Calibrating VLBI data

Slide deck

JIVE VLBI school 2025

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EUROPEAN vlbi NETWORK

JIVE
Joint Institute for VLBI ERIC

ACME
Astrophysics Centre for Multimessenger studies in Europe

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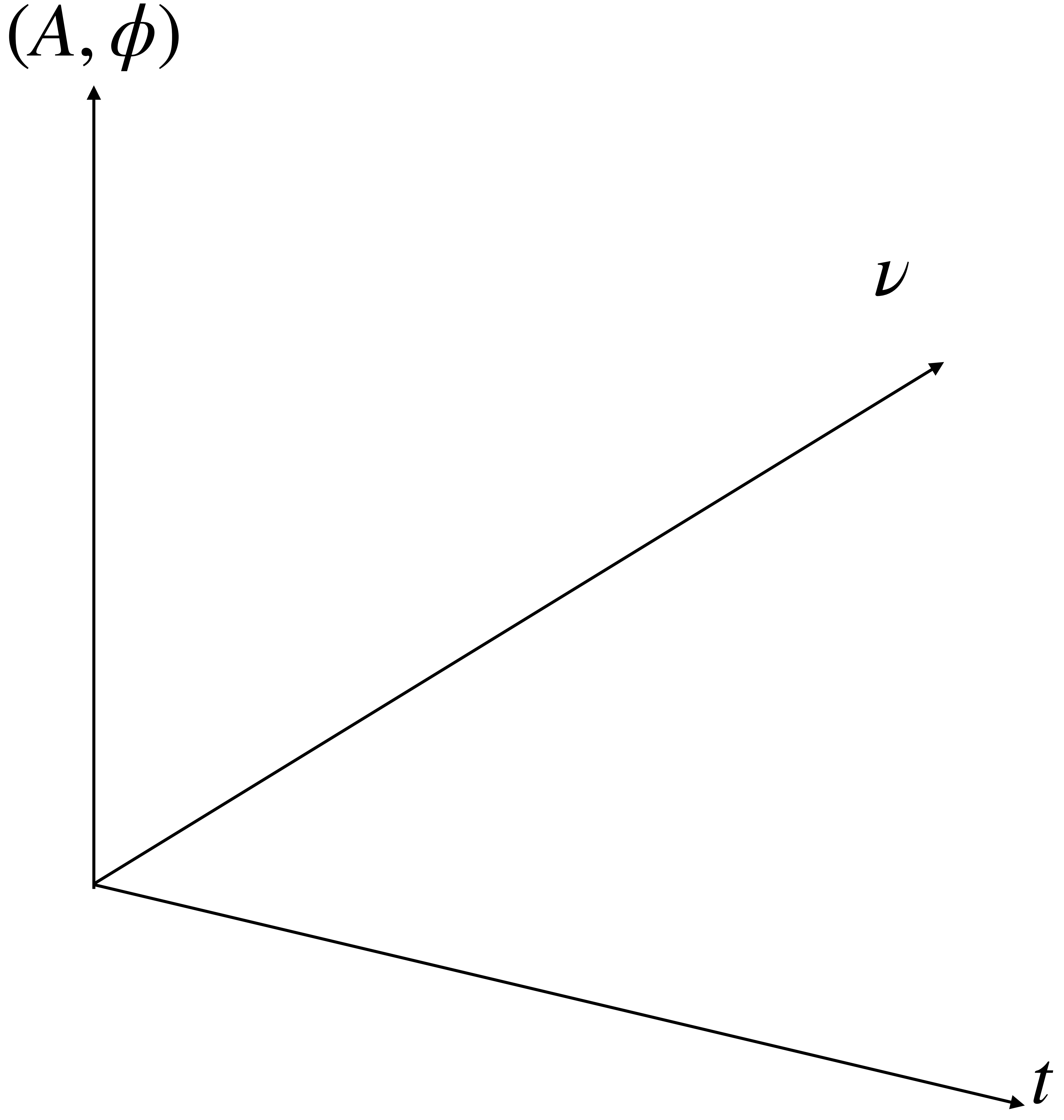
Outline

1. Interferometric data structure
2. Error sources
3. The calibration strategy
4. A priori calibration
5. Flux scaling
6. Fringe fitting
7. Bandpass corrections
8. Phase referencing

Interferometric data structure

- Our interferometer measures the FT of the sky (van Cittert-Zernike theorem) so **each baseline measures an amplitude and phase.**
- It is best to visualise the interferometric data in 3-D where your axes are:
  - Amplitude & phase ('complex gains')
  - Frequency
  - Time
- **That's a lot of data**



Interferometric data structure

- Our radio interferometer equation took no account of the frequency dependence (or time) of the incoming radiation:

$$\mathsf{V}_{pq} = \iint_{lm} \mathsf{B} \exp\left\{ -2\pi i \left(u_{pq} l + v_{pq} m + w_{pq}(n-1) \right) \right\} \mathrm{d}l \mathrm{d}m$$

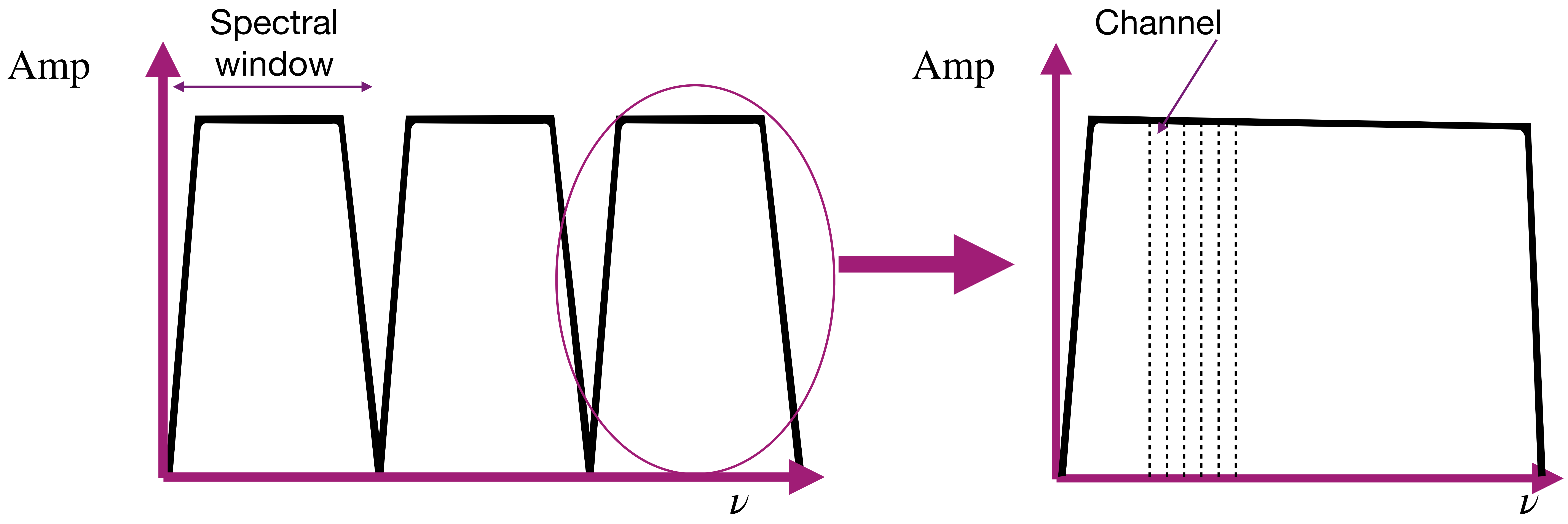
- In fact, the geometric delay will be different at different frequencies (and times) i.e.

$$2\pi\lambda^{-1} \left(u_{pq} l + v_{pq} m + w_{pq} (n-1) \right)$$

- To recover the sky brightness distribution we need to take this into account. Best way is to assume monochromatic radiation in small sub-bands (and sub-times) and invert each one.
- As a result the response of an interferometer in frequency and time space is split.

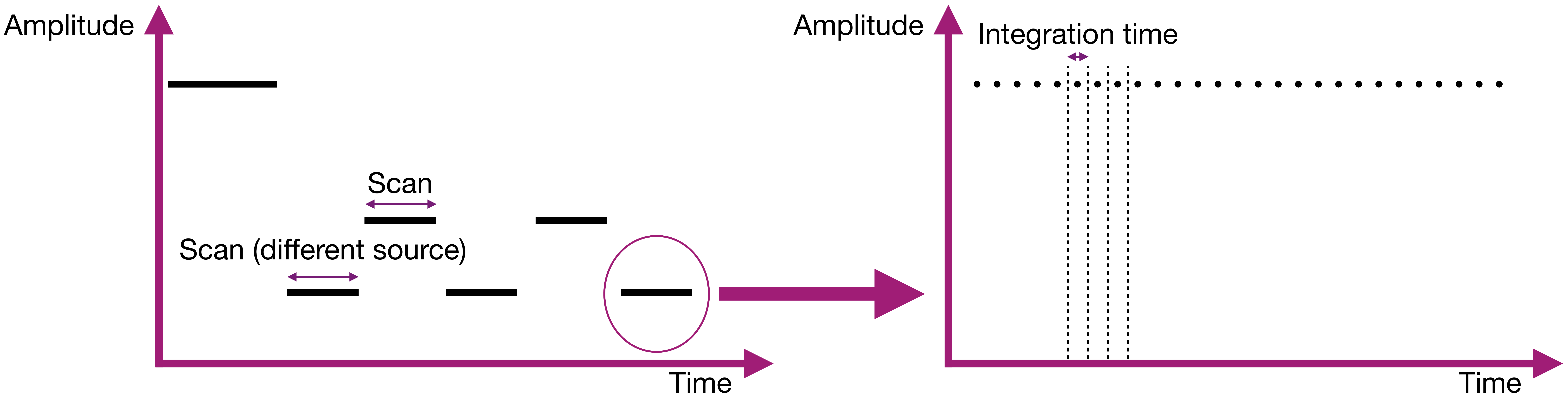
Interferometric data - frequency structure

- The frequency structure is split into two sub-band categories:
  - Semi-wide **spectral windows** - these are governed by the receiver of the antennas (and/or correlator FTs and filters), and typically cover regions where the receiver is most sensitive.
  - Each spectral window is then split further into **channels**. This are small regions of frequency space where we can assume monochromatic radiation (we will learn about when this breaks down when we talk about bandwidth smearing)



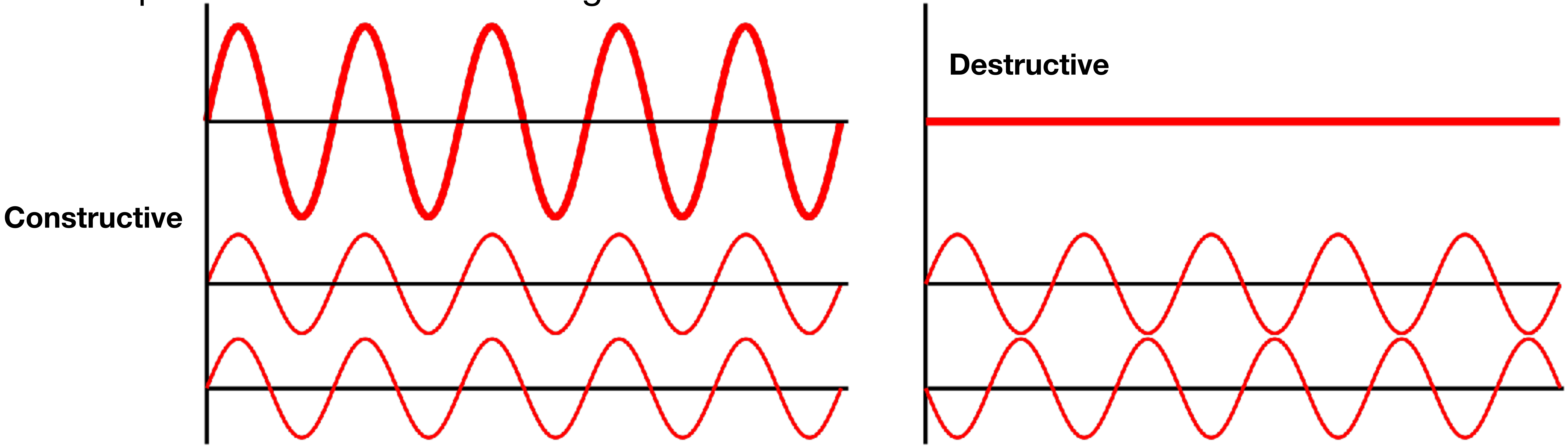
Interferometric data - time structure

- In time space it is much simpler, the data is chunked into **time integrations** so that the geometric delay doesn't change too much across the averaging time.
- These integrations are grouped into **scans**, which describes which source the telescope is pointing at.
- For both frequency and time, there is a trade off between data rates & accuracy of the FT inversion (i.e. recovering the sky brightness)



Corruption of interferometric data

- An interferometer interferes the signal coming into various antennas at once. However we need to have incoming signals in phase!
- The geometric delay is an example of a correction.
- Various other effects can make our signals become out of phase resulting in no signal - we need to correct for this.
- In addition, we assume that the source flux entering each antenna is constant - there are also corruption effects that can change this too!

