Calibration and fringe-fitting

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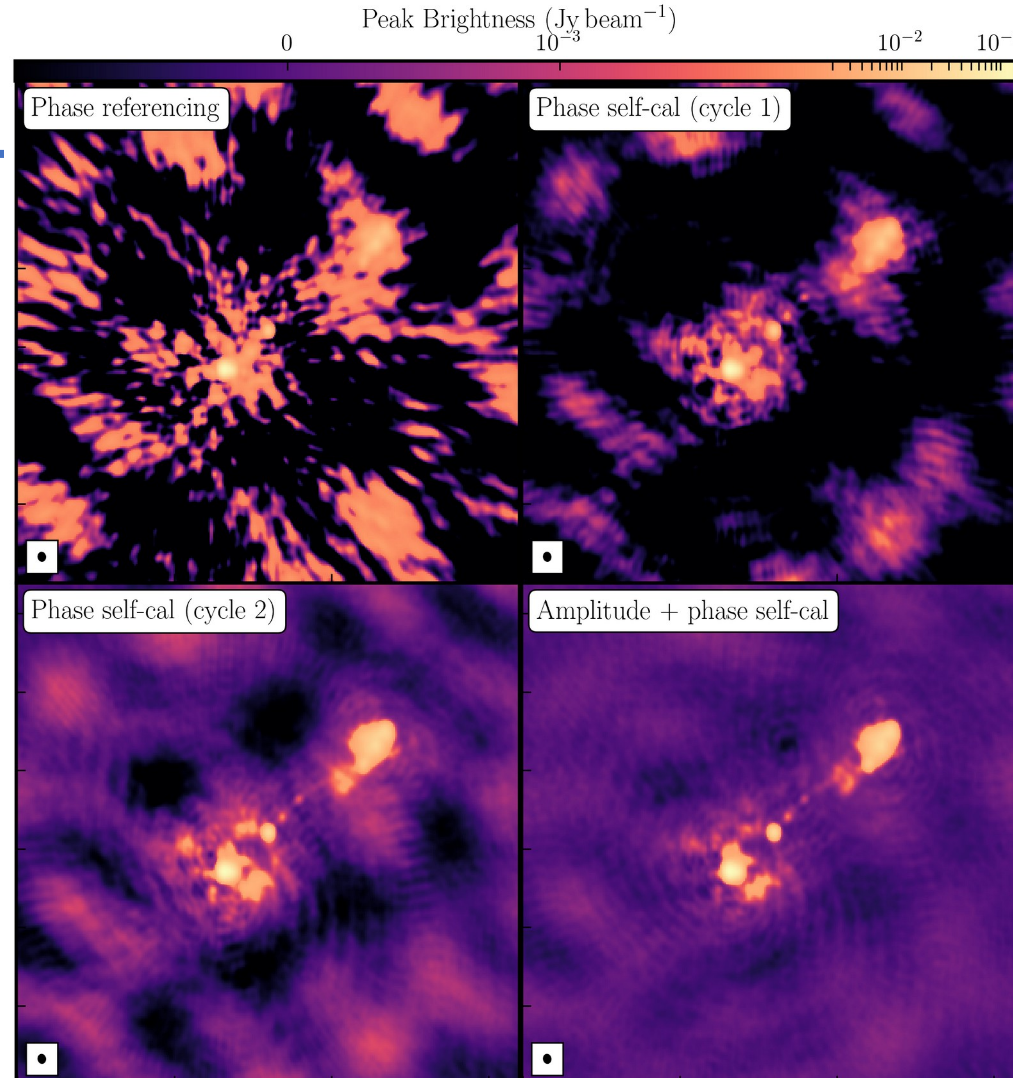

DARA
DEVELOPMENT IN AFRICA WITH RADIO ASTRONOMY

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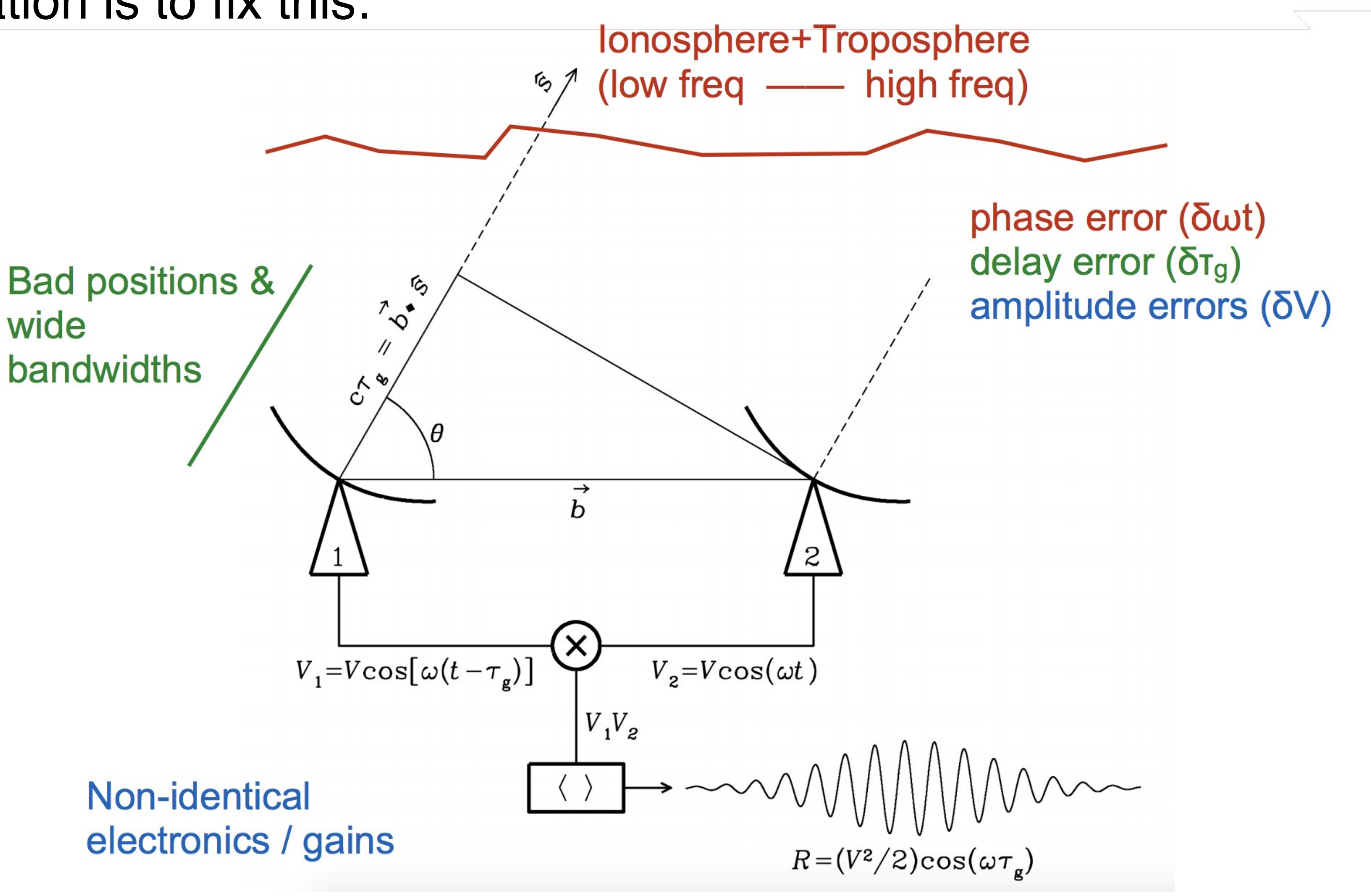
SARAO

Outline

- What affects our data
- A-priori calibration i.e. what's done before you get the data
- What we need to correct / derive and how does CASA implement this
  - Flux-scaling
  - RFI removal
  - Phase-referencing & fringe-fitting
  - Bandpass calibration

What is calibration for?

Calibration is to fix this:



Solve for these issues using calibration

What is calibration for?

Atmosphere

- Ionosphere
- Troposphere
- Water vapour

Antenna / feed

- System temperature
- Primary beam
- Pointing
- Antenna location

LNA / conversion chain

- Clock
- Gain, phase, delay
- Frequency response

Digitiser / Correlator

- Auto-leveling
- Baseline errors

Radio Frequency Interference (RFI)

Calibration before / during observations

- Science observers don't usually need to worry about these (but you might when commissioning) - i.e. applied before correlation

- Delay tracking
  - Correctable off-line if within Nyquist or sensitivity limit
  - Phase tones can be used to align antenna signals

- Antennas: receiver/subreflector at optimum focus
  - Pointing and tracking with sufficient accuracy
    - Mitigated by self-calibration at field centre only
  - Positions
    - Errors cause bad delays
    - Cannot transfer phase-ref corrections accurately to target

Calibration before / during observations

- Correlated data - series of complex visibilities
- Calibration before/ during often stored as metadata:

- Metadata includes:
  - Descriptive: antenna table, source names etc.
  - Flagging: antenna not on source etc.
  - Calibration: T_{sys} measurements etc.

Parameterising calibration

With these off-line calibration products in hand:

- We want to parameterise our knowledge of the system as some quantities need to be derived (e.g. phase, delays, amplitudes)

- CASA uses **the radio interferometry measurement equation** (RIME) to do this, which relates the observed (perturbed) visibility to the 'real'/ ideal (unperturbed) visibility i.e.:

Jones matrix | True visibility | *Jones* matrix for antenna *i*

Observed visibility

$$\vec{V}_{ij} = J_{ij}\vec{V}_{ij}^{\mathrm{true}}$$ where $$J_{ij} = J_i \times J_j$$

- The Jones matrix encodes everything that "happens" to the signal from source to correlator.

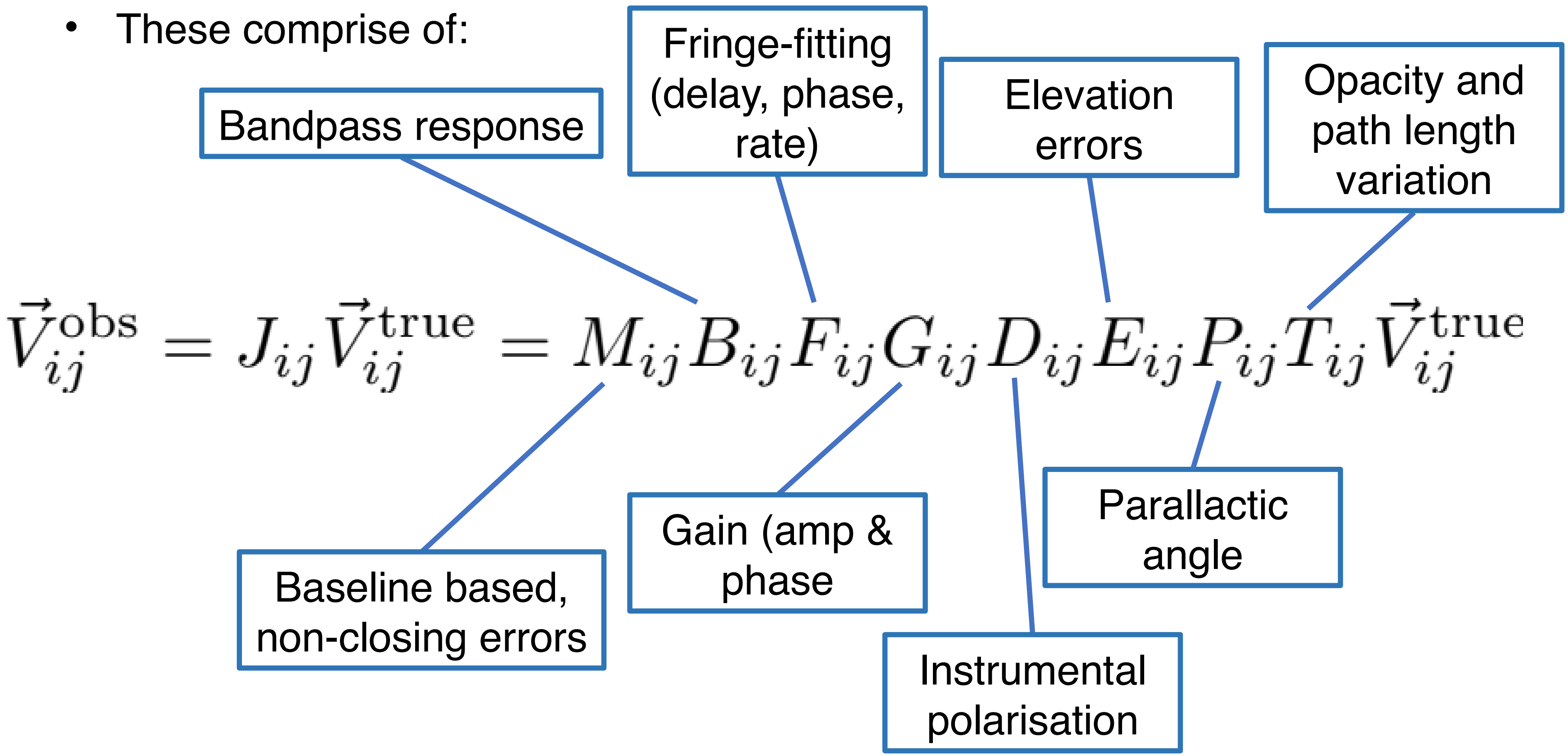
- This assumes calibration parameters should be antenna-based (we will see later that they can be baseline-dependent)

