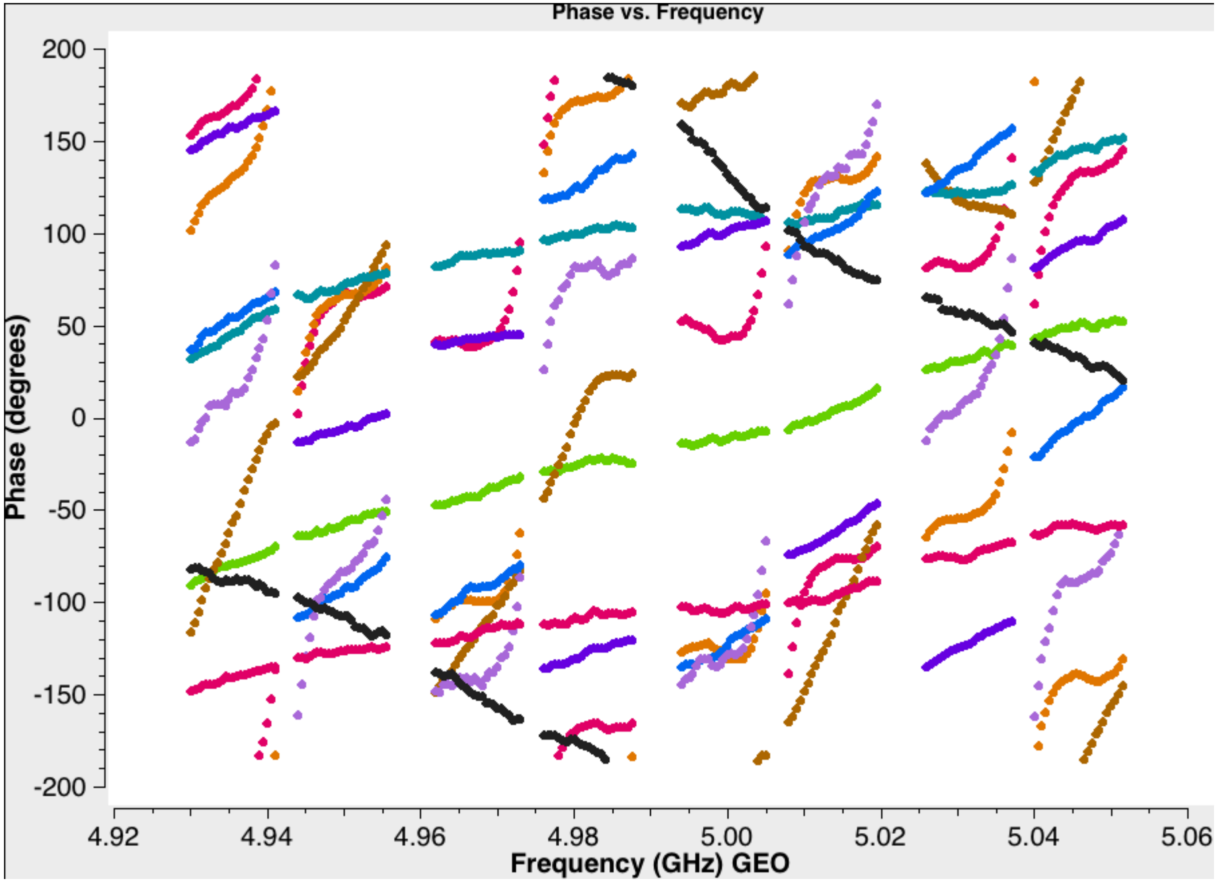


3C391
(science)

Transfer calibration solutions to target, 3C391

Fringe-fitting in practice

- **Instrumental delays**
  - Differing “instrument” responses across spectral windows
  - Time independent