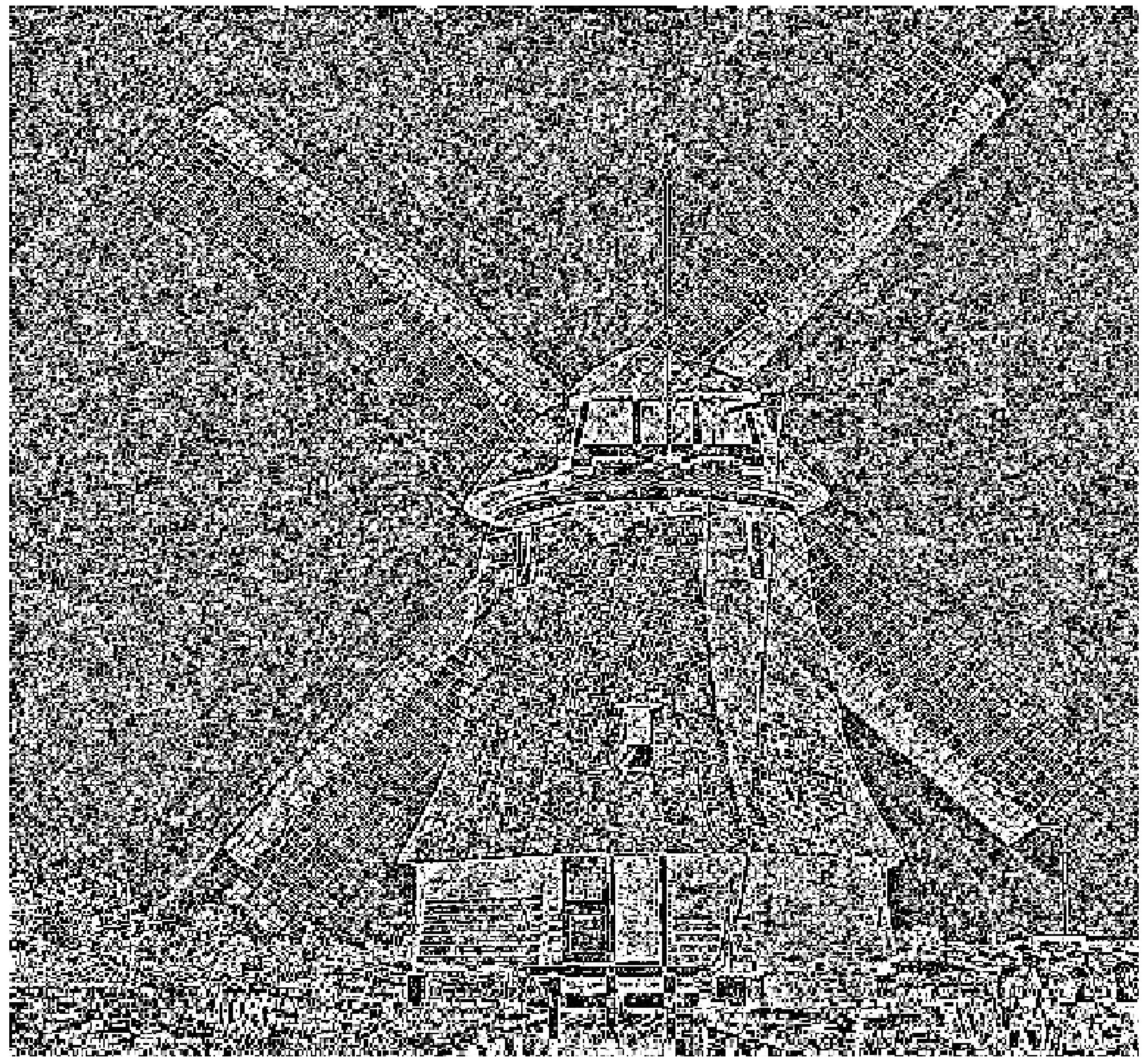


Corruption of interferometric data

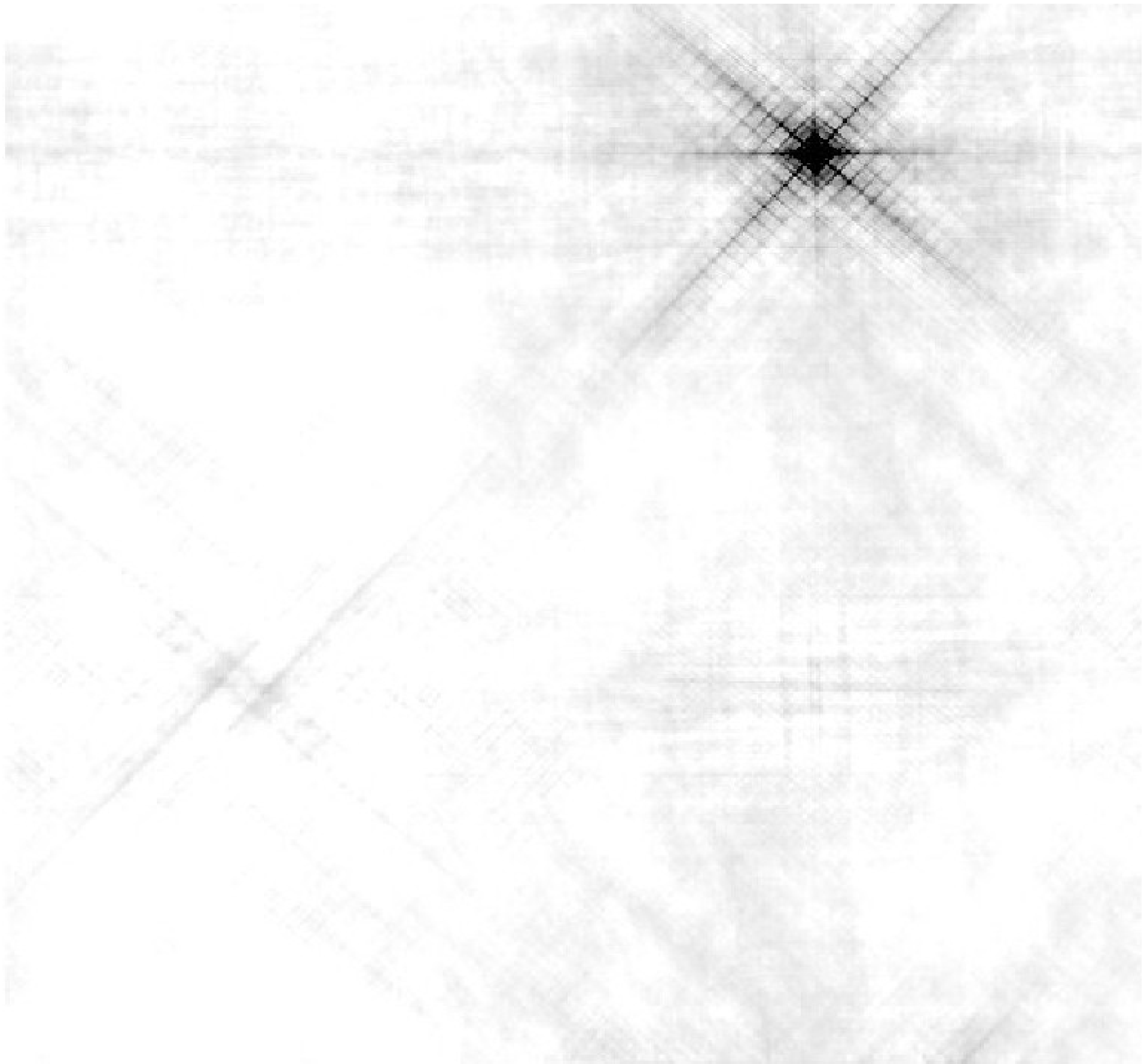
- As we measure the Fourier plane with our interferometer, not correcting for these errors can have drastic effects.
- Phase encodes position, amplitude encodes spatial frequency power!

Image

Corrupted amplitudes



Corrupted phases



Key points for calibration

- For an interferometer to work well we need to have:
  - **Phases aligned** - for constructive interference
  - **Amplitudes need to be constant -** we assume that the sky brightness distribution, B, is *constant (in flux and position)!*
  - **A flux scale** (similar to temperature scale) i.e., how bright is your source relative to something of some known (physical) brightness.
  - **Bad data removed -** any time the telescope isn't looking at a source, or there is interference (from mobiles) needs to be removed.
- *And remember that we need to do this with respect to time & frequency on all baselines!*

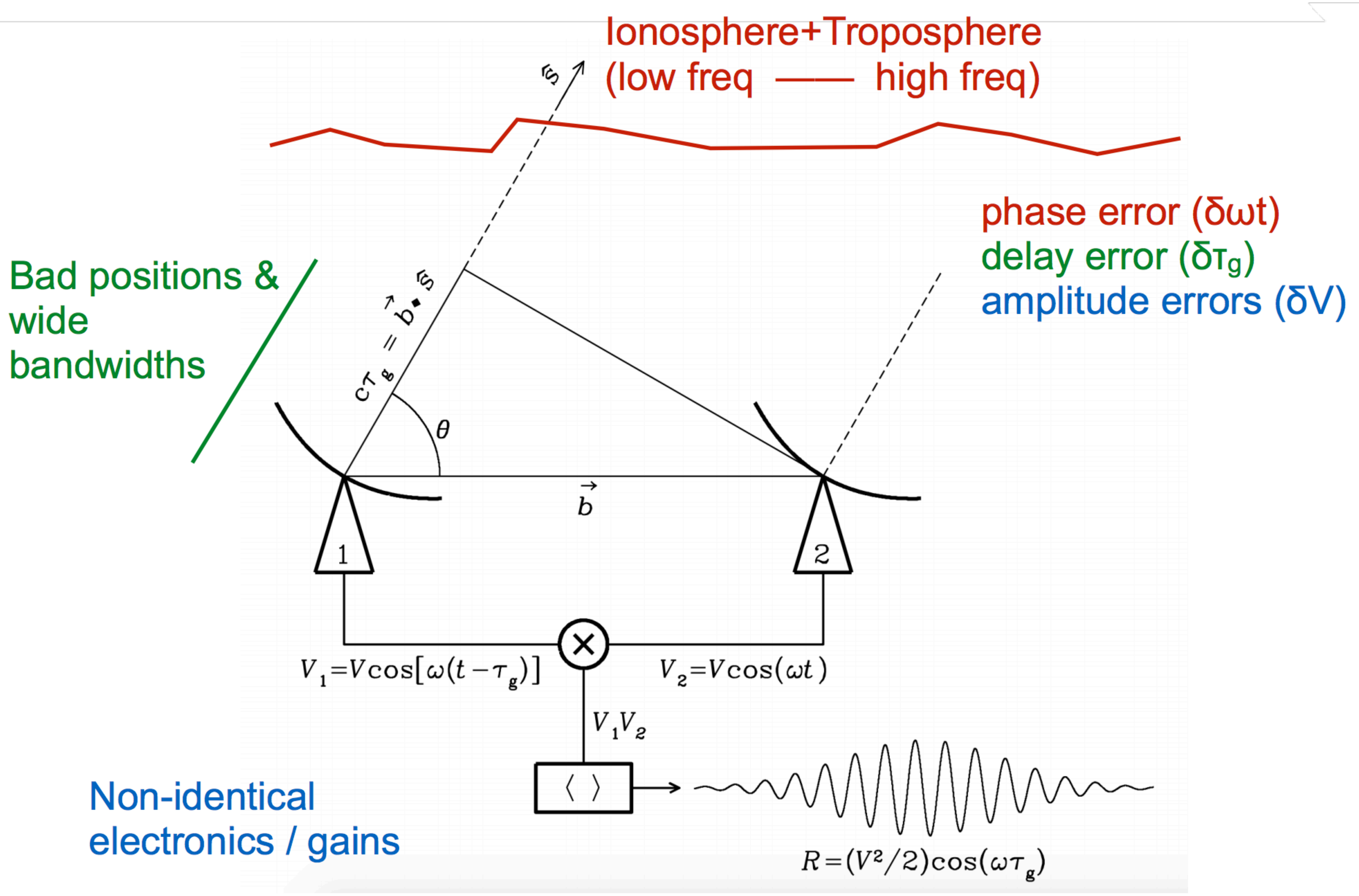
Calibration is merely removing the corrupting effects.

Some key terms

Over the course of this lecture there will be some nomenclature used which you should try to remember.

- **Complex gains** - this is both amplitude and phases
- **Bandwidth** - range of frequencies being measured by the interferometer
  - **Spectral window** - sub-bands in frequency determined by the receiver system
  - **Channel** - sub-bands of spectral windows
- **Delays** - this is the phase error derivative with respect to frequency i.e., $\mathrm{d}\phi/\mathrm{d}\nu$
- **Phases** - this is the phase error with respect to time and frequency i.e., $\phi(t, \nu)$
- **Rates** - this is the phase error derivative with respect to time i.e., $\mathrm{d}\phi/\mathrm{d}t$
- **Flagging** - the removal of bad data e.g., affected by radio interference

So what **can**, and **will**, attack our data?