Decomposing the RIME

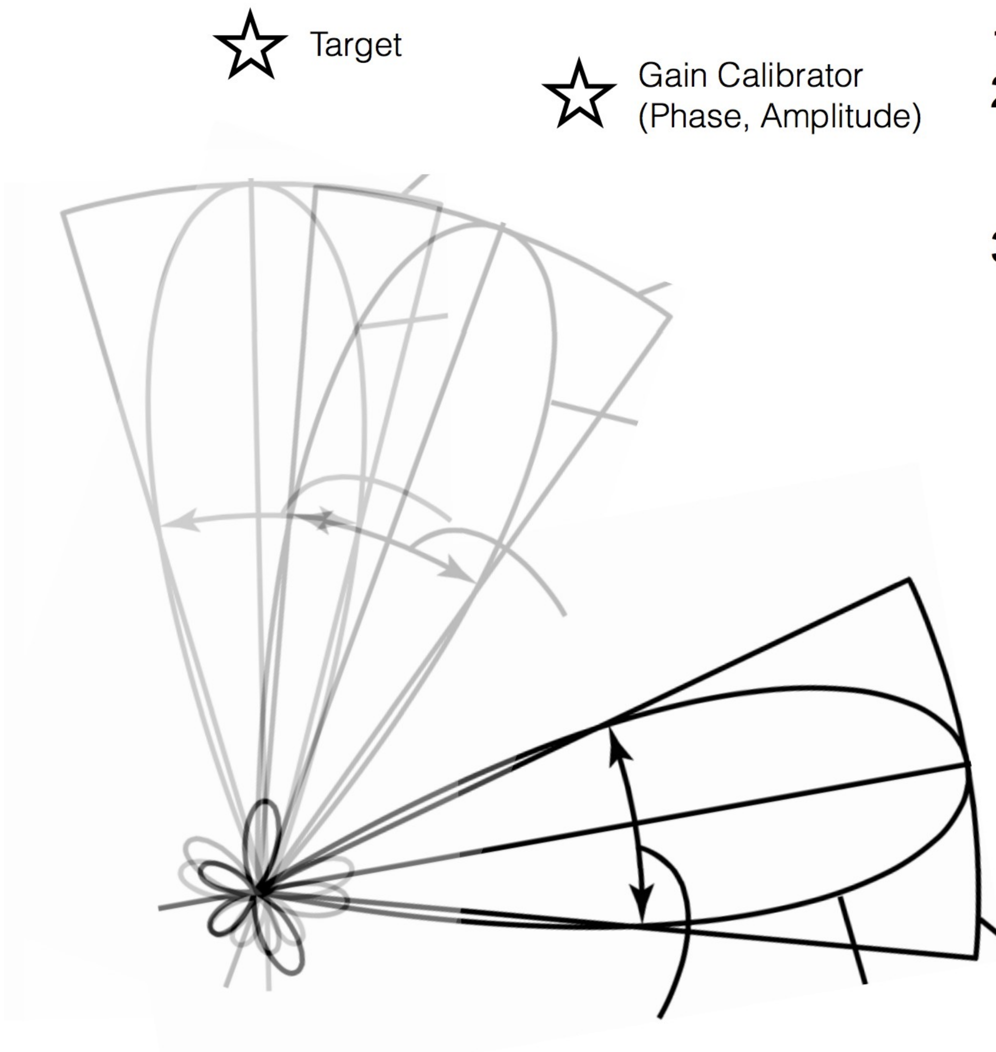
- CASA decomposes the RIME calibration equation into different terms which are solved for independently.

- These comprise of:

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



Calibration strategy



1. Observe **source**
2. Observe **calibrator** to measure gains (amplitude and phase) as a function of time.
3. Observe **bright calibrator** of known flux-density and spectrum to measure absolute flux calibration, band-pass and residual delays

Calibration strategy

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

- CASA decomposes the RIME calibration equation into different terms which are solved for independently.

- These comprise of:
  1. **Primary Calibration:** use of a "known" standard source to determine time and direction-independent quantities e.g. bandpass calibration. These are typically antenna-based effects!

  2. **Secondary Calibration:** estimate local time-dependent conditions with nearby calibrator (e.g. gain calibration – amp & phase)

  3. **Self-Calibration:** use of the target field itself to determine highly time dependent quantities, e.g. refine gain calibration

Choosing Calibrators

- Primary/secondary calibrators should have:
  - Excellent positions (for astrometry)
  - Proper source size ("just compact enough") - standard calibrator lists
  - Compact enough to be unresolved on the longest baselines but not so compact that the source is variable

- Well-understood flux density (for flux scale) and spectral shape (for bandpass)

- For polarization calibration: well understood polarimetric properties (including Faraday rotation measure, where appropriate)

VLBI calibration - a priori calibration

- We want to start with things which are derived by other means e.g. ones that are tracked during observation or known properties of the antenna

- With VLBI calibration, we normally can solve for two terms of the calibration RIME namely:
  - flux-scale
  - Gain curves

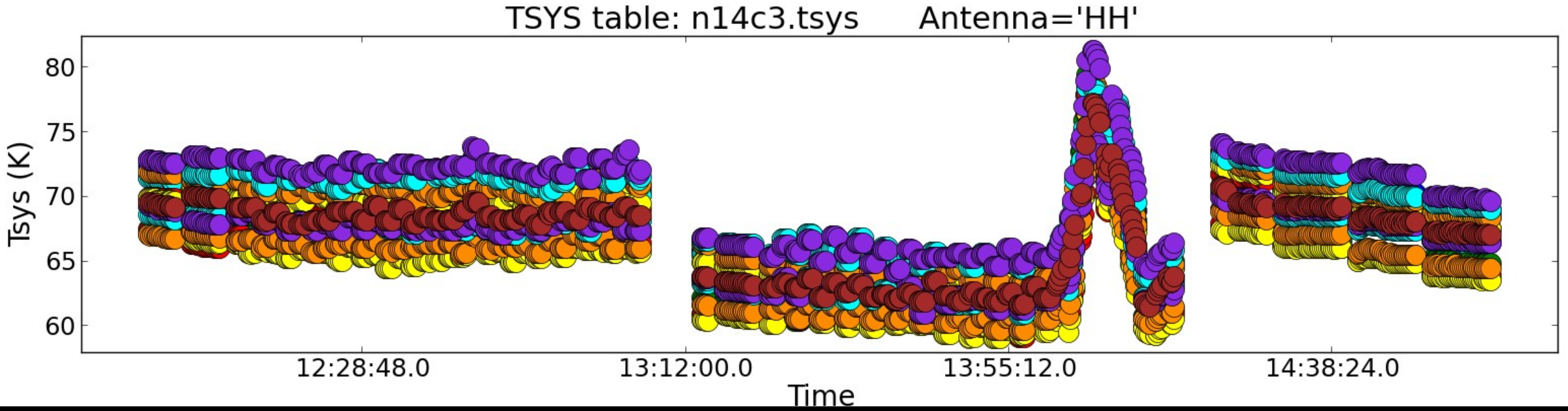
$$\vec{V}_{ij}^{\text{obs}} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\text{true}}$$

A priori calibration

System temperature measurement ()

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

- Time-dependent measure of the sensitivity of each telescope
- Comparison to 'standard' signal allows for **relative** scaling of amplitudes (considering weather, gain-elevation, source brightness)
- For long wavelengths (as with the EVN) – use a noise diode



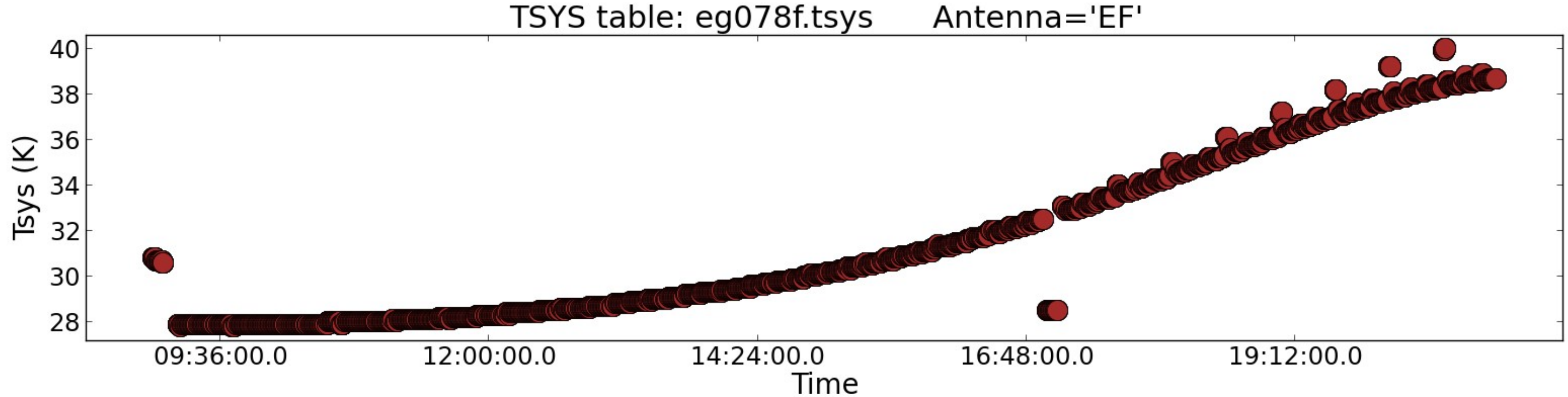
A priori calibration

System temperature measurement ()

- can be used to provide a scaling from correlator units
- System Equivalent Flux Density -

where K/Jy]) (Antenna area , efficiency $_A$)

- Typical values are 10 - 100 K at frequencies from 1 to ~200 GHz (Lower = more sensitive)
- Few bright (Jy) sources raise significantly (must allow for this for accurate amplitude calibration)