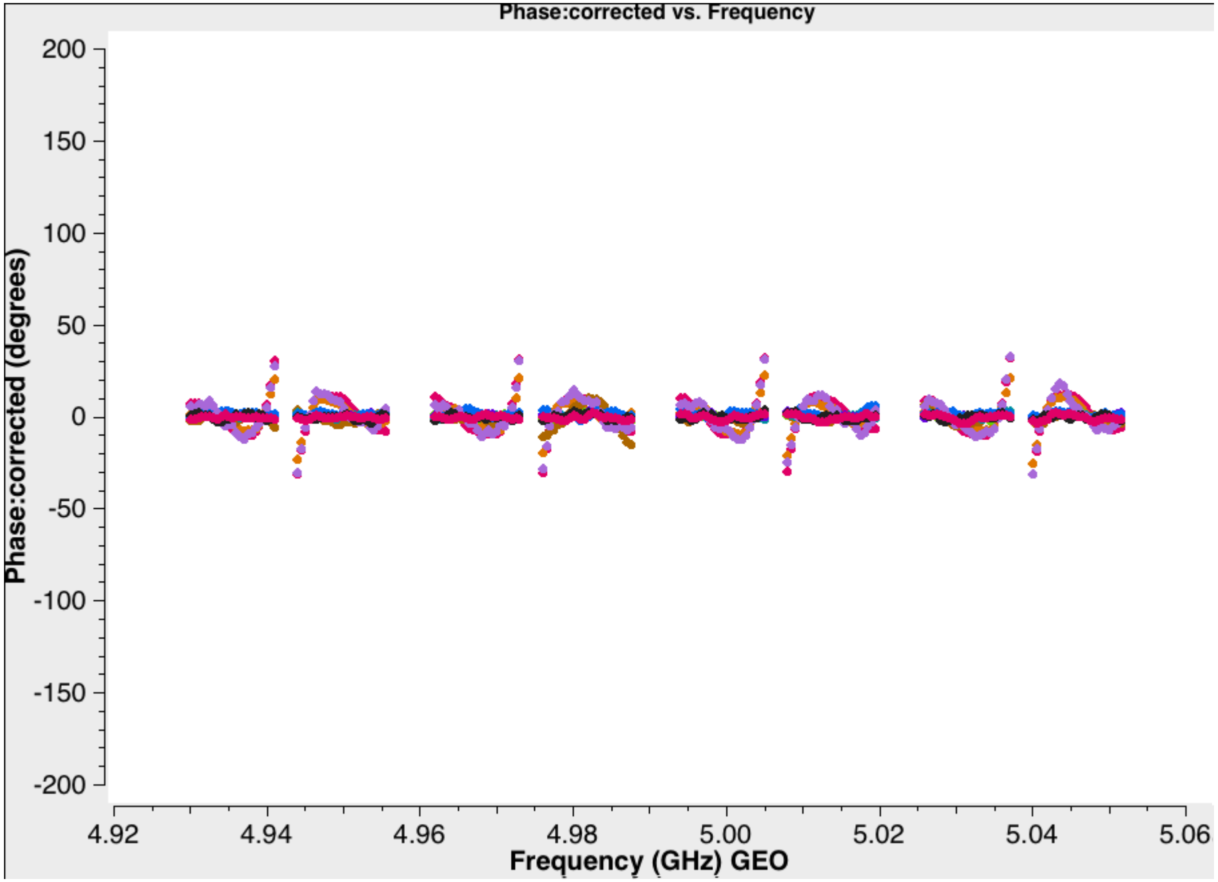
before
instrumental delay correction

colours are baselines to Effelsberg

single short scan

Fringe-fitting in practice

- **Instrumental delays**
  - Differing “instrument” responses across spectral windows
  - Time independent