Solve for these issues using calibration

Sources of errors i.e. what attacks our data

Atmosphere
- Ionosphere
- Troposphere
- Water vapour

Antenna / feed
- System temperature
- Primary beam
- Pointing
- Antenna location

LNA / conversion chain
- Clock
- Gain, phase, delay
- Frequency response

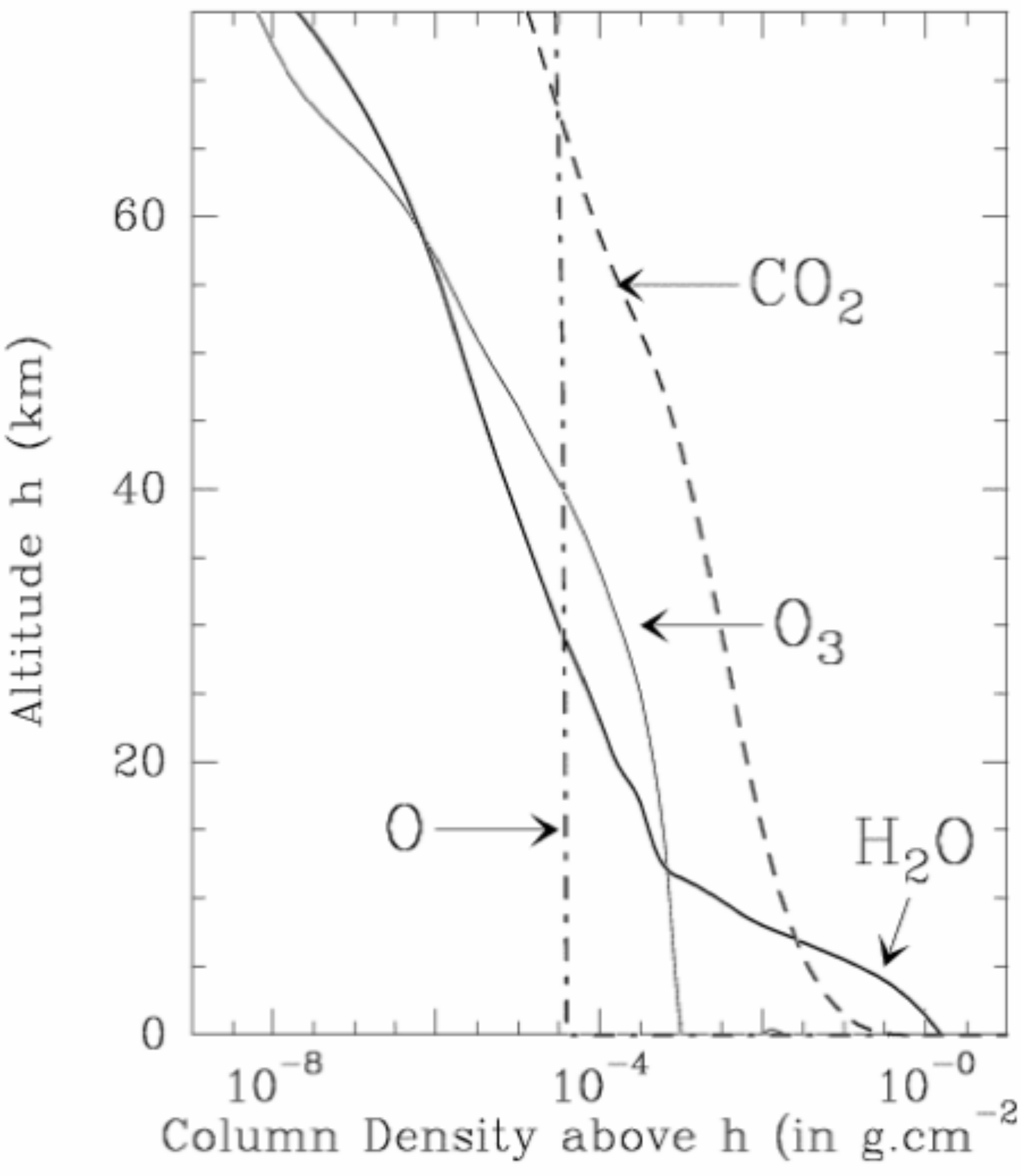
Digitiser / Correlator
- Auto-leveling
- Baseline errors

Radio Frequency Interference (RFI)

The troposphere

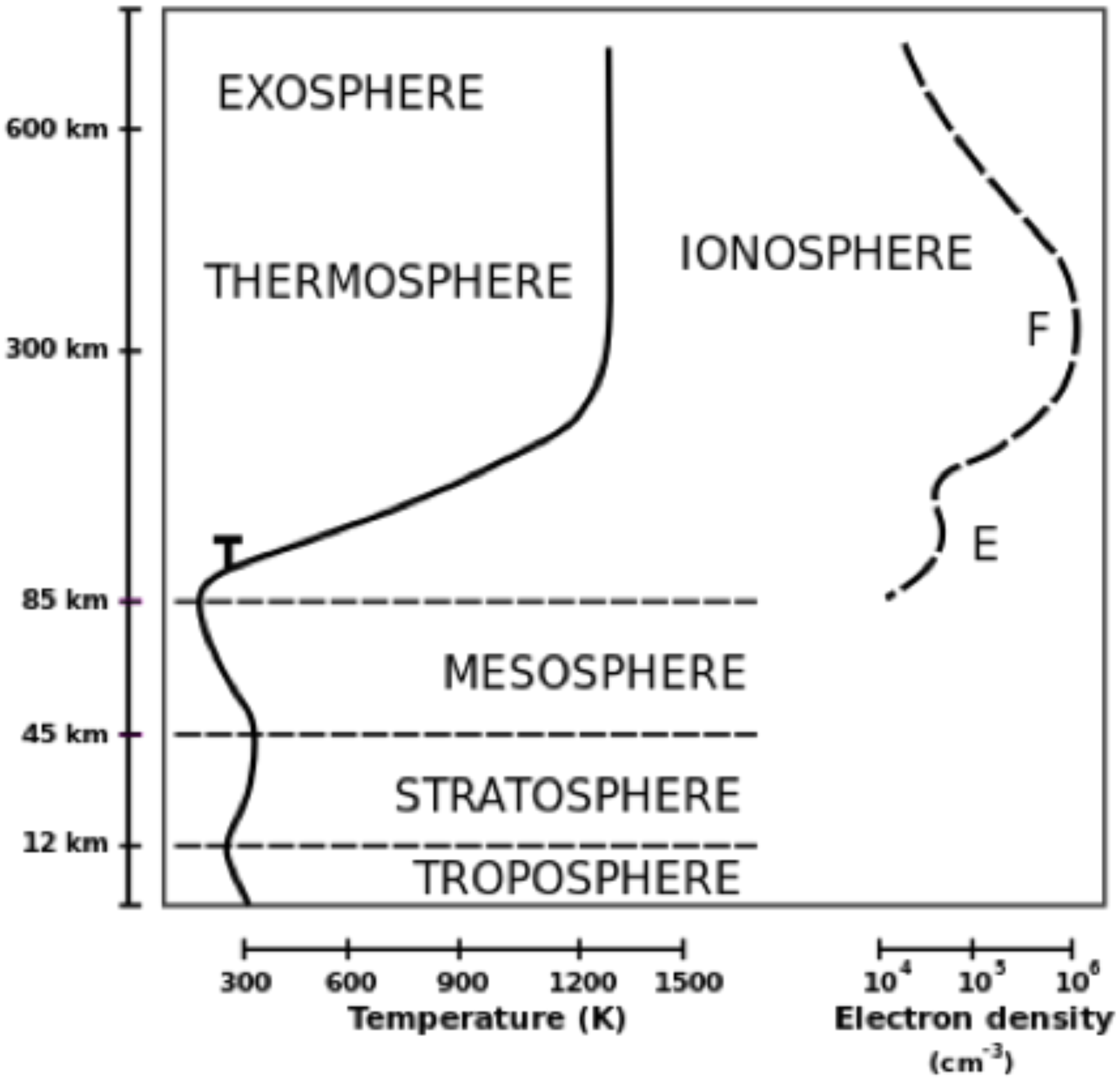
- Molecular refraction
  - 'Wet' H2O vapour (Clouds worse)!
  - 'Dry' e.g. O2, O3
- Refracts radio waves
- Phase distorted
  - $\phi = \frac{n_{\mathrm{w}} 2\pi}{\lambda}$
  - n_{w} is water vapour refractive index
- Tropospheric errors $\propto 1/\lambda$
  - Significant at high frequencies $\nu > 15\,\mathrm{GHz}$
  - Sub-mm observing at cold, high, dry sites

Column density as function of altitude



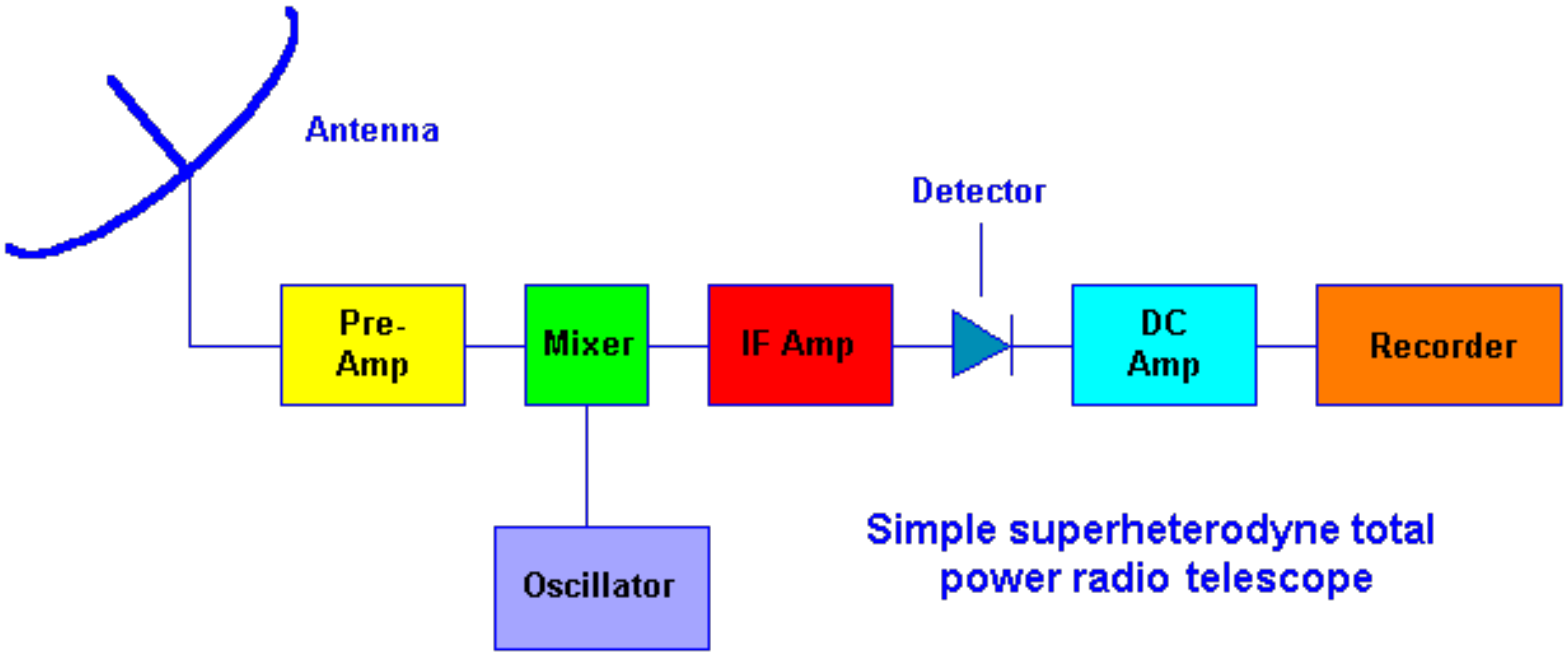
The ionosphere

- Refraction by electrons
- Delay - $\mathrm{d}\phi/\mathrm{d}\nu \propto N_e\lambda^2$
  - N_e = atmospheric electron column density
- Electrons spiral round Earth's magnetic field
  - Polarisation angle of radiation Faraday rotated
- Ionospheric errors worst at $\nu < 1\,\mathrm{GHz}$
  - Exacerbated by solar activity
  - $\lambda > 20\,\mathrm{m}$ only from space



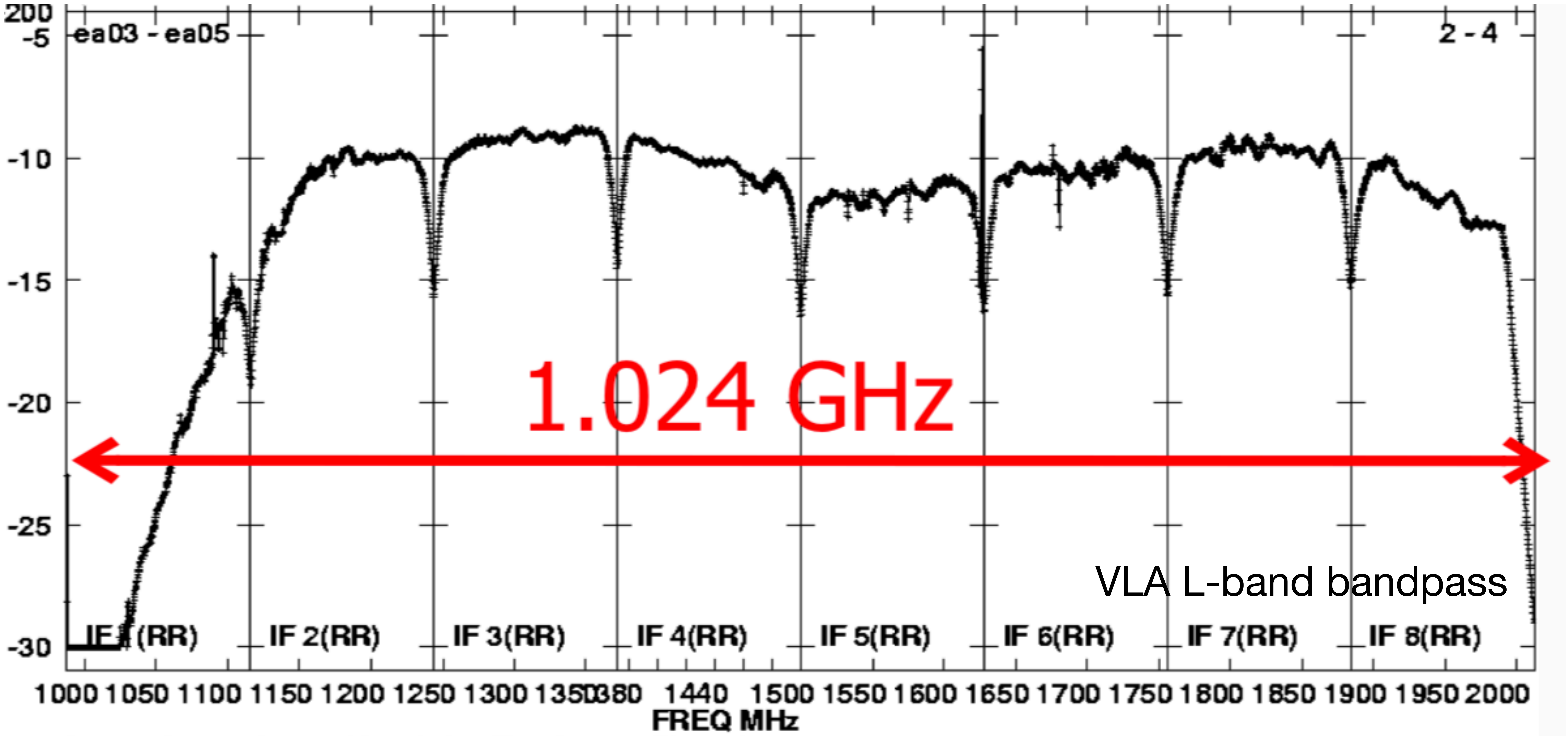
At the telescope - gain variations & delay chains