A priori calibration

Gain curve calibration

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

- Atmosphere adds noise and absorbs signal

$$T_{\text{received}} = T_{\text{source}} \exp(\tau_{\text{atm}} / \cos(z)) + T_{\text{atm}}(1 - \exp(\tau_{\text{atm}} / \cos(z)))$$

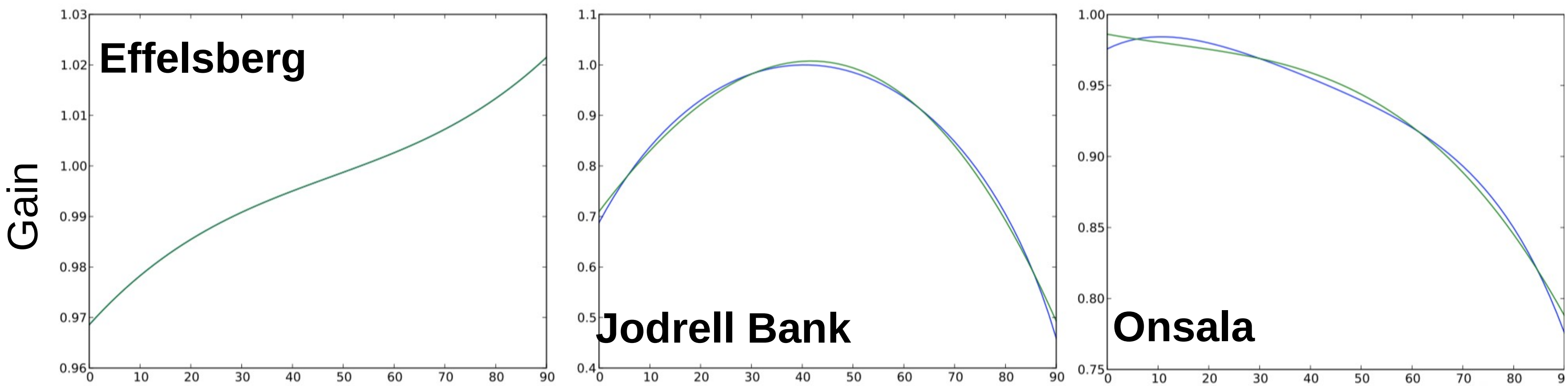
- Source would provide temperature *T* if measured above the atmosphere optical depth τ_{atm} and z is the zenith distance.
- Noise is increased for observing at low elevation (large z)
  - Some T_{sys} measurements include this
  - &/or apply analytic gain curve (assume τ_{atm} stable)

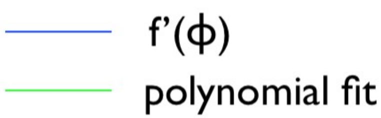
A priori calibration

Gain curve calibration

- As well as correcting for the atmosphere noise antennas not rigid → their effective collecting area and net surface accuracy vary with elevation as gravity deforms the surface.

- More important at higher frequencies





Courtesy M. Kettenis

A priori calibration

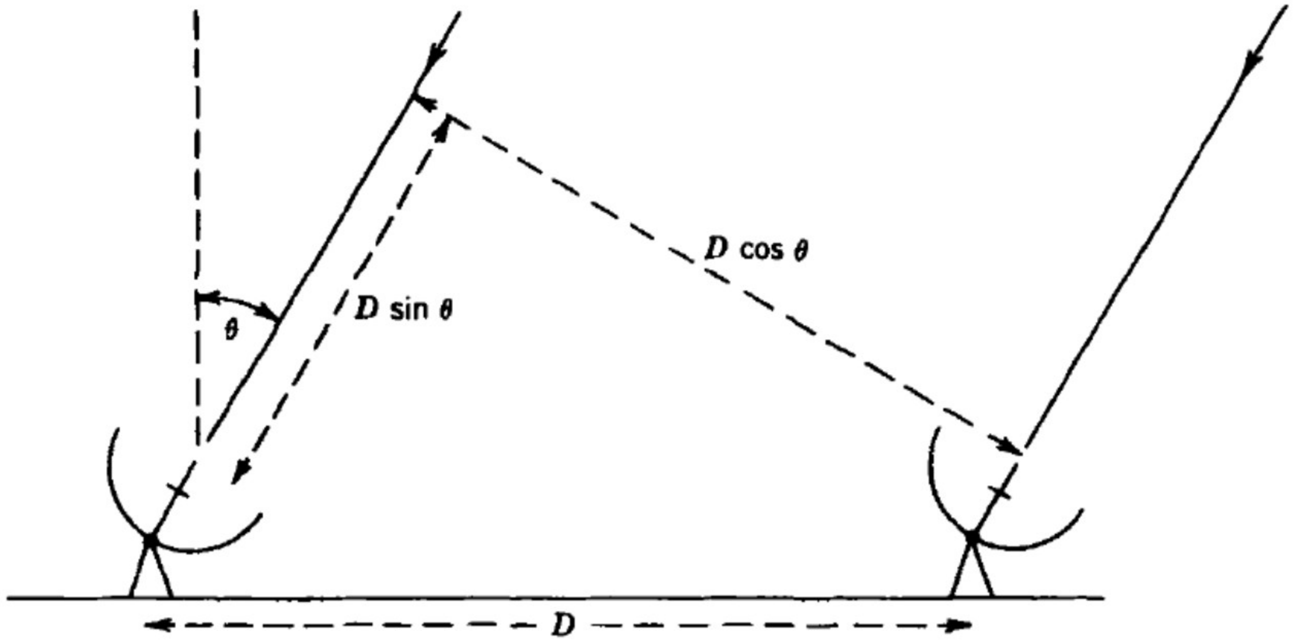
Other a priori calibration

- Calibration measurements supplied with data can includes Tsys, gain-elevation and WVR
  - Water Vapour Radiometry (at mm/sub-mm wavelengths): measure atmospheric water line every few seconds, calculate refractive delay of phase and/or absorption
- Antenna position corrections may also be available.
- For VLBI and low frequency, ionospheric total electron content measures can be used to correct dispersive delays (i.e. curvature of delay term across band)
- Others include weather tables to refine gain-el; GPS measurements for position and Faraday rotation
- May need reformatting or removal of bad values
  - Usually employing standard scripts, often by observatory staff

To CASA – do a priori calibration

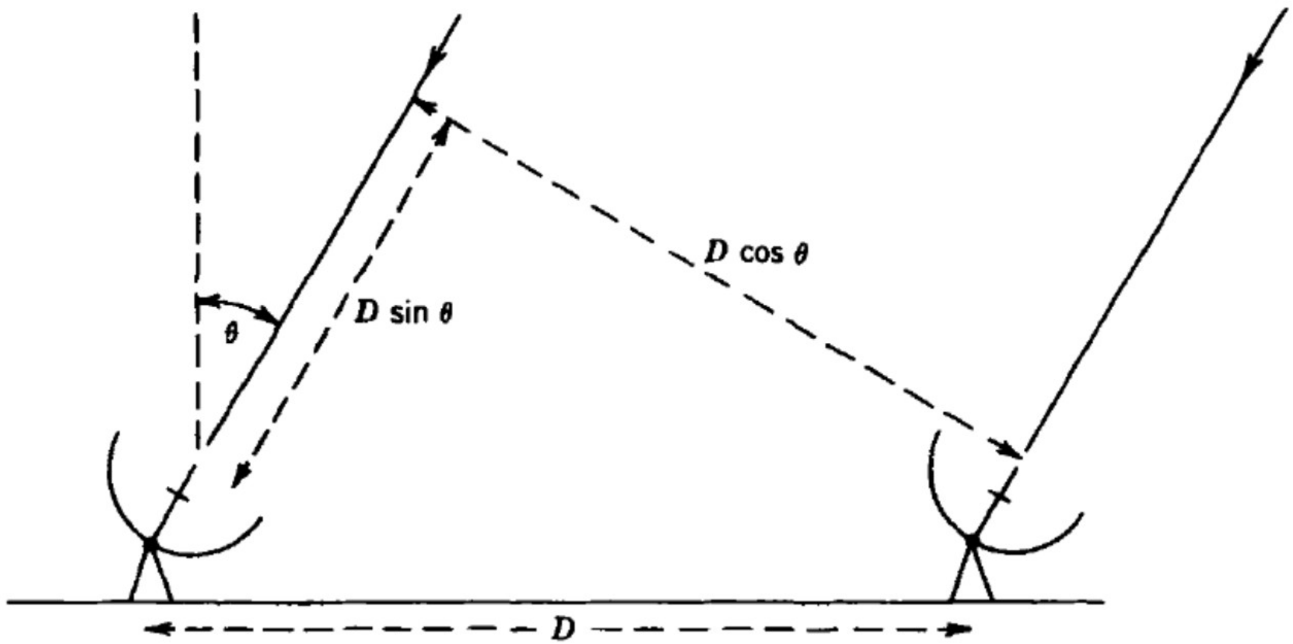
Fringe fitting - introduction

- Recall the simple 2-element interferometer



- Wave-fronts of a signal from a distant source, arrives at one antenna with a geometrical delay, $\tau_{\mathrm{obs}} = (D/c)\sin(\theta)$
- Phase difference – 'interferometer phase', $\phi = 2\pi\nu\tau_{\mathrm{obs}}$
- ϕ changes with time!

Fringe fitting - introduction

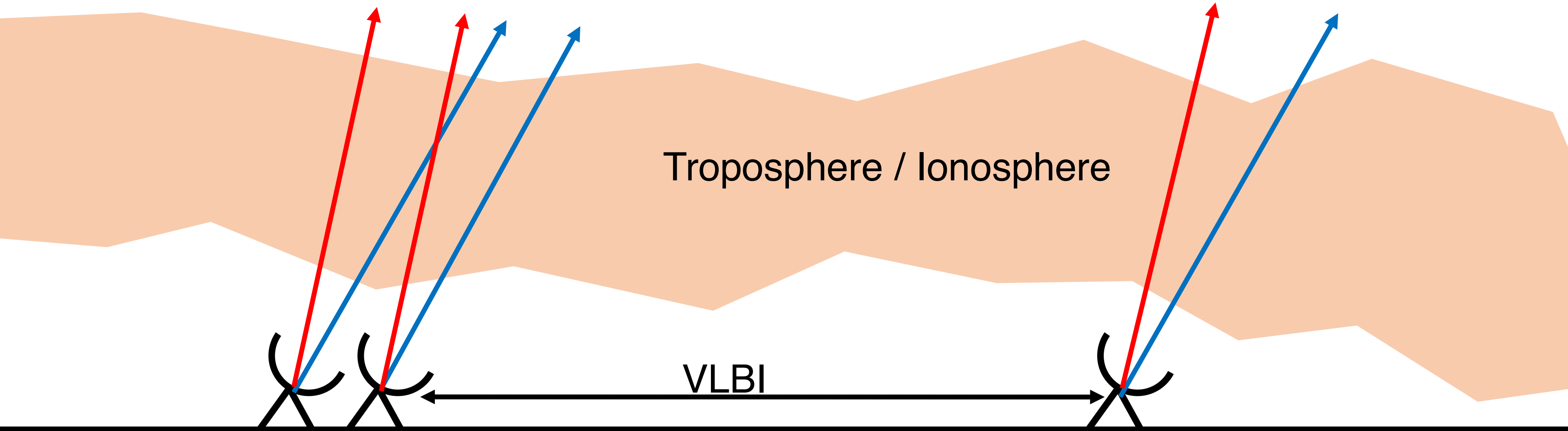


- Signals from both antennas are combined in a correlator
- Correlator estimates and corrects for geometric delays
- For connected arrays e.g. JVLA, ATCA, MeerKAT this simple geometrical delay is enough ... not so for VLBI.