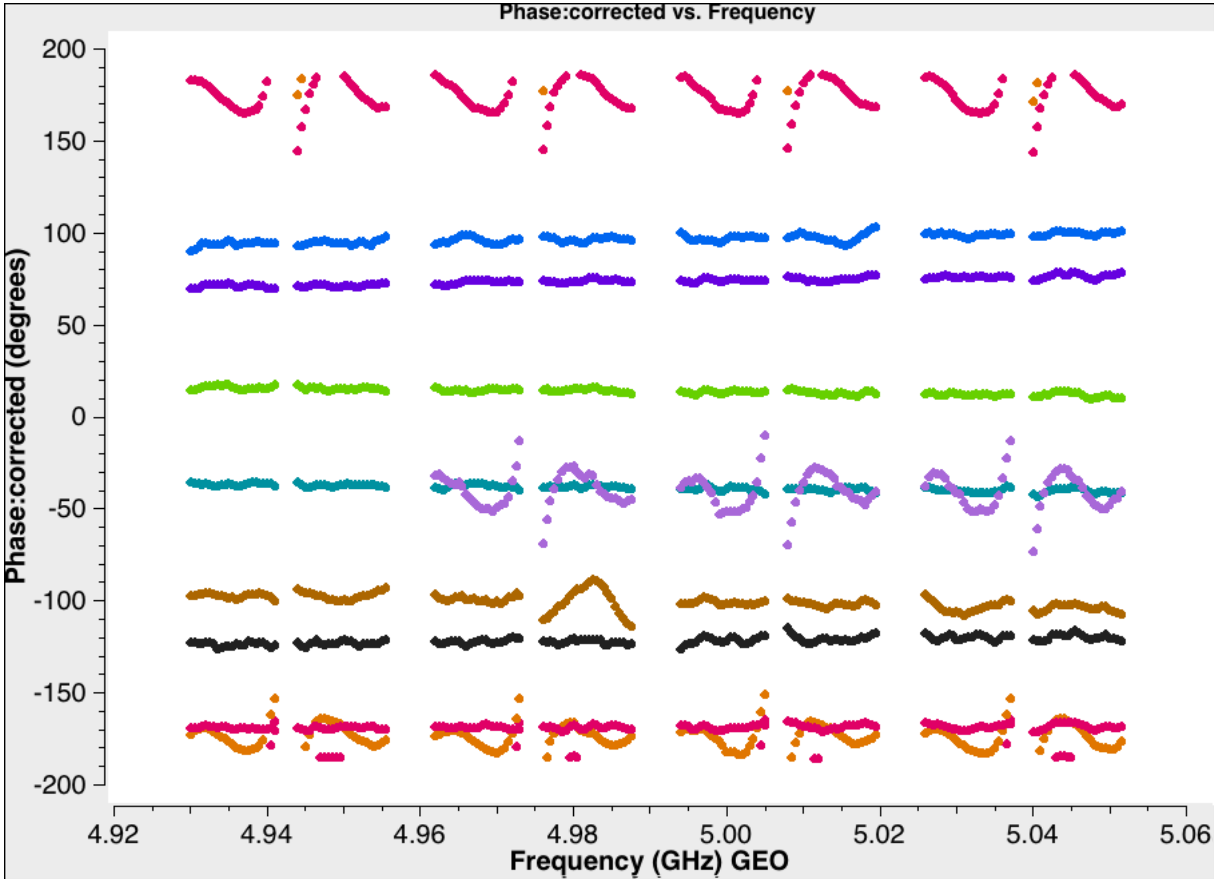
after
instrumental delay
correction

colours are baselines
to Effelsberg

single short scan

Fringe-fitting in practice

- **Instrumental delays**
  - Differing “instrument” responses across spectral windows
  - Time independent