- Signals at antenna need to be amplified but LNA has variable gains - corrupts amplitude
- Signals also pass through different electronics at different frequencies - corrupts phase vs frequency



At the telescope - bandpass

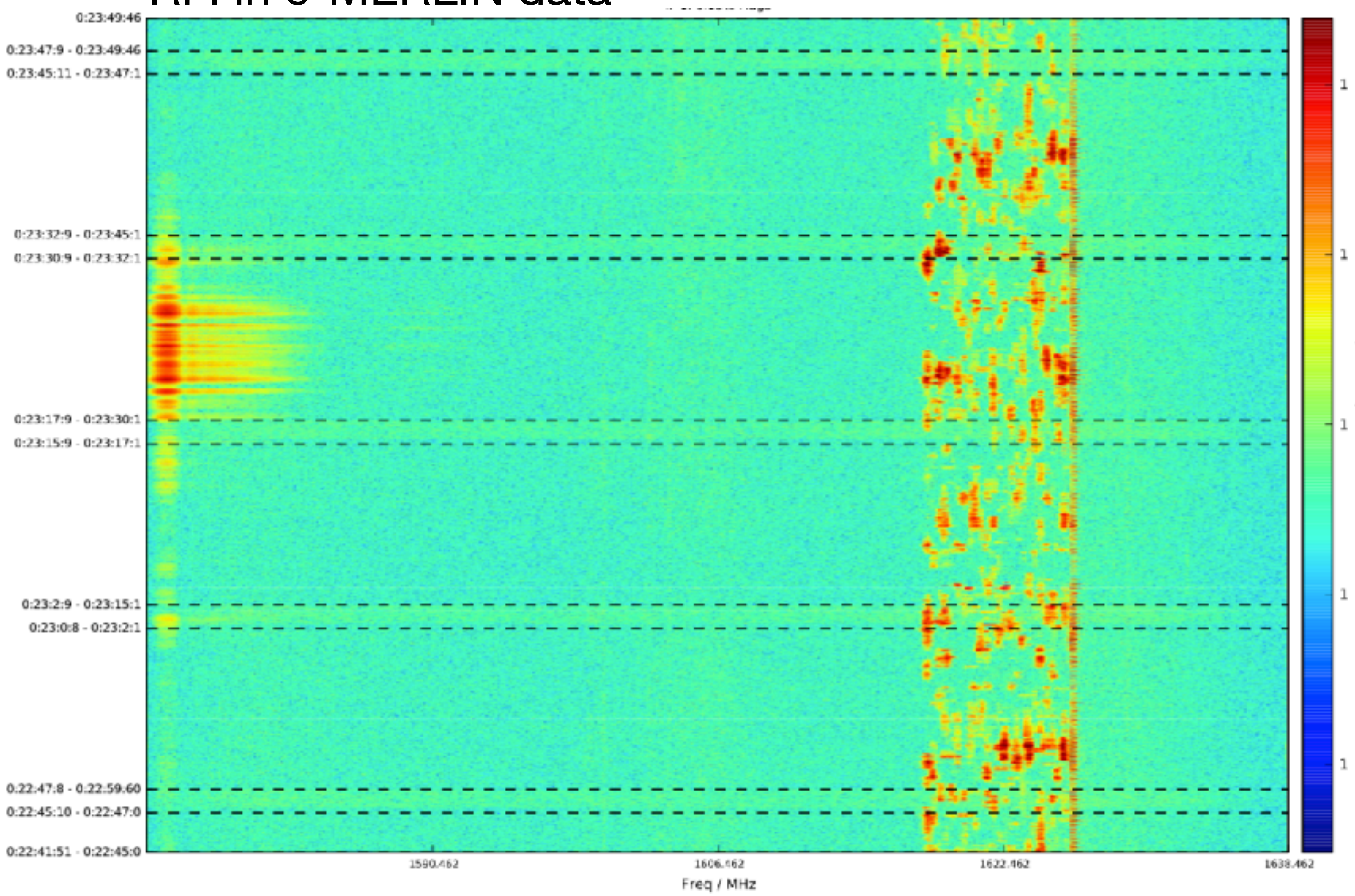
- Antenna receivers and filters gives the sensitivity of each antenna vs frequency a distinctive shape called the bandpass. This needs to be corrected and flattened.



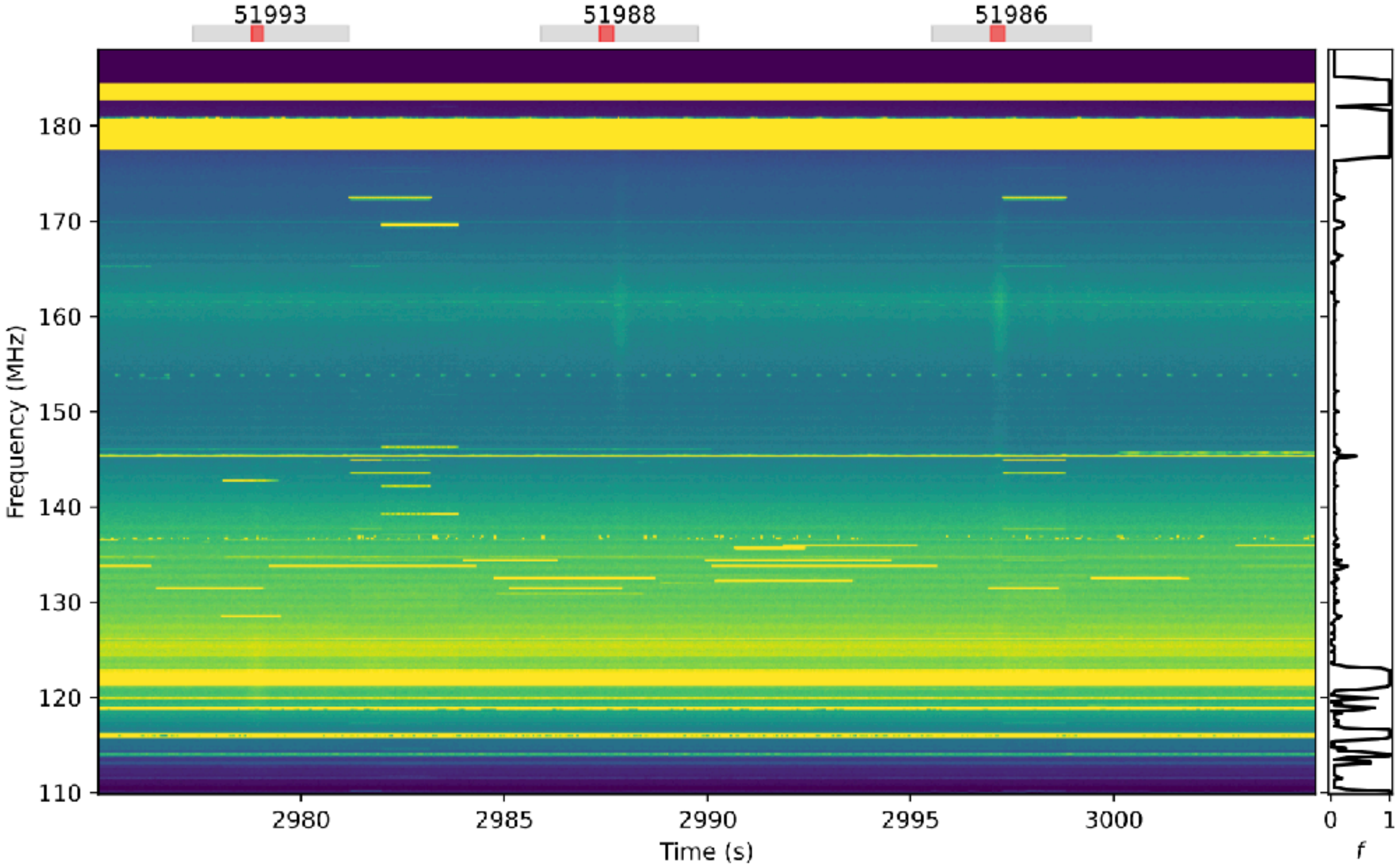
Radio frequency interference (RFI)

- Your mobile phone is brighter than any radio source in the sky…
- Causes errors, so this needs to be removed from our data! — see the flagging slide deck.

RFI in e-MERLIN data



Starlink in LOFAR data (di Vruno+23)



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- *And remember that we need to do this with respect to time & frequency on all baselines!*

Calibration is merely removing the corrupting effects.

Parameterising calibration

- We want to parameterise our knowledge of the system as some quantities need to be derived (e.g. phase, delays, amplitudes)
- We use the **radio interferometry measurement equation** (RIME) to do this, which relates the observed (perturbed) visibility to the 'real'/ ideal (unperturbed) visibility i.e.:

Jones matrices

Observed visibilities

$$\mathrm{V}_{pq} = \boldsymbol{J}_p \mathrm{V}_{pq}^{\mathrm{true}} \boldsymbol{J}_q^H$$

True visibility

- The **Jones matrices** encodes everything that "happens" to the signal from the source to correlator.
- This assumes calibration parameters should be antenna-based.

Decomposing the corruption effects

- We decompose the RIME calibration equation into different terms which are solved for independently.
- These comprise of:

$$
\begin{aligned}
\mathsf{V}_{pq}^{\text{obs}} &= \boldsymbol{J}_p \mathsf{V}_{pq}^{\text{true}} \boldsymbol{J}_q^H \\
&= \boldsymbol{M}_p \boldsymbol{B}_p \boldsymbol{F}_p \boldsymbol{G}_p \boldsymbol{D}_p \boldsymbol{E}_p \boldsymbol{P}_p \boldsymbol{T}_p \mathsf{V}_{pq}^{\text{true}} \boldsymbol{T}_q^H \boldsymbol{P}_q^H \boldsymbol{E}_q^H \boldsymbol{D}_q^H \boldsymbol{G}_q^H \boldsymbol{F}_q^H \boldsymbol{B}_q^H \boldsymbol{M}_q^H
\end{aligned}
$$

- $\boldsymbol{M}_p$: Baseline based Non closing errors
- $\boldsymbol{B}_p$: Bandpass response
- $\boldsymbol{F}_p$: Fringe-fitting (delay, rate, phase) VLBI only
- $\boldsymbol{G}_p$: Complex gains (amp & phase)
- $\boldsymbol{D}_p$: Instrumental polarisation
- $\boldsymbol{E}_p$: Elevation errors (gain curves)
- $\boldsymbol{P}_p$: Parallactic angle
- $\boldsymbol{T}_p$: Opacity and path length variation