Why we need fringe-fitting

VLBI vs short baseline arrays

- No fundamental difference but with longer baselines (100's to 1000's km)
- However VLBI arrays are not connected so:
  - Independent clocks and equipment → phase/delay errors
  - The delay and rate of the wavefronts vary more rapidly due to completely different atmospheric paths.
  - Geometric delay needs to be exact - must be estimated and removed during correlation



Why we need fringe-fitting

The geometric model

Table 22–1. Terms of a VLBI Geometric Model [a]

Item	Approx max Magnitude [b]	Time scale
Zero order geometry.	6000 km	1 day
Nutation	~ 20"	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration	20"	1 year
Retarded baseline	20 m	1 day
Gravitational delay	4 mas @ 90° from sun	1 year
Tectonic motion	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	~1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	0.5"	~ 1.2 years
UT1 (Earth rotation)	Random at several mas	Various
Ionosphere	~ 2 m at 2 GHz	seconds to years
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	0 – 30 cm at zenith	seconds to seasonal
Antenna structure	<10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years

- Terms that affect the delay > few cm
- Most radio astronomers don't have to worry about these effects
- **However, correlator model, not perfect model** (due to atmosphere / clock errors)
- Residual phase / delay errors cause decorrelation of signal

→ **fringe-fitting solves for this!**

How to fringe-fit?

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

- Need to solve for phase errors in time (rate) and frequency (delay) space
- Remember the interferometer phase: $\phi = 2\pi\nu\tau_{\rm obs}$

→ phase error depends on delay (i.e. against frequency)

- Fringe fitting solves these errors assuming a linear model of the phase error for each antenna i.e.

$$\Delta\phi_i(t,\nu) = \phi_{i,0} + \frac{\partial\phi_i}{\partial\nu}\Delta\nu + \frac{\partial\phi_i}{\partial t}\Delta t$$

Phase error at time t and ν

Delay term

Rate term

- Some cases (e.g. space, mm-, low-frequency VLBI) need require higher orders e.g. dispersive delays - $\mathcal{O}\frac{\partial^2\phi}{\partial\nu^2}\Delta\nu$

How to fringe-fit?

- Therefore, for each baseline ij this error becomes.

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

- Fringe-fitting involves solving the above equation, to obtain the errors.
- Via observations of a bright calibrator → phase referencing Typically assumes that source is a point source at the phase centre.
- Can be done per baseline or globally (i.e. combine all baselines and derive per antenna)
- Without fringe fitting cannot average in phase and time
- Worse for weaker targets

How to fringe-fit?

In CASA

Global fringe fitting

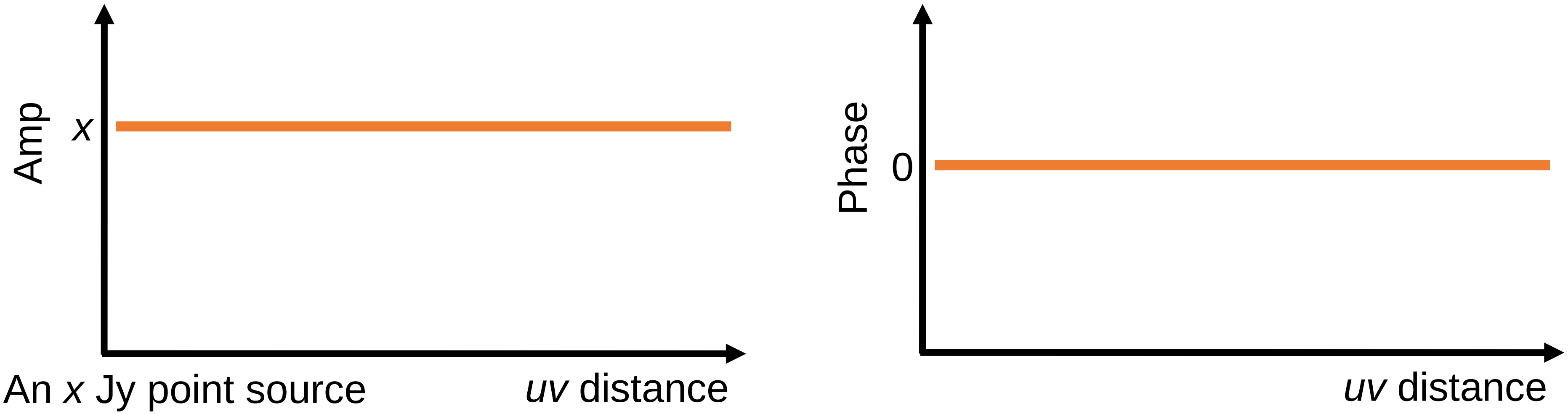
- Use all baselines to jointly estimate the antenna phase, delay and rate relative to a reference antenna
- Solves the baseline phase error equation, with one of the antennas set to the reference antenna
- Delay, rate and phase residuals for reference antenna are set to zero.
- Hence only measures difference, not absolute errors
- **Assumes calibrator is a bright point source at phase center (unless model specified!)**

```
--------> 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
```

Important aside

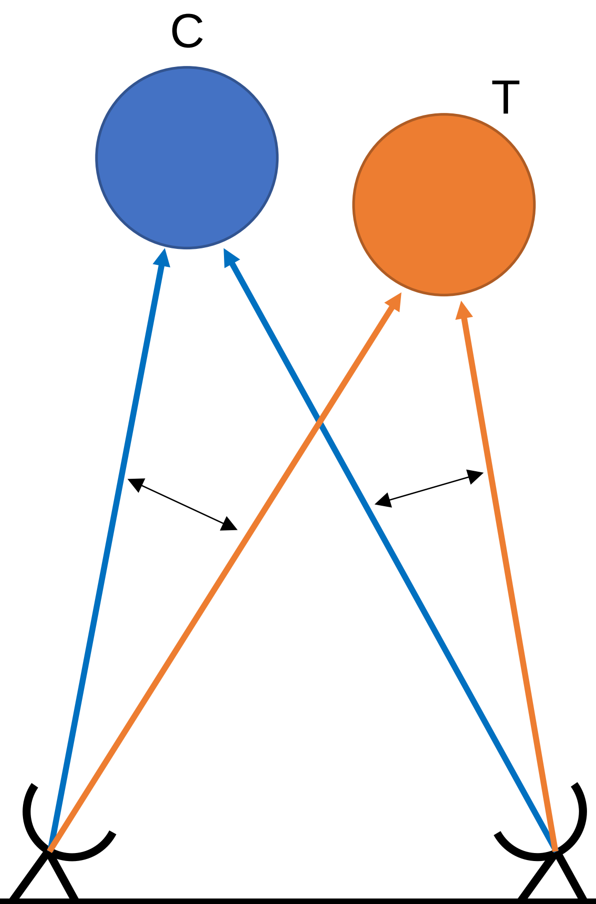
Point sources

- Lots of calibration assumes that your phase calibrator is point-like **and** in the centre of the field (i.e. phase center).
- Calibration essentially compares your model (i.e. point source) with the observed visibilities and derives corrections.
- **A true point source is flat in amplitude and phase space** (see below)
- If your phase calibrator is **not** point-like then we need to derive a model. We will learn more about this in the self-calibration lecture.



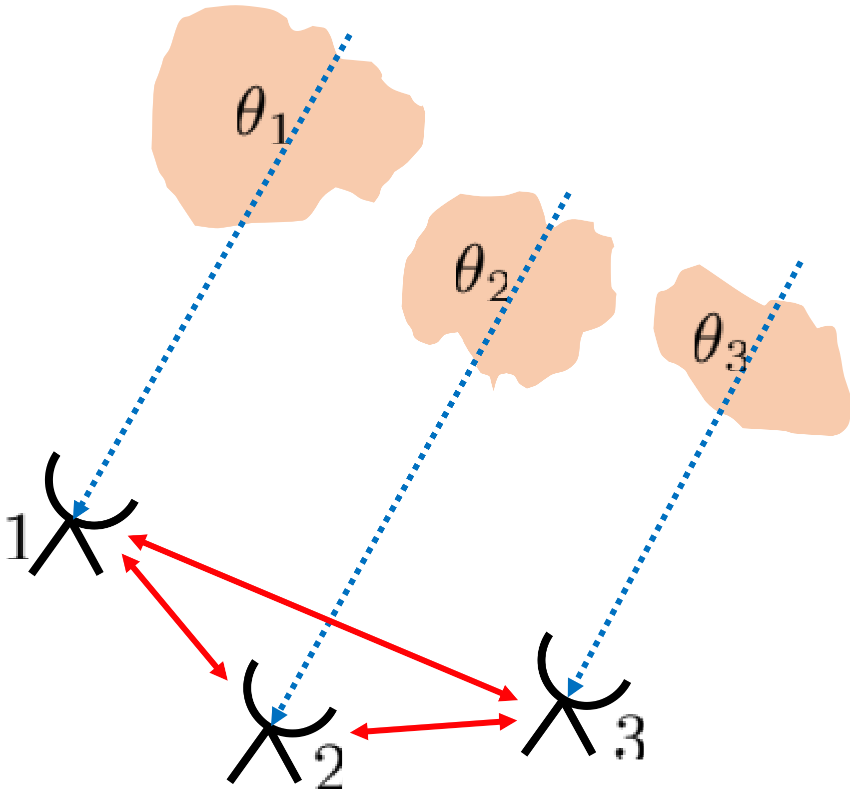
An *x* Jy point source

Phase referencing requirements



- Fringe-fitting requires observations of a bright, compact source → the phase-calibrator, C.
- Nodding between C and target (T)
- Cycle time must be shorter than the atmospheric fluctuations
  ~10 mins at 5 GHz; ~5 mins at 1.6 GHz
- C must be close to T (typically deg)
- Antenna positions must be known to within a few cm!
- Obtain solutions of the phase, rate and delay by applying the fringe-fitting technique to C and interpolate to T
- **Biggest problems:**
  - Wet troposhere & fewer calibrators at high frequencies
  - Ionosphere at low frequencies

Closure Phases



ϕ_{ij} is the true phase

$$\Theta_{12} = \phi_{12} + \theta_1 - \theta_2$$
$$\Theta_{23} = \phi_{23} + \theta_2 - \theta_3$$
$$\Theta_{31} = \phi_{31} + \theta_3 - \theta_1$$

- All antennas have different random phase fluctuations due to atmosphere.
- Closure phase, Θ_c is the sum of simultaneously observed phases of a source on three baselines forming a triangle
- Independent of station-based phase errors.
- Phase errors due to different atmospheric variations are cancelled in the closed loop
- Fringe-fitting (and self-cal) uses this triangle to solve for the residual phases, rates and delay

$$\Phi_c = \phi_{12} + \phi_{23} + \phi_{31} + \text{noise}$$

Fringe-fitting in practice

- Used to be an AIPS-only task but is now part of CASA (since v 5.3)
- For VLBI, there are (normally) two times we need to fringe-fit.
  1. For removing instrumental delays
  2. Deriving time, rates and delays variations vs time (known as a multi-band fringe fit)