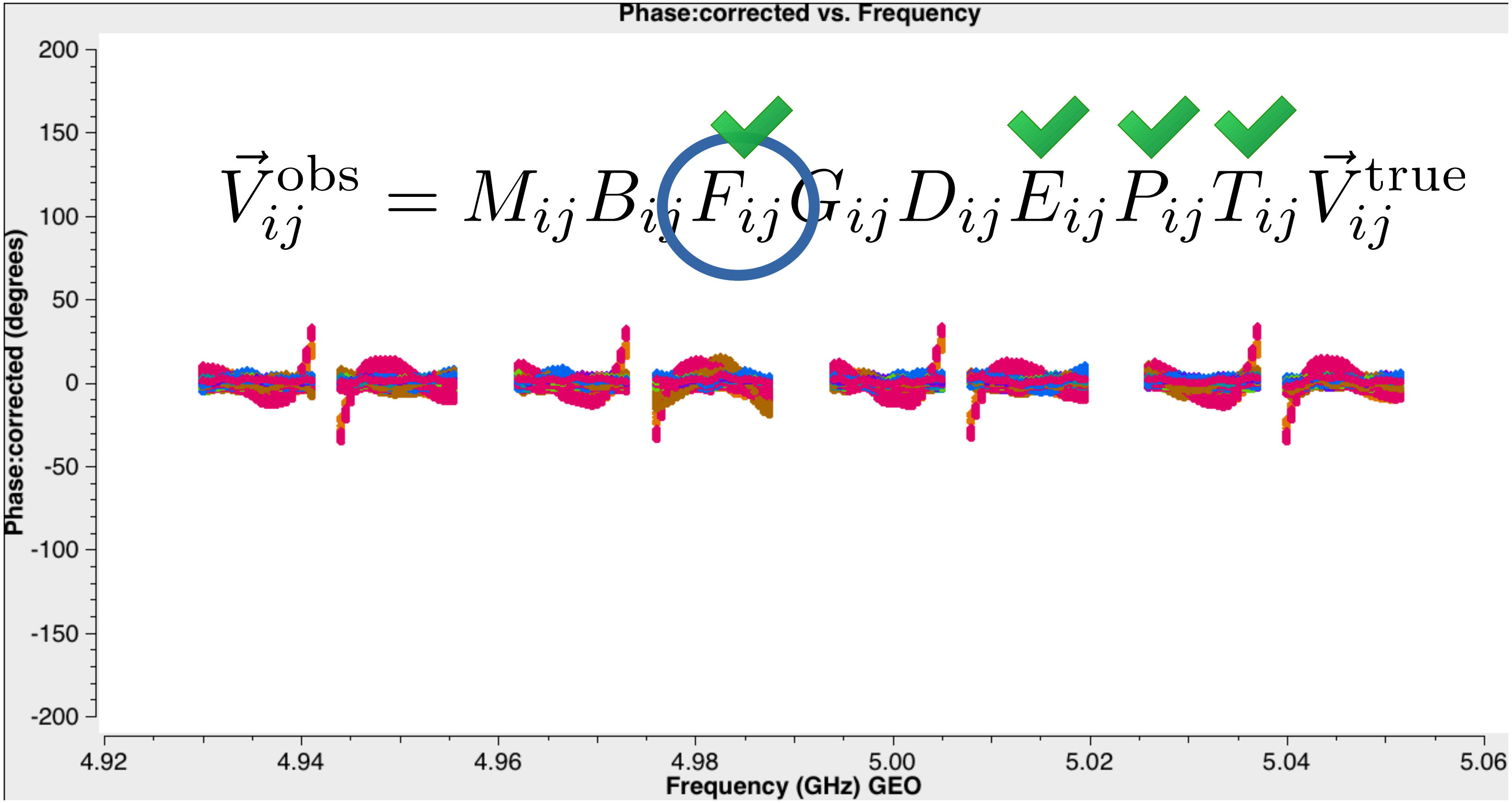
applied to a different scan

colours are baselines to Effelsberg

single short scan

Fringe-fitting in practice

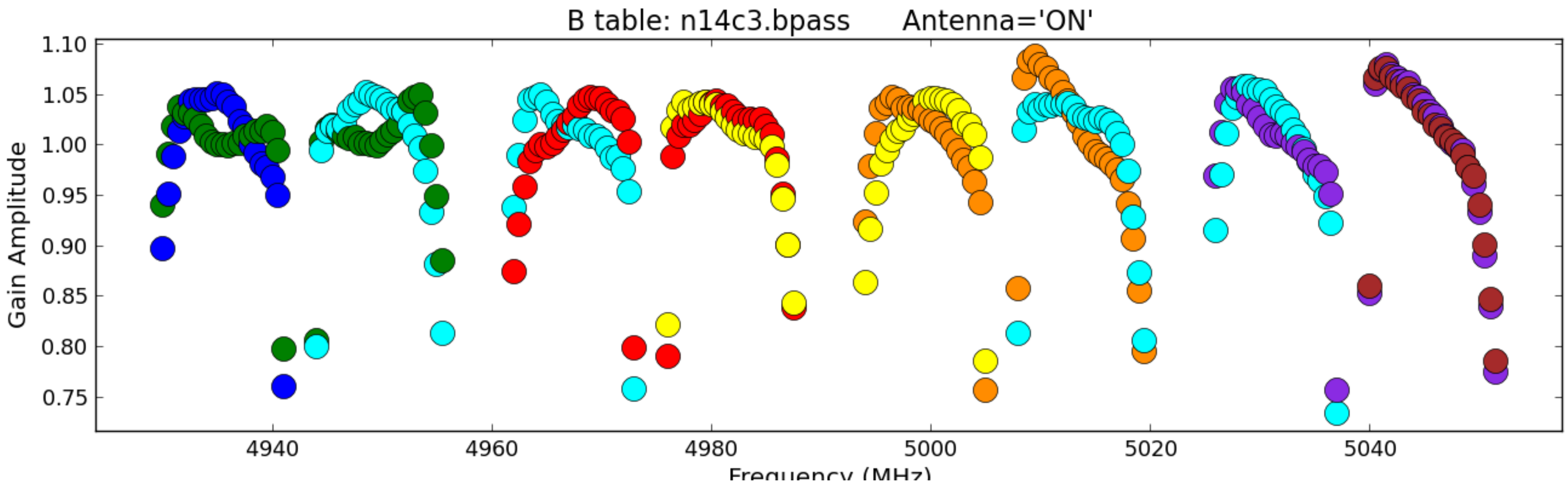
- **Multi-band fringe-fitting**
  - Have removed the instrumental effects, now get rid of atmospheric effects