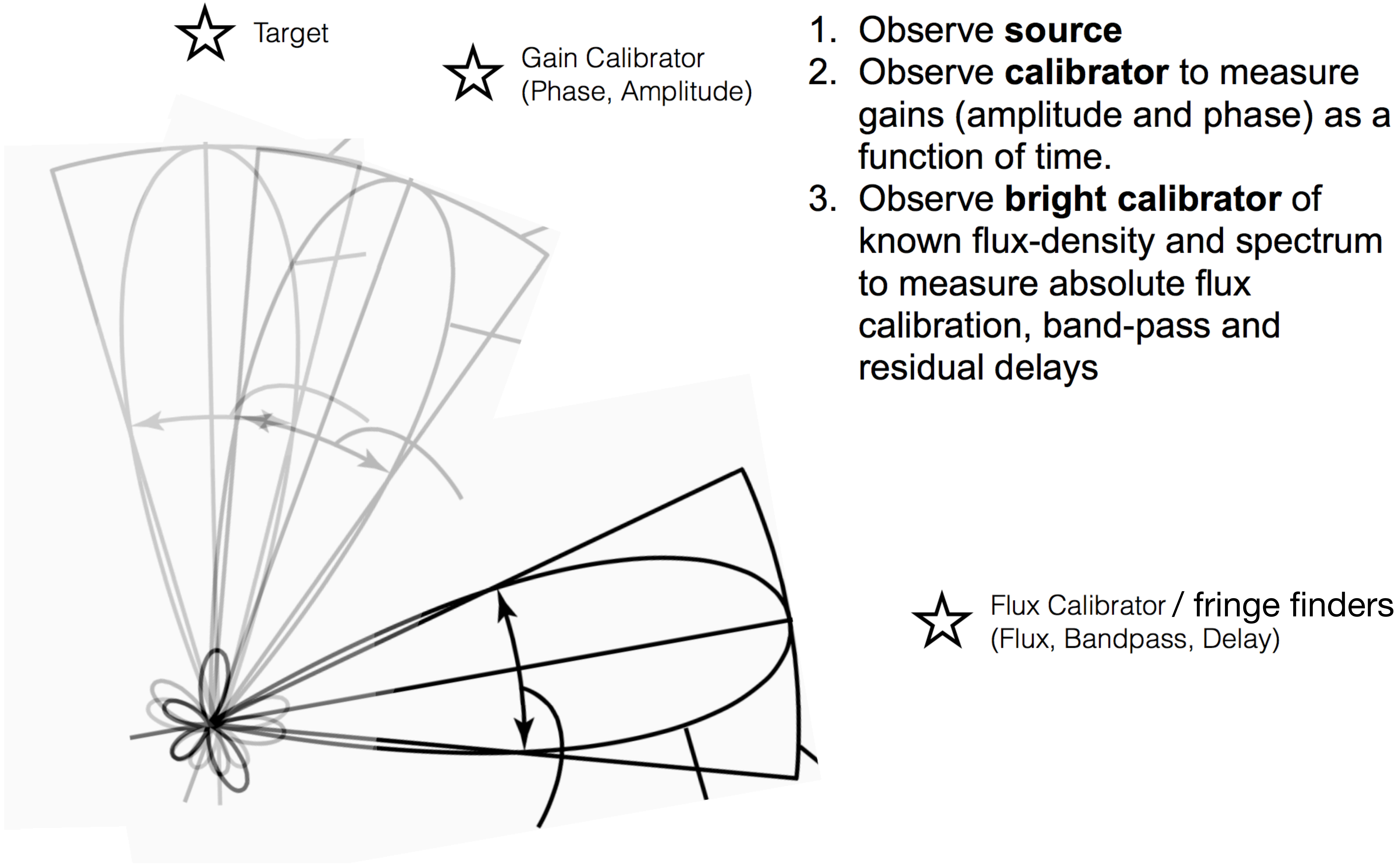
Observational set-up

- To be able to mediate these corrupting effects we need to set up our observations such that we can correct for all of these.
- To be able to do this we normally split our calibration products into certain categories
    - **a priori calibration** - these are calibration products that are either given to you, or are corrected for by the radio observatory - e.g. the geometric delays!
    - **flux scaling -** setting the ‘temperature’ scale of your observations.
    - **source-based calibration & phase referencing** - the observational set-up allows you to calibrate for complex gains (i.e. amplitude and phase) using a bright source - e.g. removing the atmospheric contributions.

On-source calibration

- However, the on-source calibration can be split into two main terms:
  - **Time-independent terms** - i.e. the errors occur on long timescales > observation time and are often located at the antenna so are also direction-independent (bandpass is one example).
  - **Time-dependent terms** - the errors change on quick timescales and often do care about the pointing direction e.g. residual geometric delay errors, atmospheric phase shifts, LNA gain variations
- For the time independent terms, the observatory can measure these and give them to you a priori OR you observe a very bright calibrator.
- For the time-dependent terms, we often use a useful FT relation to calibrate our phases and amplitudes - that of a **point source!**

A typical VLBI set up



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

A priori calibration

- A priori calibration concerns calibration done either by the observatory or given to you once you receive the data.
- The following effects are often calibrated by the observatory
  1. Delay tracking
     - Correctable off-line if within Nyquist or sensitivity limit
     - Phase tones can be used to align antenna signals
  2. Antenna positions
     - Errors cause bad delays
     - Cannot transfer phase-ref corrections accurately to target
  3. Geometric delay correction
     - Done during correlation using accurate antenna locations
- You still need to apply with information given by observatory:
  - Gain curves - antenna efficiency vs source elevation (explained next)
  - $T_{\rm sys}$ - for flux scaling (explained later)

A priori calibration - gain curves

$$\mathsf{V}_{pq}^{\mathrm{obs}} = \boldsymbol{M}_p \boldsymbol{B}_p \boldsymbol{F}_p \boldsymbol{G}_p \boldsymbol{D}_p \boldsymbol{E}_p \boldsymbol{P}_p \boldsymbol{T}_p \mathsf{V}_{pq}^{\mathrm{true}} \ldots$$

- Atmosphere adds noise and absorbs signal

$$T_{\mathrm{received}} = T_{\mathrm{source}} \exp\left(\frac{\tau_{\mathrm{atm}}}{\cos(z)}\right) + T_{\mathrm{atm}} \left[1 - \exp\left(\frac{\tau_{\mathrm{atm}}}{\cos(z)}\right)\right]$$

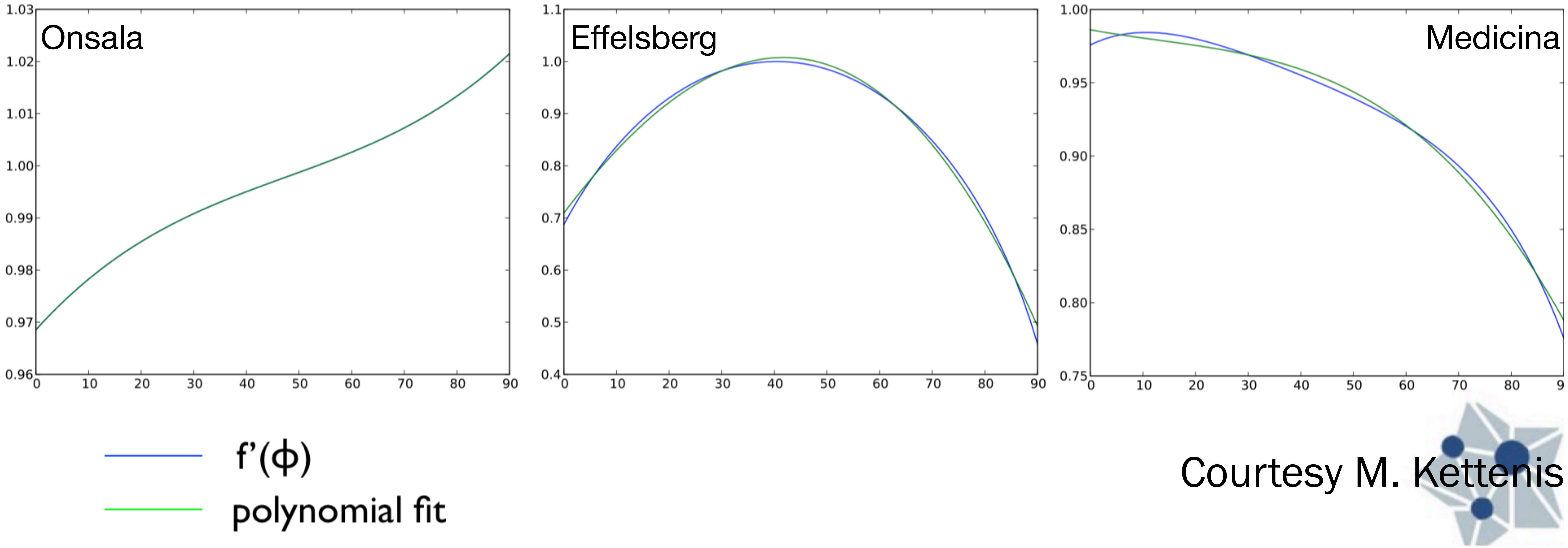
- Source would provide temperature T if measured above the atmosphere optical depth τ_{atm} and z is the zenith distance.
- Noise is increased for observing at low elevation (large z)
- We normally apply an analytic gain curve (assume τ_{atm} stable)

A priori calibration - gain curves

- As well as correcting for the atmospheric noise, antennas are 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

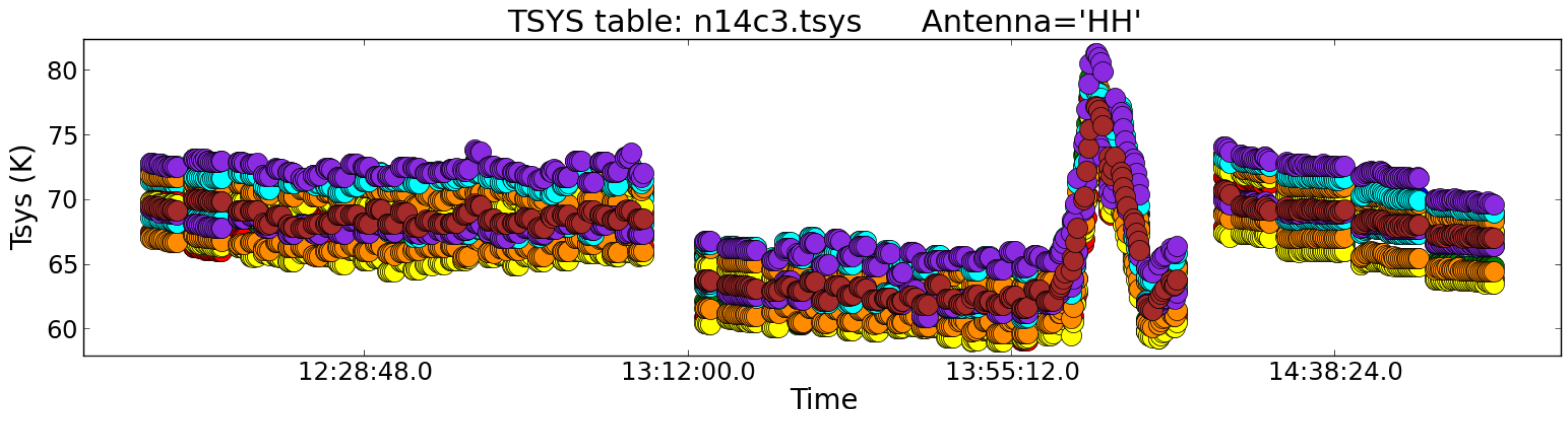
- Calibration measurements supplied with data can includes Tsys, gain-elevation and WVR
- Water Vapour Radiometry (at mm/sub-mm wavelengths): measure atmospheric water line every few seconds, calculate refractive delay of phase and/or absorption.
- Antenna position corrections may also be available.
- 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

Flux scaling

- The visibility amplitudes that come out of the correlator have some arbitrary scaling.
- Flux scaling is concerned with converting these amplitudes to physically meaningful units i.e. Janskys
- To do this, you need to observe something with a **physically known flux density**.
- This is normally either:
  - A standard source e.g. 3C84 - known as **bootstrapping (not typical for VLBI observations)**
  - Or by **reference to a noise diode** (of known brightness) on the antenna - known as a T_{sys} measurement (remember this value encodes the antenna sensitivity)

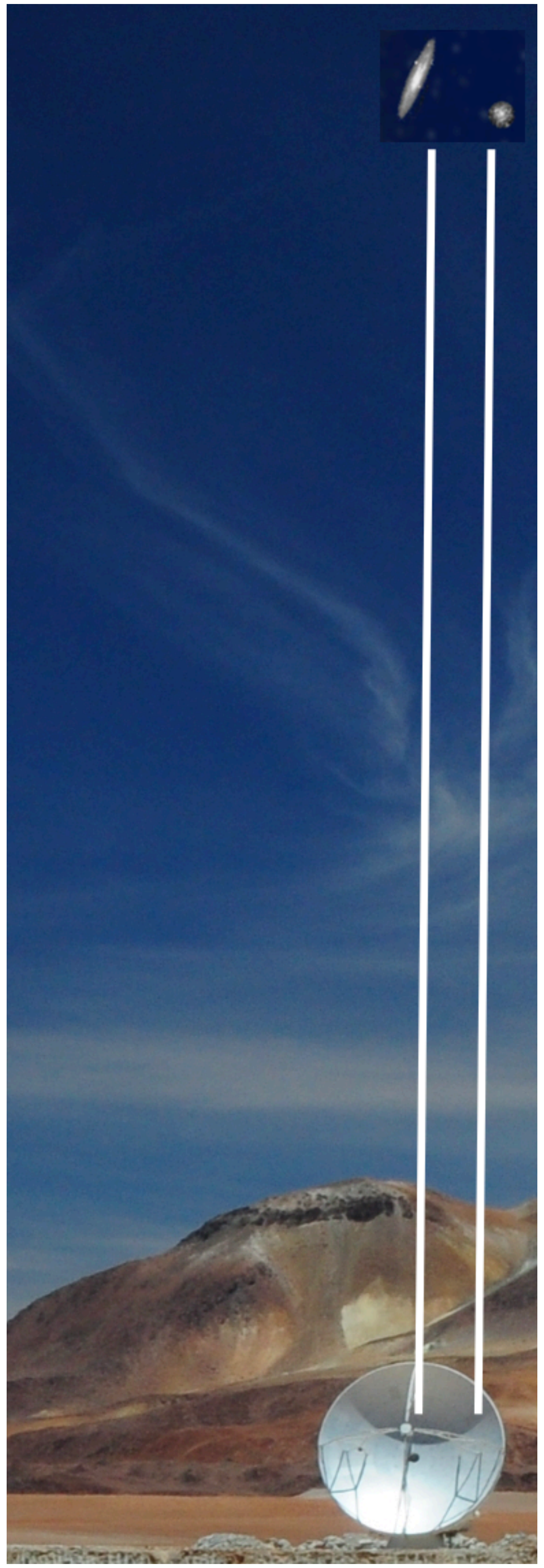
Flux scaling - Tsys

- The normal method for VLBI is to observe a noise diode with known flux density every few minutes.
- This gives you a measure of your telescope system 'temperature', T_{sys}. You can then work out what the source flux density is relative to that.