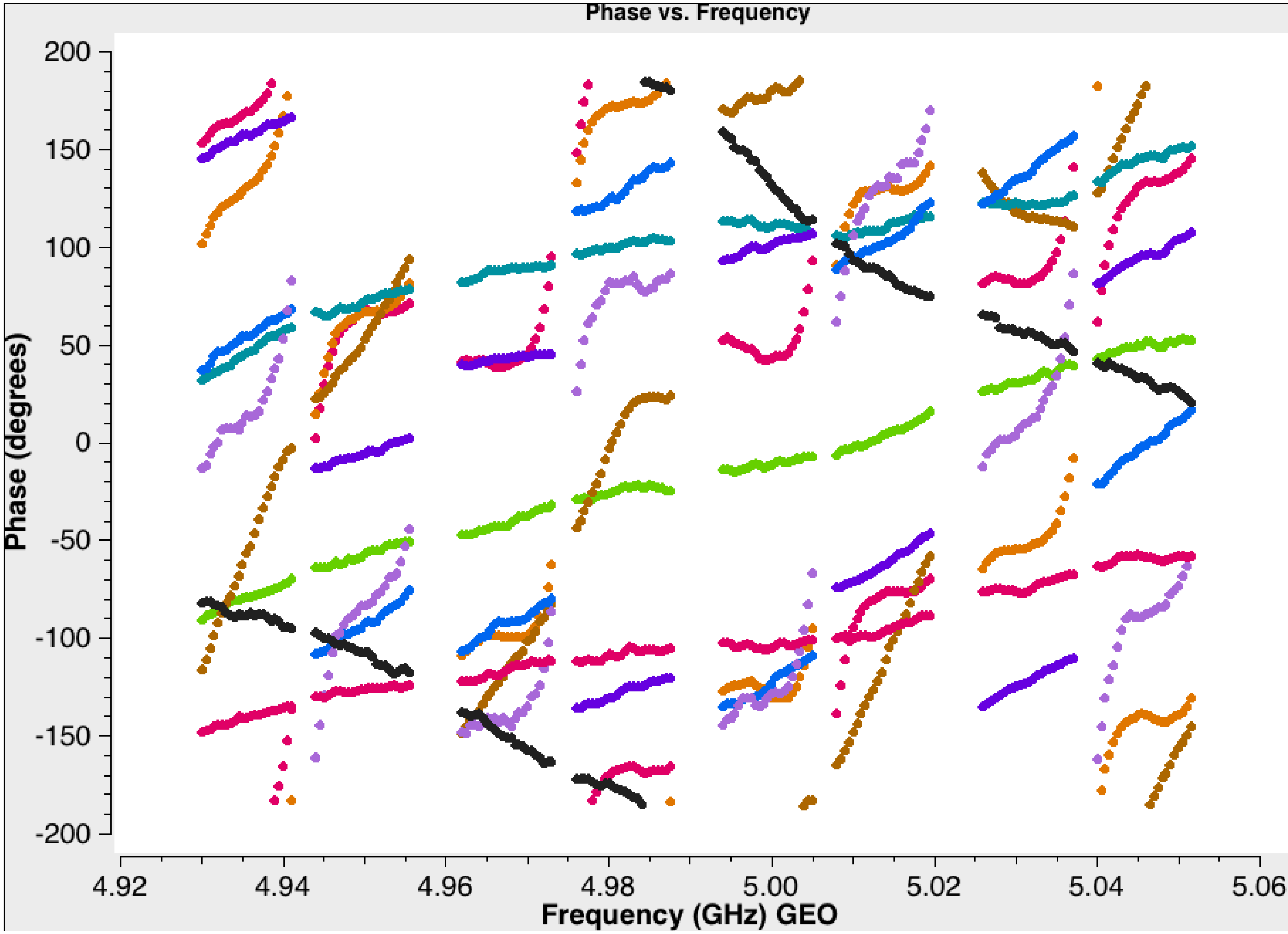
1. Instrumental delays

- Typically induced by differing instrumental paths across the receiver subbands (spws)
- Causes ‘jumps’ in phase across the sub-bands
- Use short integration (~2 mins), on a bright source to get enough S/N per subband.
- Instrumental delays are due to antennas and are not expected to vary across time.

Fringe-fitting in practice

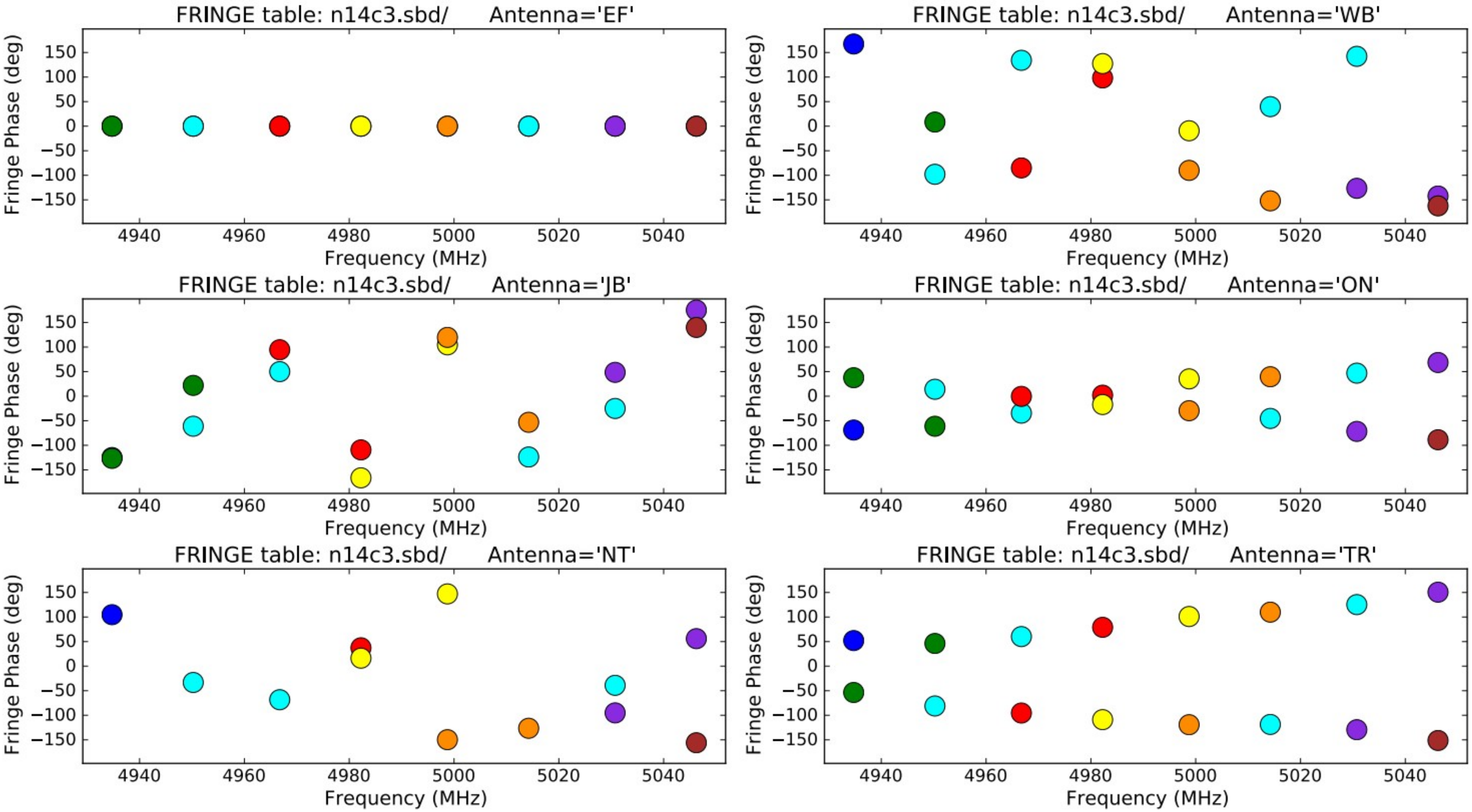
Instrumental delays

- **Before instrumental delay**
- Showing phase vs. frequency on bright calibrator (Effelsberg baselines, 1-scan, LL polarisation)
- Coloured by antenna!
- This scan used for deriving solutions.