$$\vec{V}_{ij}^{\mathrm{obs}} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\mathrm{true}}$$

And now for the amplitudes ...

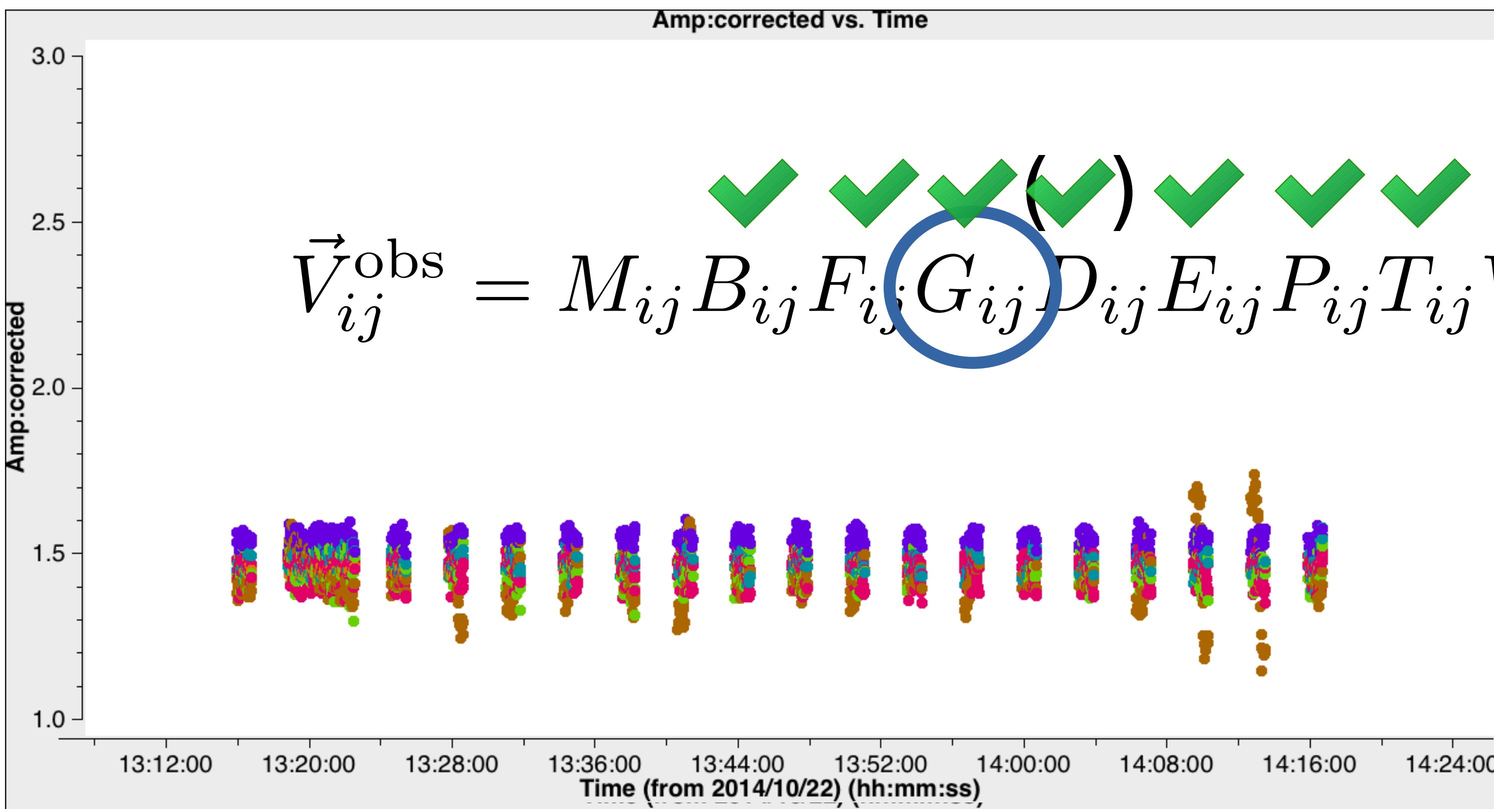
- **Fringe-fitting** only solves for phases, so the amplitudes still need to be corrected.
- **Bandpass calibration** derives amplitude as a function of frequency for each antenna
  - using a well-known, *very bright* calibrator source – need good S/N per channel!