Phase referencing

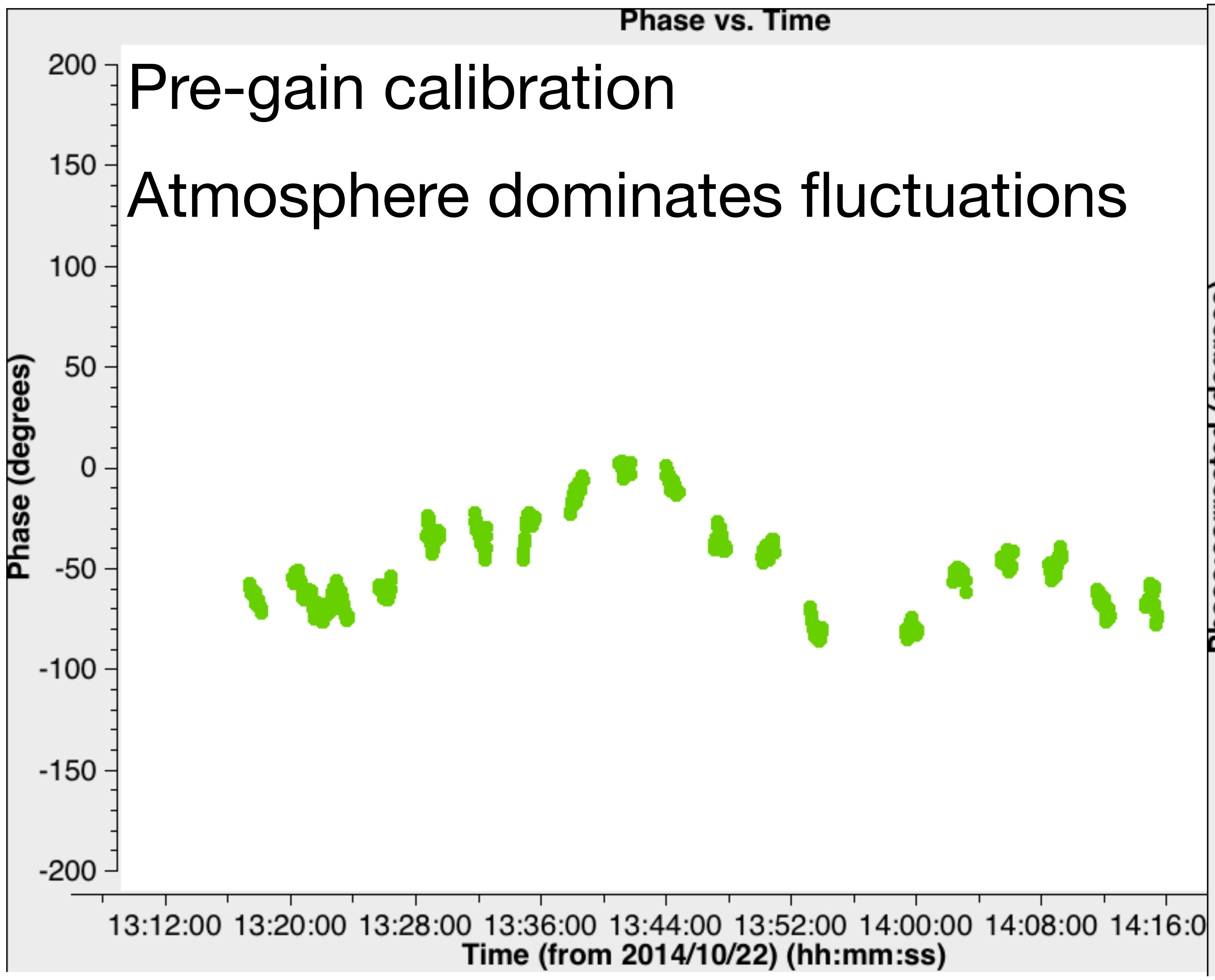
$$\mathsf{V}_{pq}^{\text{obs}} = \boldsymbol{M}_p \boldsymbol{B}_p \boldsymbol{F}_p \boldsymbol{G}_p \boldsymbol{D}_p \boldsymbol{E}_p \boldsymbol{P}_p \boldsymbol{T}_p \mathsf{V}_{pq}^{\text{true}} \ldots$$

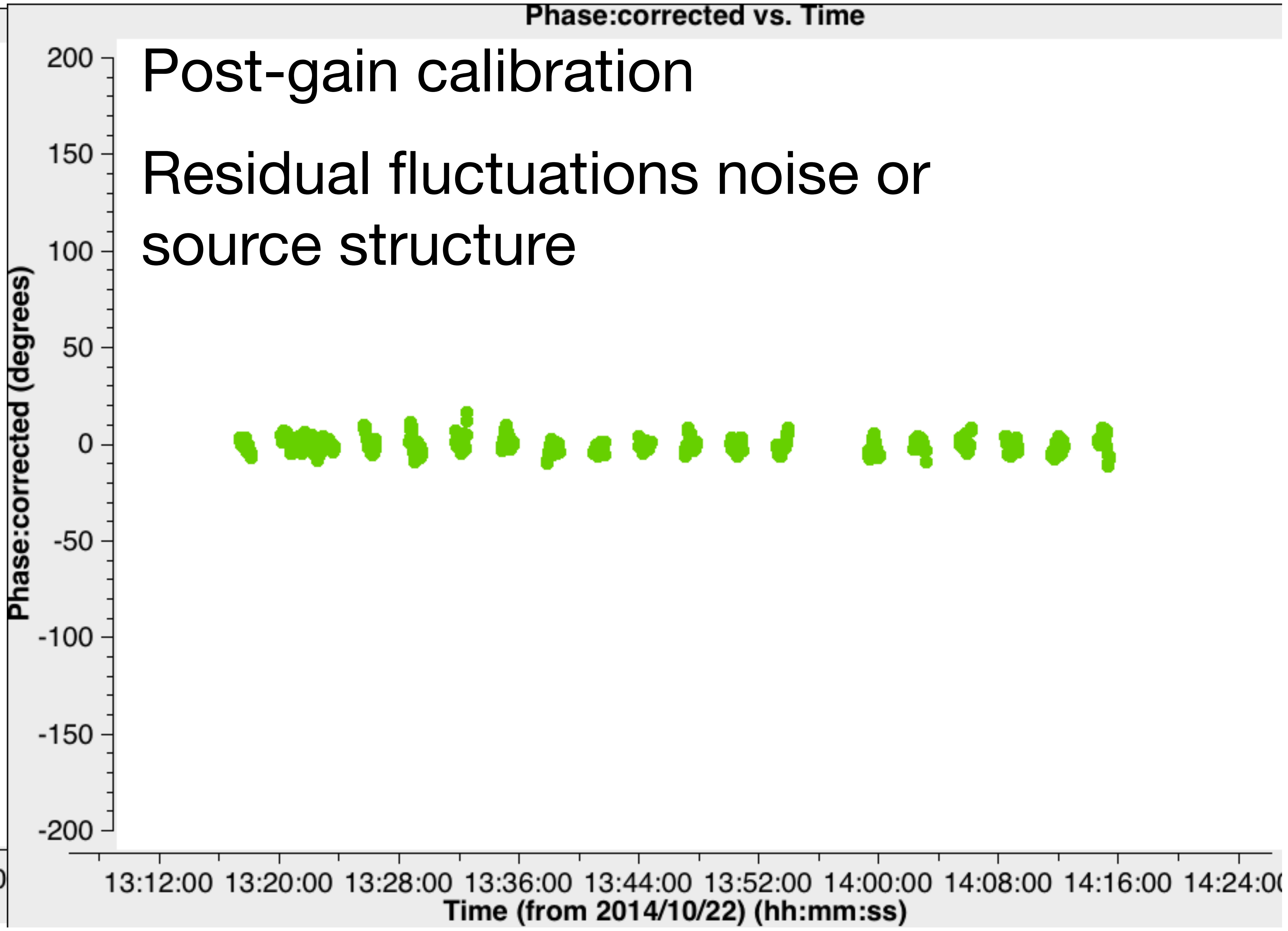


- Your target / science target has unknown structure but we can use a point source to remove the effects of the atmosphere (corrupting phases) & the antenna gains (corrupting the amplitudes) by simply comparing the differences between a point source in FT space and observed visibilities
- The atmosphere is not the same everywhere so we need the point source to be near the target field.
- Also the atmosphere changes rapidly (~ 5 min at 1.4 GHz) so we need to track these variations.

Phase referencing

- Therefore, to do this we have to move between calibrator (known as the phase calibrator) and our target field often (cycle time ~ 10 mins at 1.4 GHz, more frequent at higher frequencies)
- We can calibrate phases & delays (phase vs frequency). For VLBI, it's a little more complicated and you need higher order terms to solve for phases, this is called **fringe fitting**.