Fringe-fitting in practice

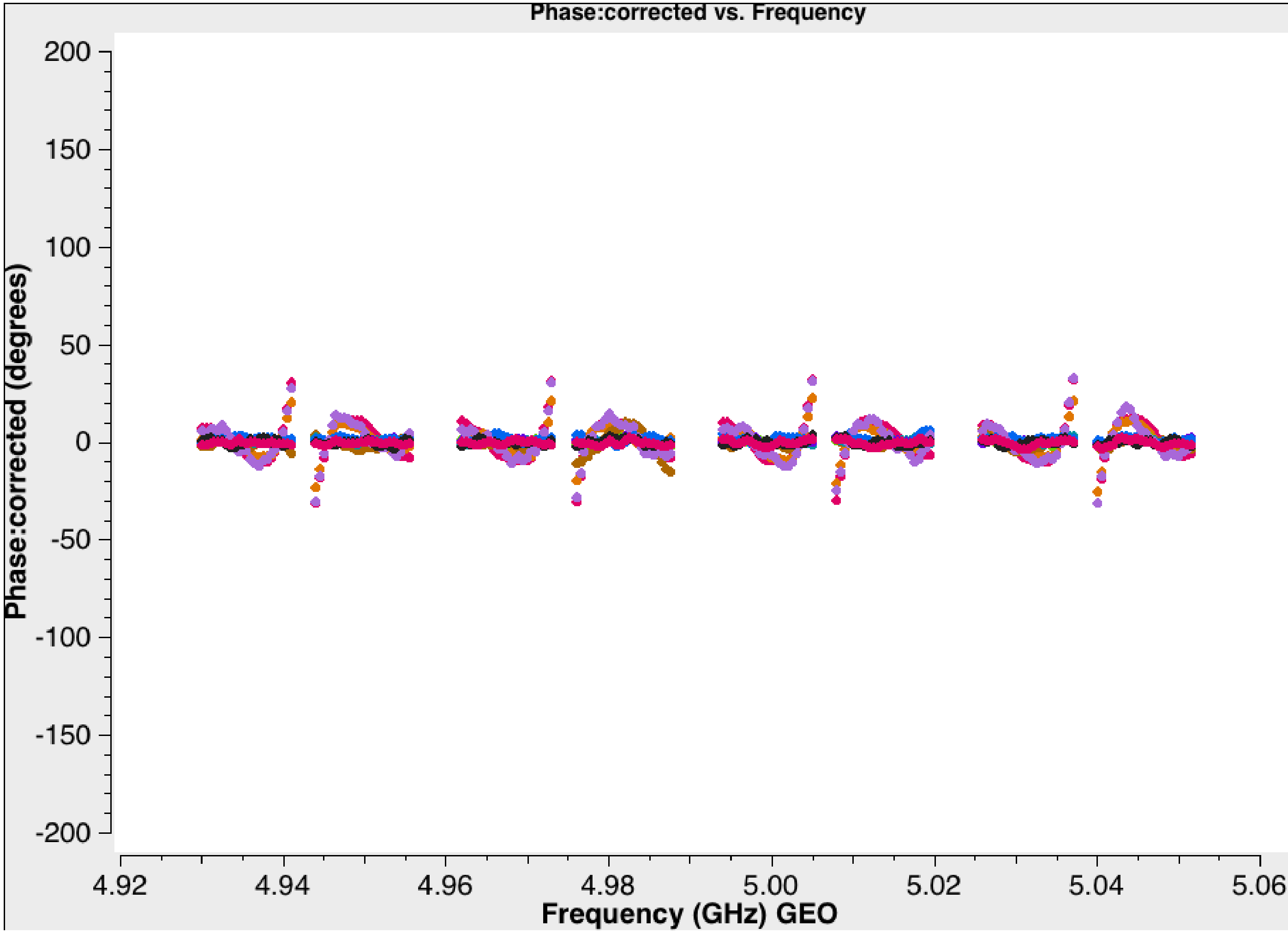
Instrumental delays



Fringe-fitting in practice

Instrumental delays

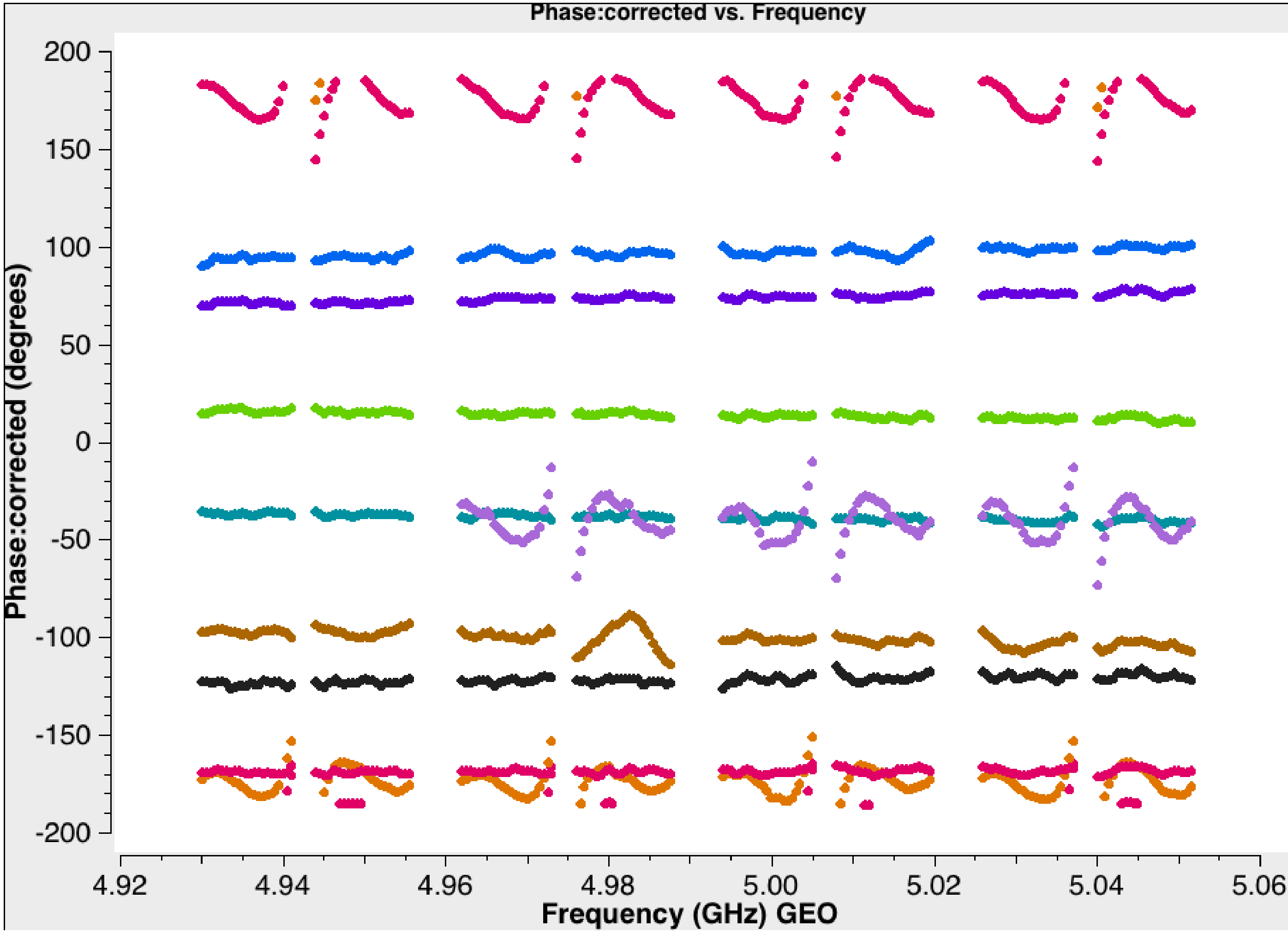
- **After instrumental delay**
- Showing corrected phase vs. frequency on bright calibrator (Effelsberg baselines, 1-scan, LL polarisation)
- Coloured by antenna!
- **Same scan as solutions derived for!**



Fringe-fitting in practice

Instrumental delays

- **After instrumental delay**
- Showing corrected phase vs. frequency on bright calibrator (Effelsberg baselines, 1-scan, LL polarisation)
- **On different scan!**
- Phase jumps between sub-bands gone but time variable remains!



Fringe-fitting in practice

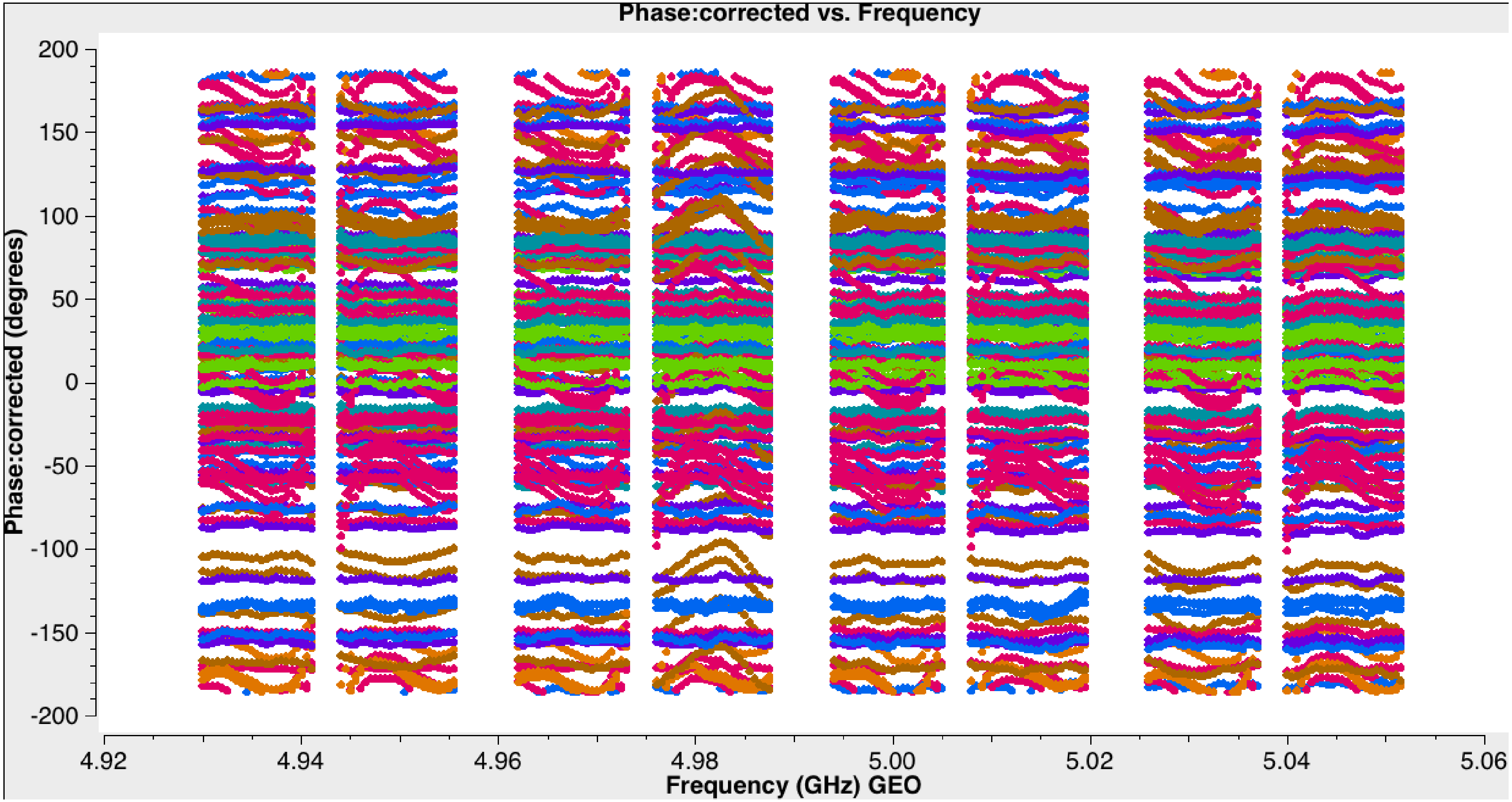
2. Multi-band fringe-fitting

- With instrumental delays removing contributions from the antennas – we can expect that the dominant contributor is now the atmosphere.
- This means that any solutions needs to be on the phase calibrator as atmosphere is approximately same as target source
- We want to derive the rate, phase and delays vs time.
- The instrumental delays (time-independent) now allow us to combine the sub-bands together when deriving our time-dependent solutions, therefore phase ref source doesn't need to be so bright!

Fringe-fitting in practice

Multi-band fringe-fitting

Instrumental delays only
(All baselines to Effelsberg)