$$\vec{V}_{ij}^{\rm obs} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\rm true}$$

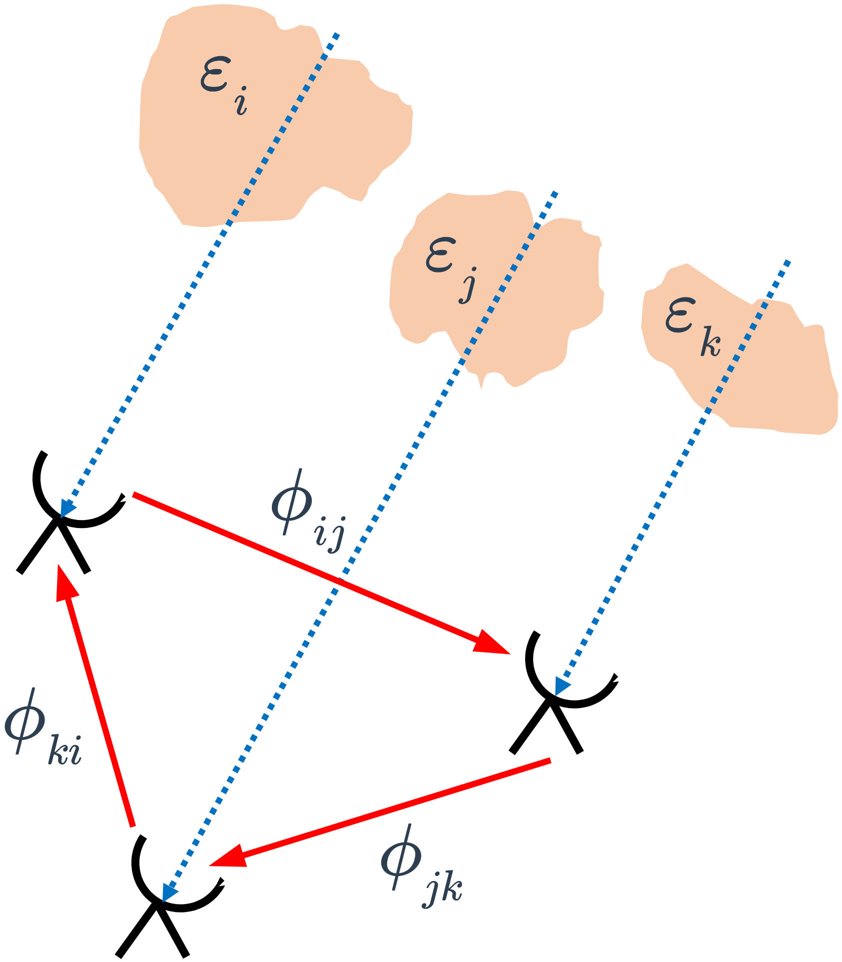
And now for the amplitudes ...

- **Gain calibration** will take care of time-dependent amplitudes
  - due mainly to variable gain in the antenna amplifiers



$$\vec{V}_{ij}^{\rm obs} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\rm true}$$