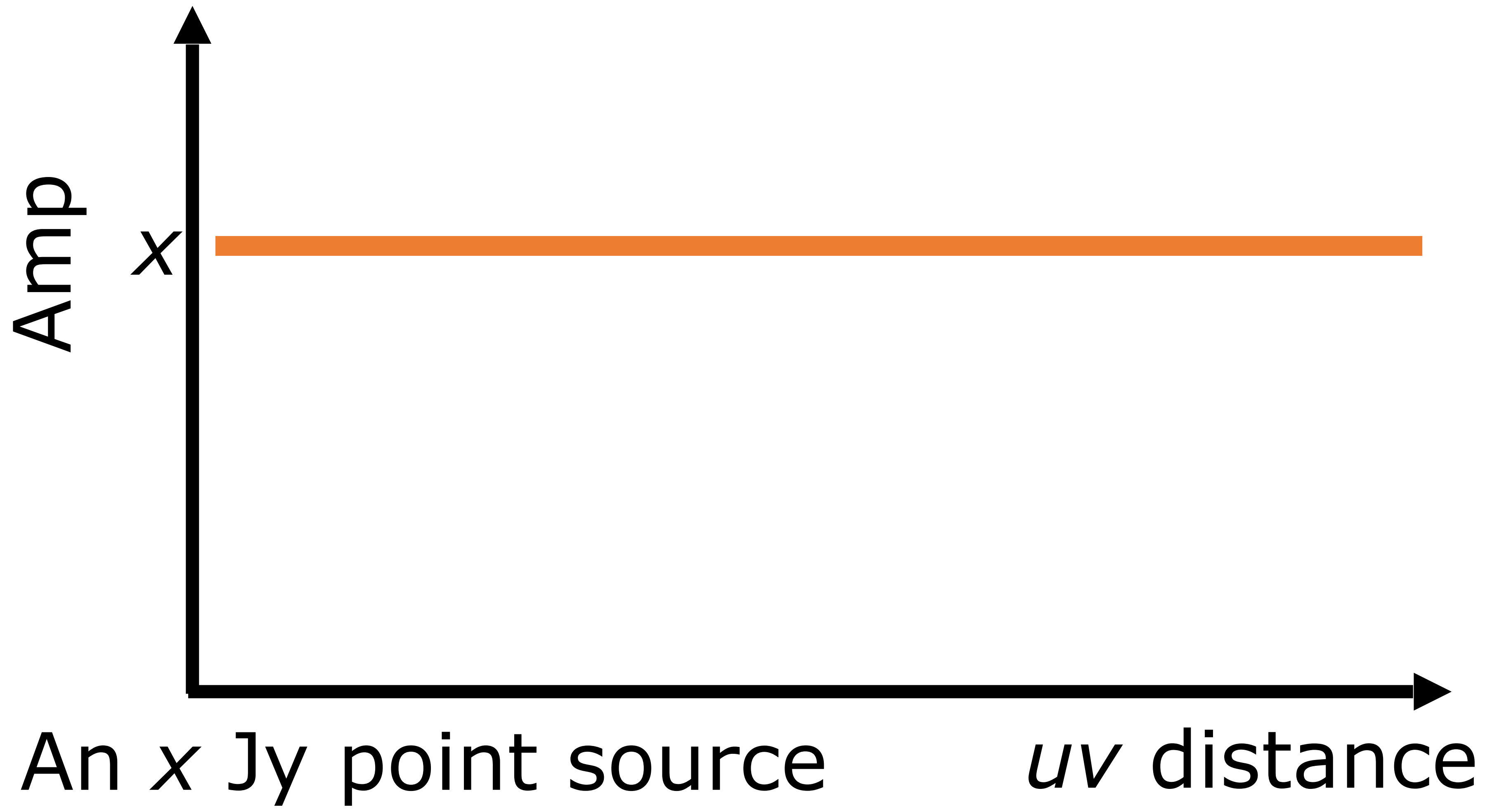


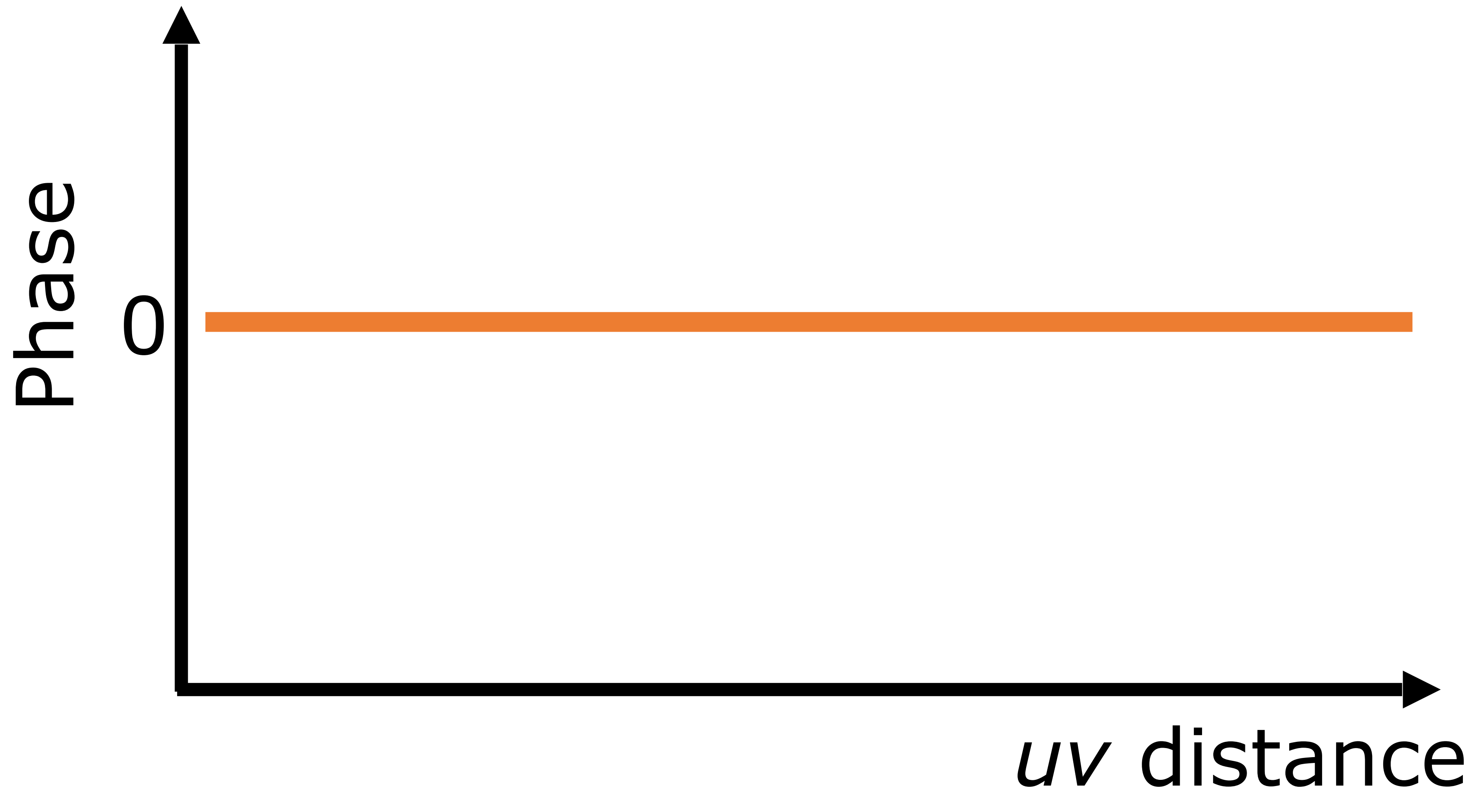


Important aside

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.

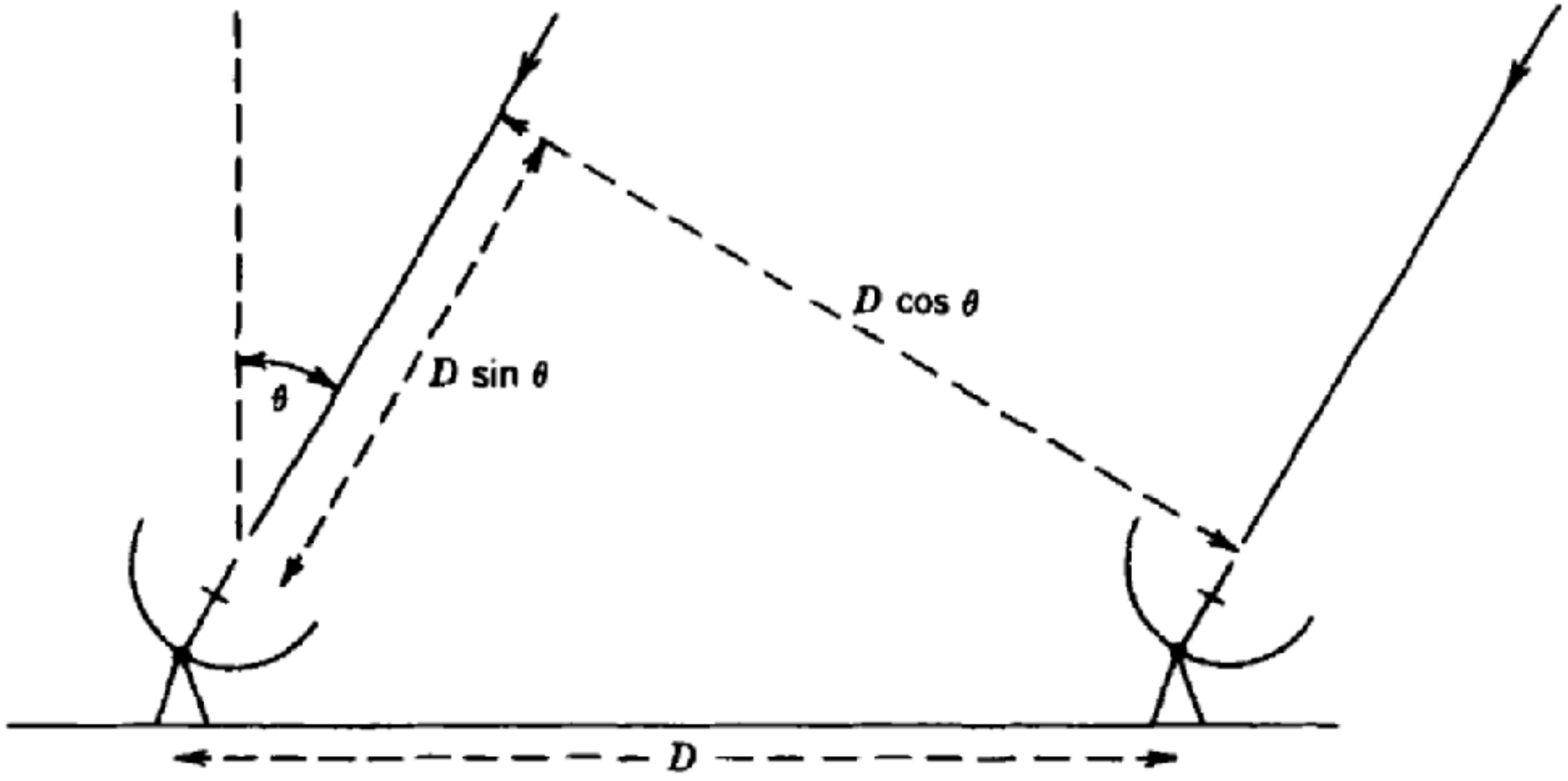




An x Jy point source

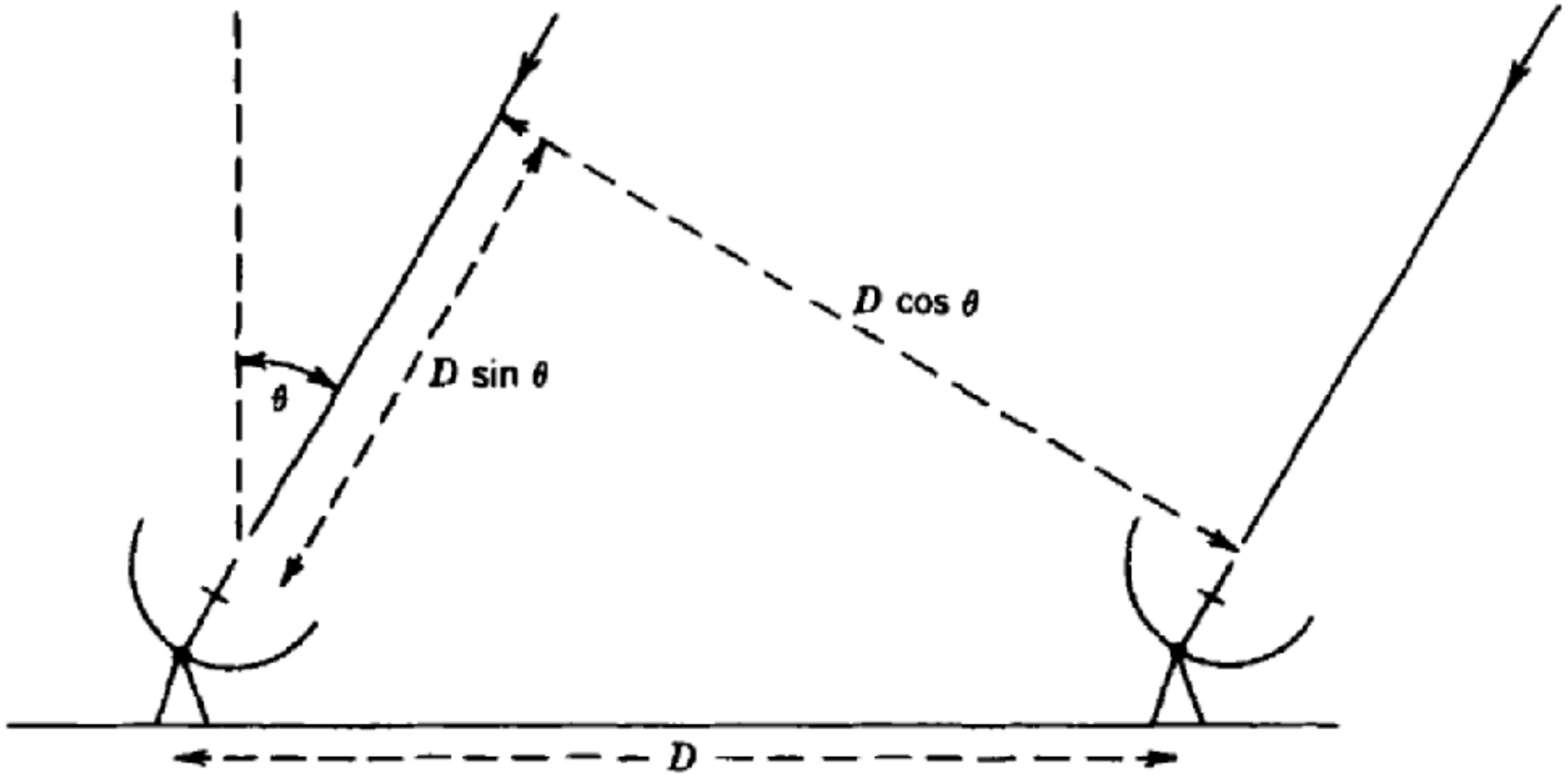
Fringe fitting - introduction

- Recall the simple 2-element interferometer



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

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

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

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 -

How to fringe-fit?

- Therefore, for each baseline pq this error becomes:

$$\Delta\phi(t,\nu)_{pq} = \phi_{0p} - \phi_{0q} + \left(\left[\frac{\partial \phi_p}{\partial \nu} - \frac{\partial \phi_q}{\partial \nu} \right] \Delta\nu + \left[\frac{\partial \phi_p}{\partial t} - \frac{\partial \phi_q}{\partial t} \right] \Delta t \right).$$

- 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!)**

Fringe-fitting in practice

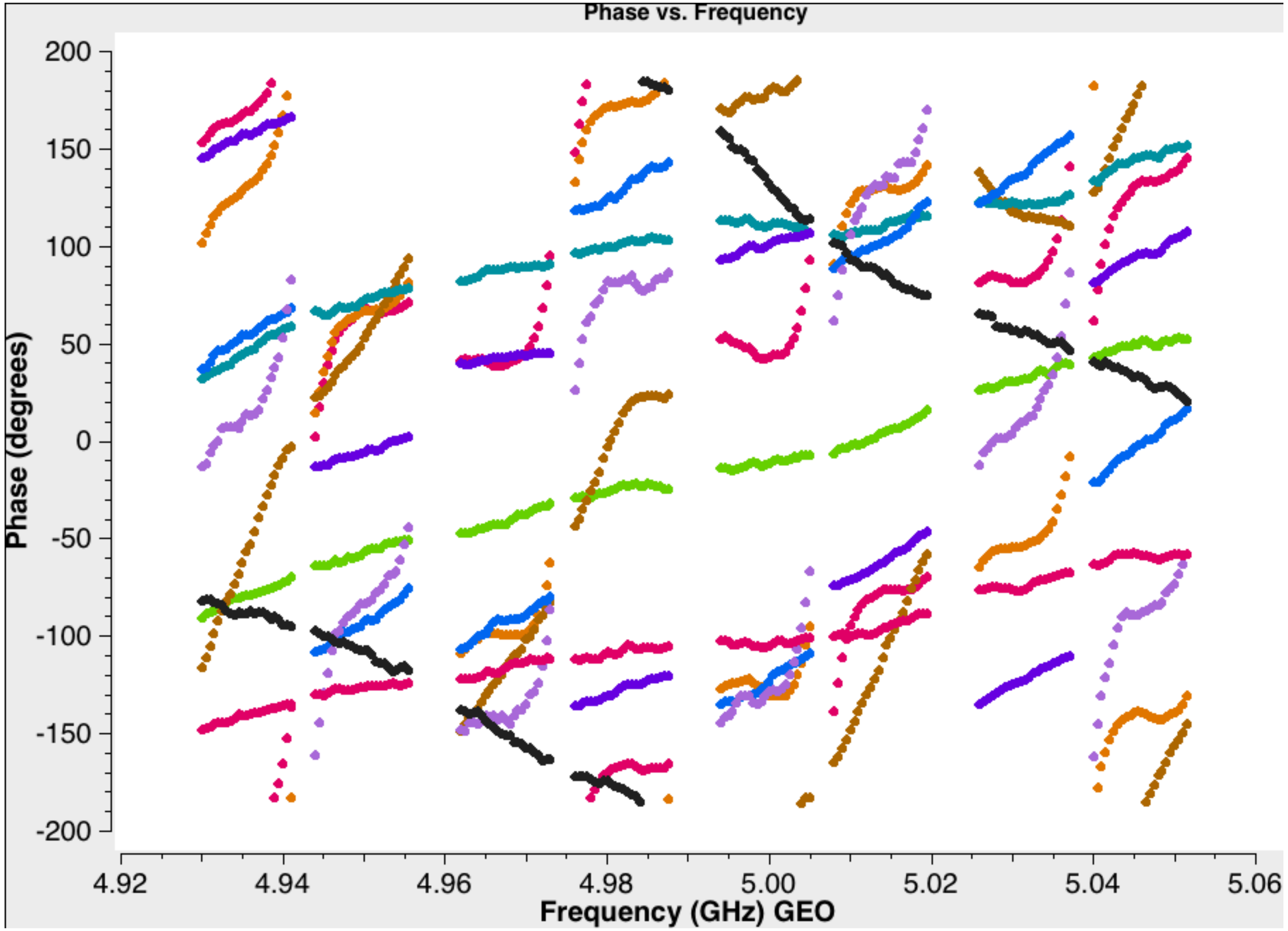
- Used to be an AIPS-only task but is now part of CASA (since v 5.3)
- For VLBI, there are (normally) two times we need to fringe-fit.
    1. For removing instrumental delays
    2. Deriving time, rates and delays variations vs time (known as a multi-band fringe fit)