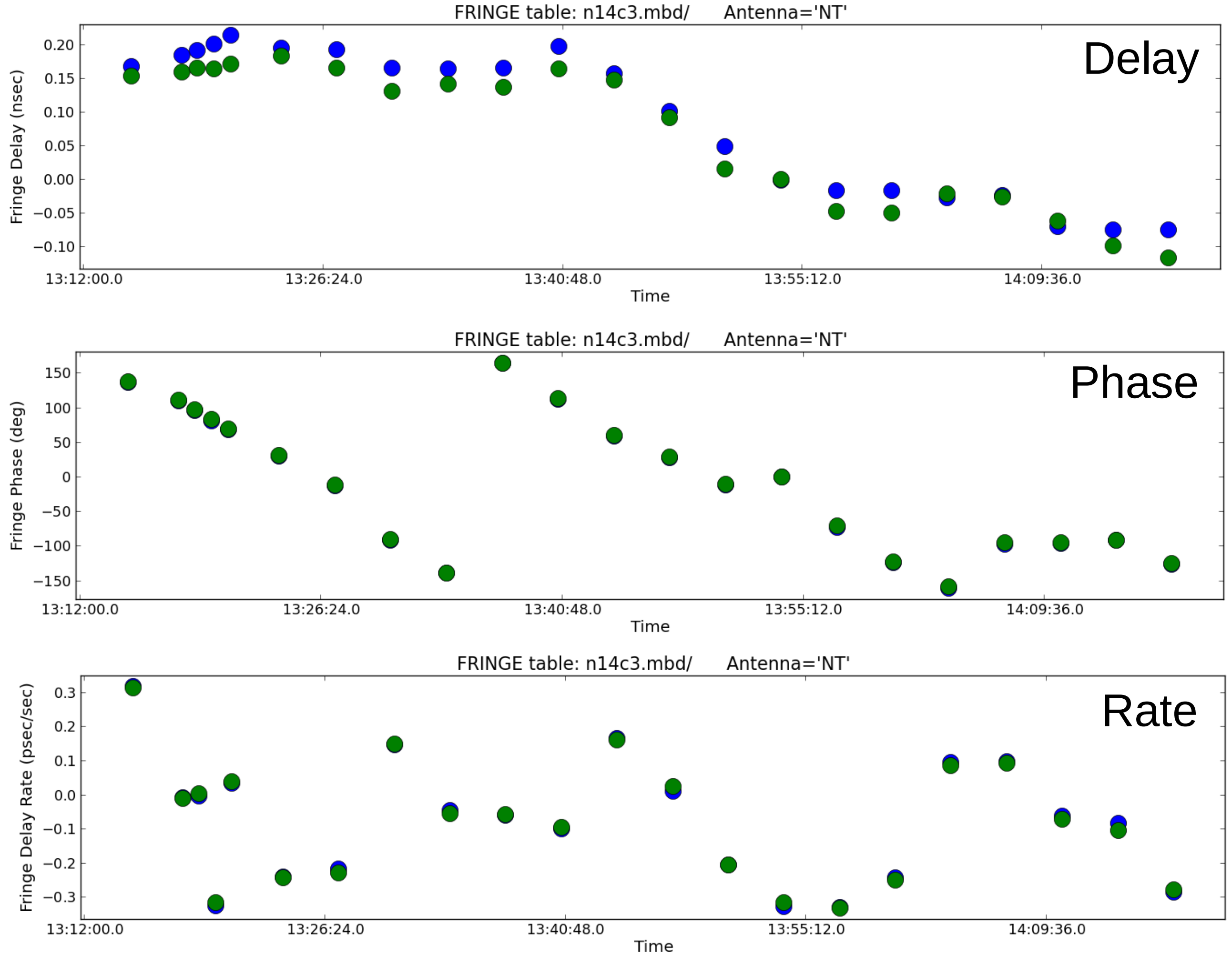


Fringe-fitting in practice

Multi-band fringe-fitting

Multi-band delay solutions

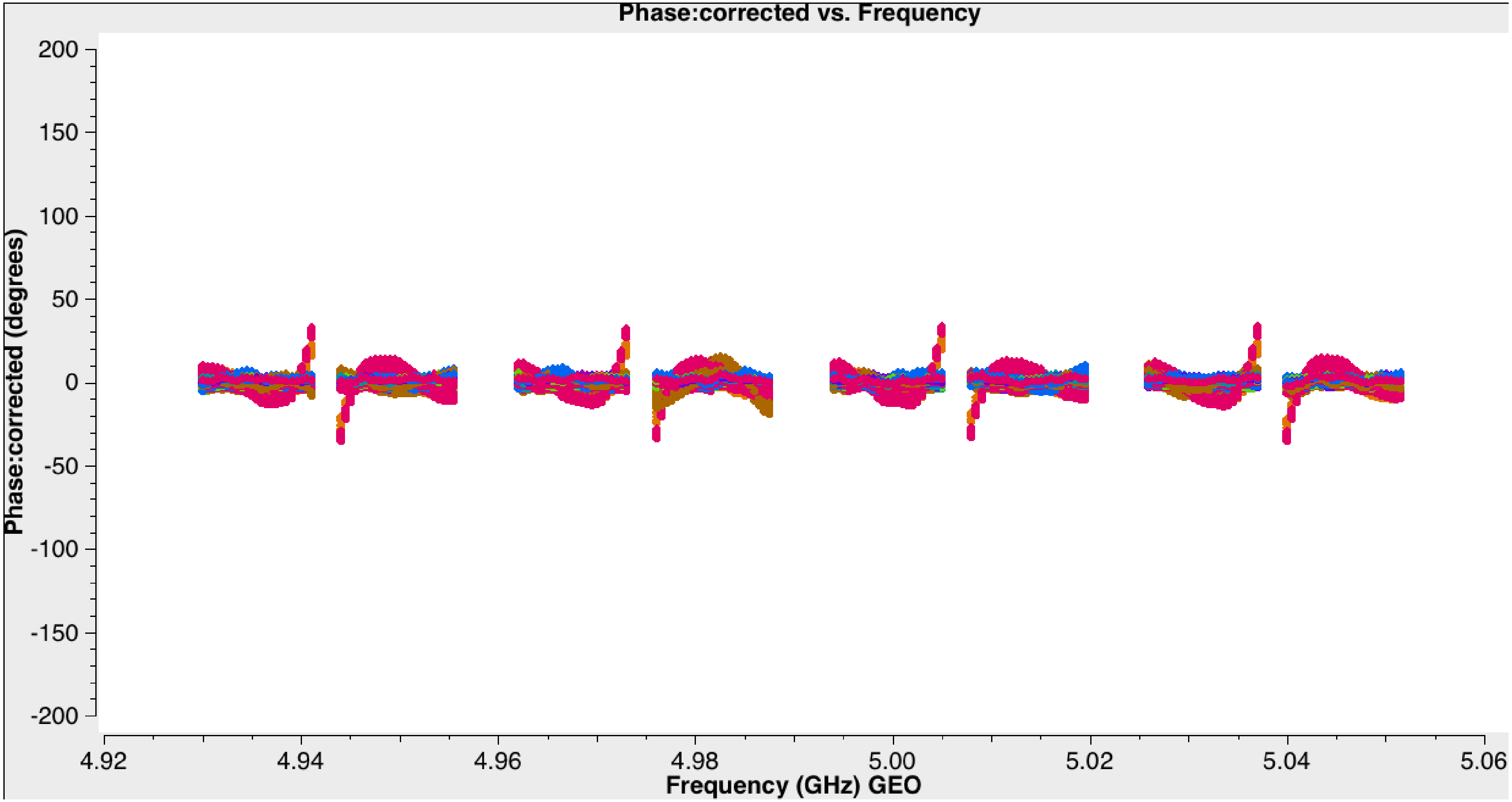
- Noto telescope only shown here
- One solution per scan and spw combined
- Delay, phase, rate solutions primarily due to atmosphere



Fringe-fitting in practice

Multi-band fringe-fitting

Instrumental delays + multi-band delays
(All baselines to Effelsberg)

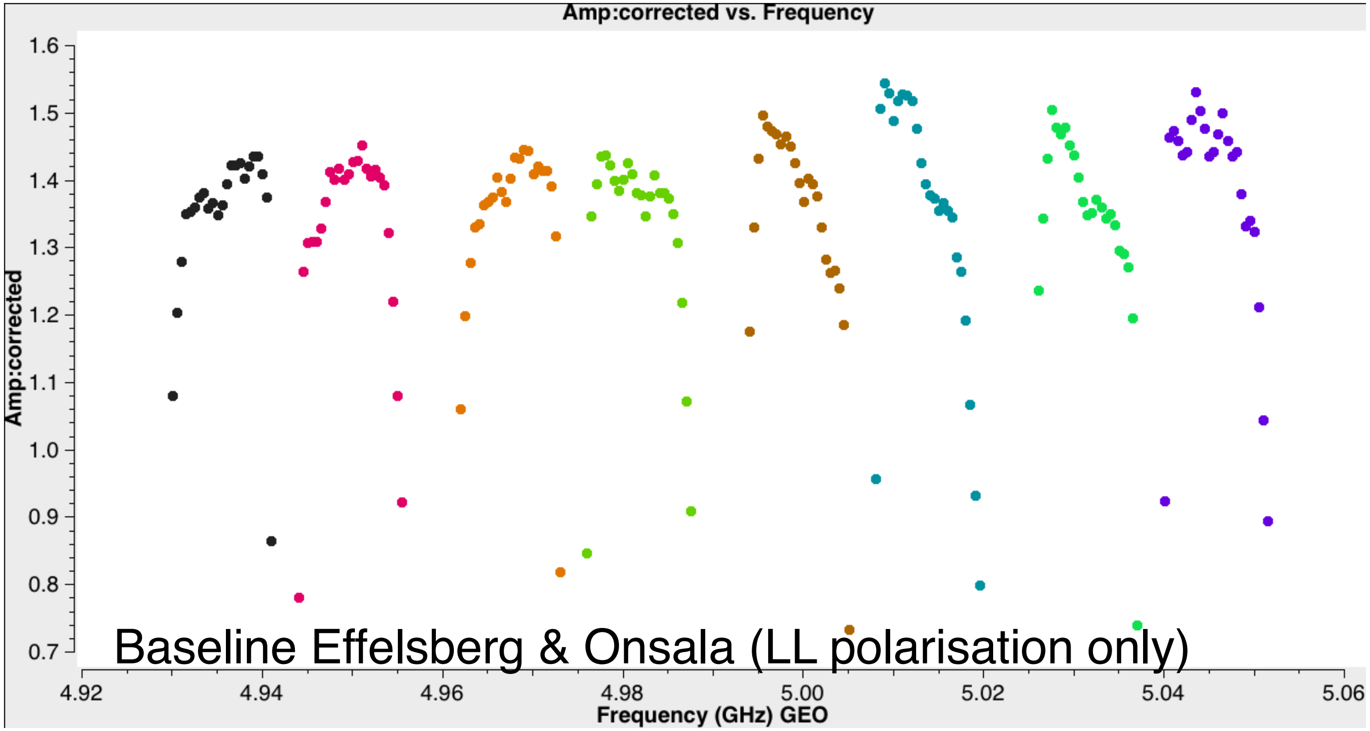


Back to CASA – fringe-fitting

Bandpass calibration

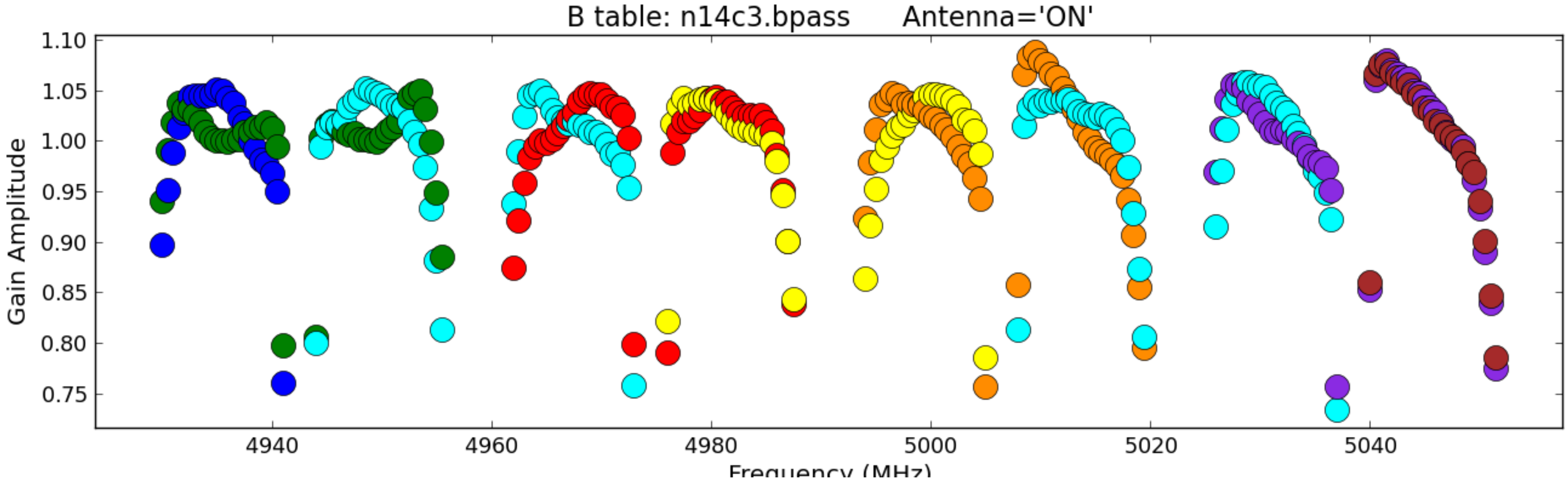
$$\vec{V}_{ij}^{\rm obs} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\rm true}$$

- With the first-order phases, delays & rates corrected, what is left is to correct the bandpass.
- Bandpass is the **frequency-dependent sensitivity** across the observed frequency range
- Variations are due to filters, receiver sensitivity variations & signal processing artefacts.



Bandpass calibration

- Bandpass correction derives the amplitude and phases **per** antenna.
- Each antenna will have a distinctive amp vs freq shape which can be derived from all baselines to that antenna! (It's a bunch of lots of simultaneous equations)
- Bandpass calibrators **must** be extremely bright as we need to get solutions per channel (and not subband!) to track the shape across the bandwidth.