Non-closing errors



On each baseline, the observed phase is related to the real phase + antenna errors:

$$\phi_{ij,obs} = \phi_{ij} + \varepsilon_i - \varepsilon_j$$

$$\phi_{jk,obs} = \phi_{jk} + \varepsilon_j - \varepsilon_k$$

$$\phi_{ki,obs} = \phi_{ki} + \varepsilon_k - \varepsilon_i$$

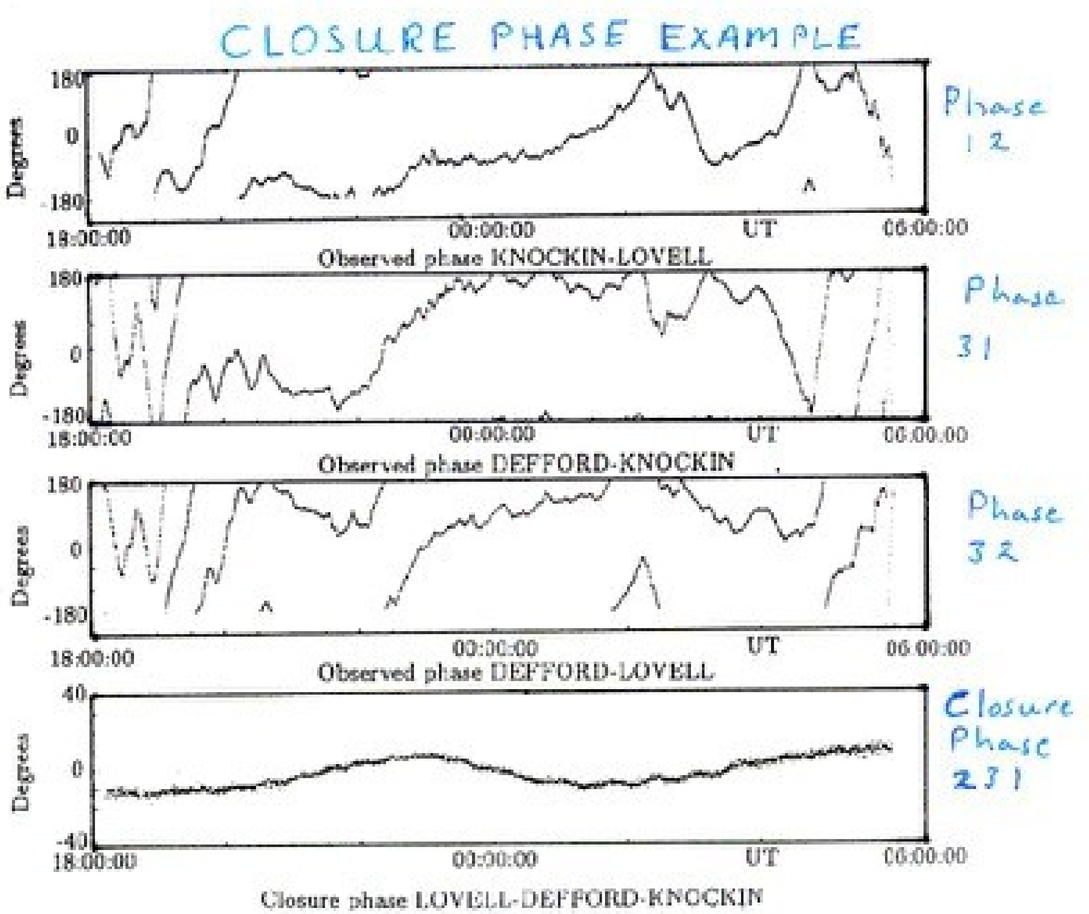
Summing these around a triangle of antennas gives us the **closure phase:**

$$\phi_{ij,obs} + \phi_{jk,obs} + \phi_{ki,obs}$$

$$= \phi_{ij} + \phi_{jk} + \phi_{ki}$$

note that the errors all cancel if you go around the triangle in one direction!

Non-closing errors



If everything is calibrated perfectly, the closure phases should be flat!

Residuals are *non-closing errors,* which can come from baseline-based errors

Three main sources:

- Source structure not correct in model **(self-calibration)**
- Time averaging
  - Atmospheric conditions can change on very short timescales **(don't average)**
- Frequency averaging
  - Bandpass response varies per telescope as function of frequency **(don't average)**

$$\vec{V}_{ij}^{\text{obs}} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\text{true}}$$

Summary

(✓) ✓ ✓ ✓ (✓) ✓ ✓ ✓

$$\vec{V}_{ij}^{\mathrm{obs}} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\mathrm{true}}$$

non-closing errors

bandpass

fringe-fitting

gains

polarisation (use polarised calibrator)

- **Recap of Very Long Baseline Interferometry (VLBI)**
- **Fringe-fitting fundamentals**
- **Fringe-fitting in practice**