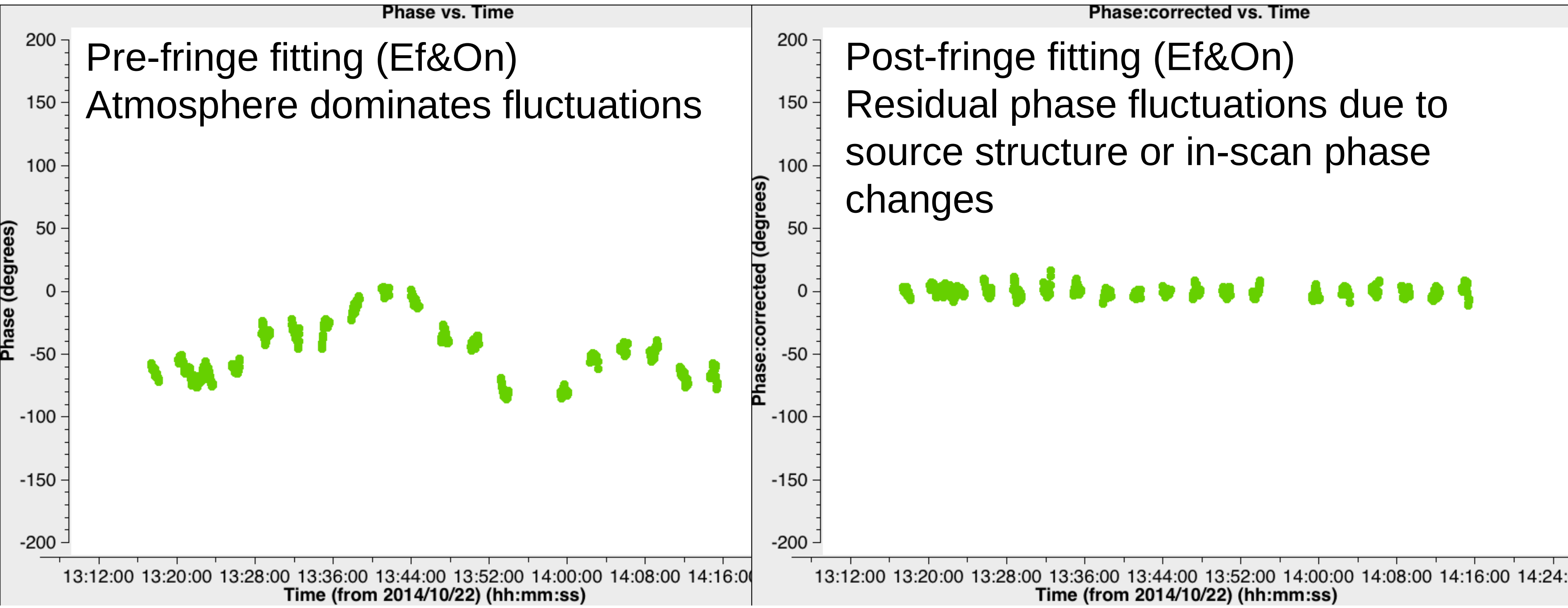


Back to CASA – bandpass & data splitting

Amplitude & phase calibration

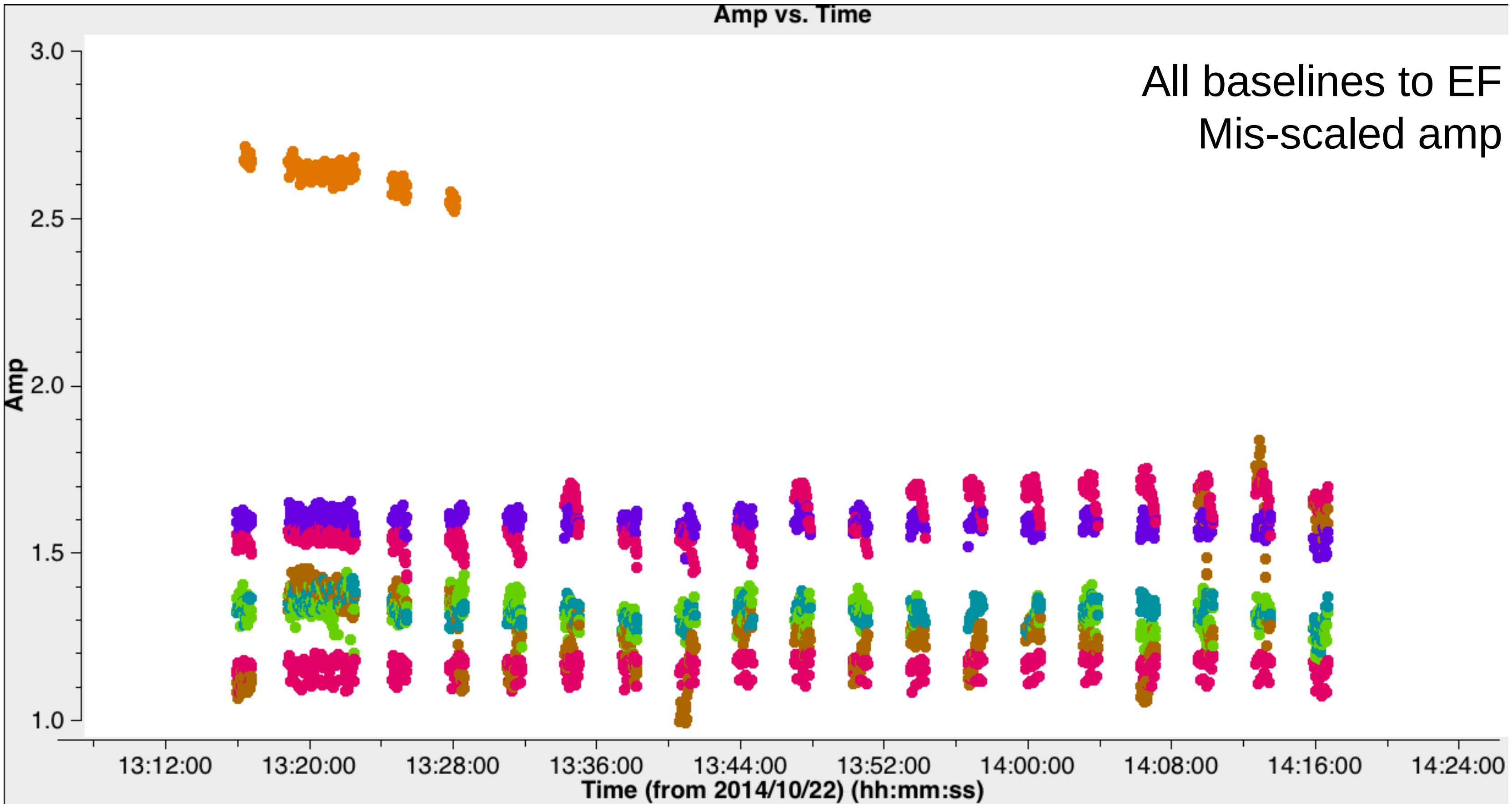
$$\vec{V}_{ij}^{\rm obs} = M_{ij} B_{ij} F_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} \vec{V}_{ij}^{\rm true}$$

- Complex gain calibration solves for phases and amplitudes versus time.
- Fringe-fitting will typically solve for phases (assuming a point source) i.e. :



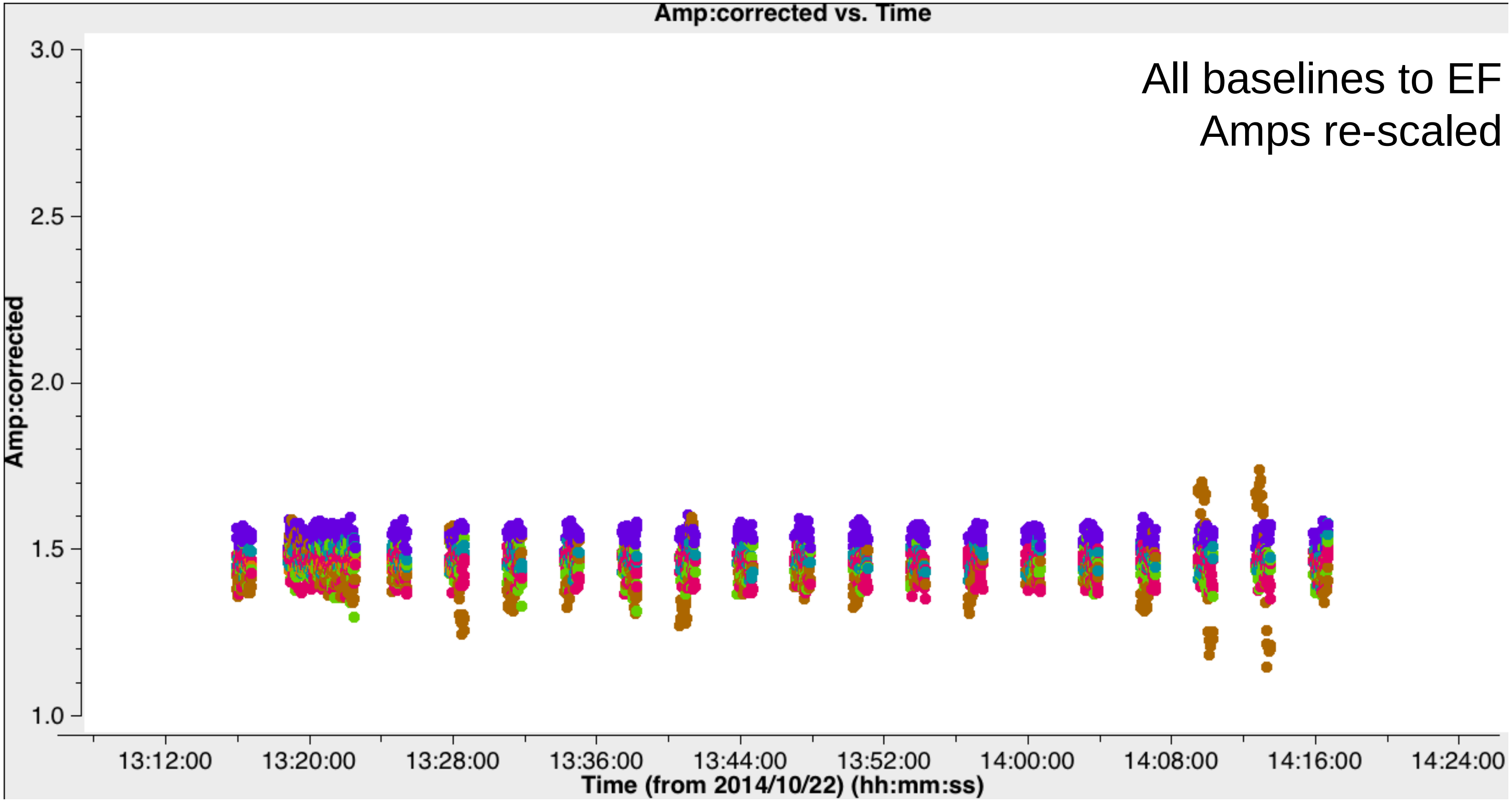
Amplitude & phase calibration

- Fringe-fitting does not correct amplitudes so you should do this separately
- Amplitude variations due mainly to variable gain in the antenna amplifiers.



Amplitude & phase calibration

- Fringe-fitting does not correct amplitudes so you should do that separately
- Amplitude variations due mainly to variable gain in the antenna amplifiers.



Tips for calibration

- Inspect your data – bad data i.e. telescopes off source / RFI can adversely affect your data. (We will discuss more on this in the RFI lecture)
- Make notes and backup your data – you will need to describe the data calibration when you write papers and it helps you identify where things go wrong.
- Experiment. E.g. try different solution intervals, calibration techniques. We will discuss this in more detail in a future lecture
- Visualise your data. It allows you to see where things go wrong.

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