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

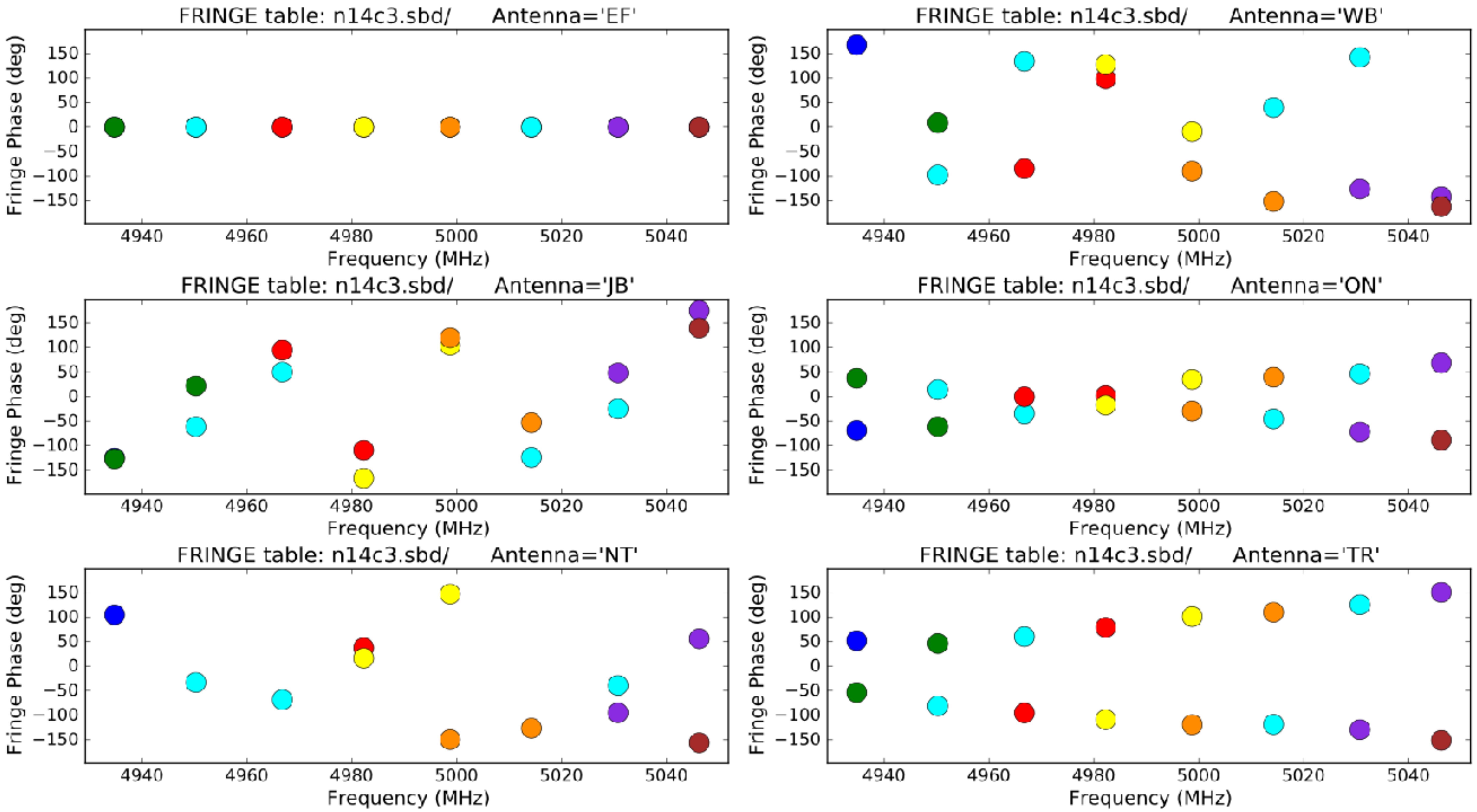
Instrumental delays

- **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

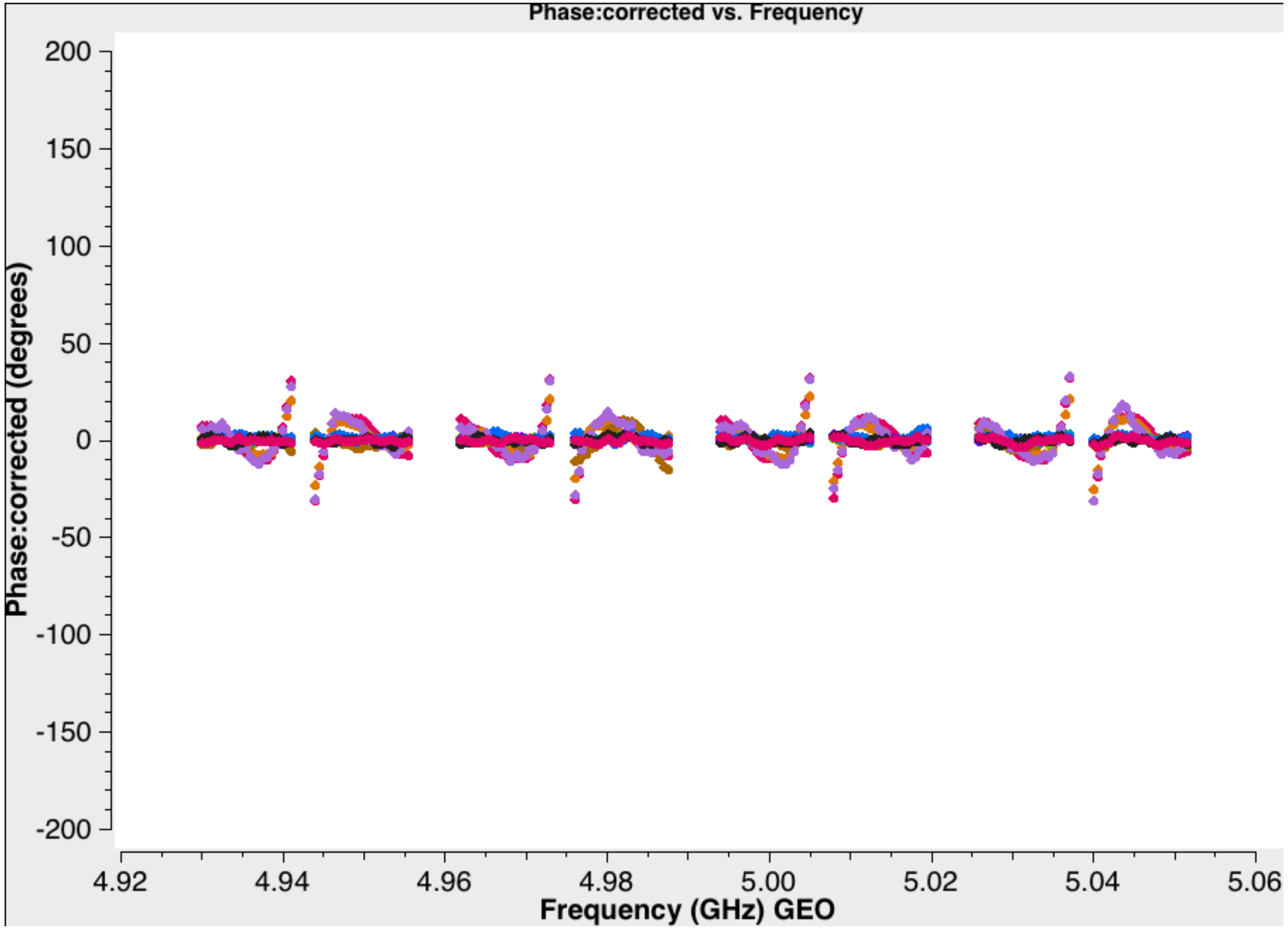
Instrumental delays



Fringe-fitting in practice

Instrumental delays

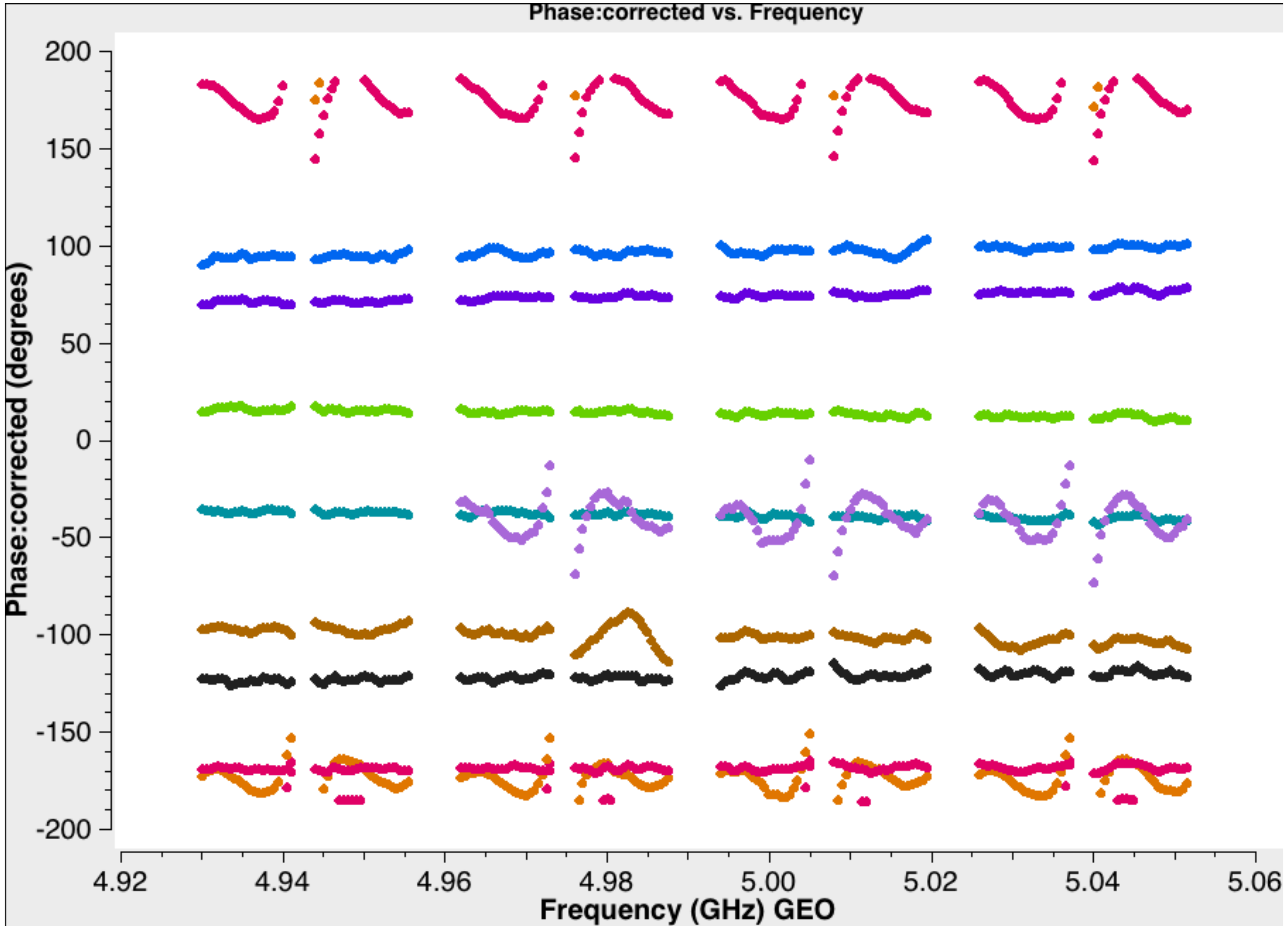
- **After instrumental delay**
- Showing corrected phase vs. frequency on bright calibrator (Effelsberg baselines, 1-scan, LL polarisation)
- Coloured by antenna!
- **Same scan as solutions derived for!**



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

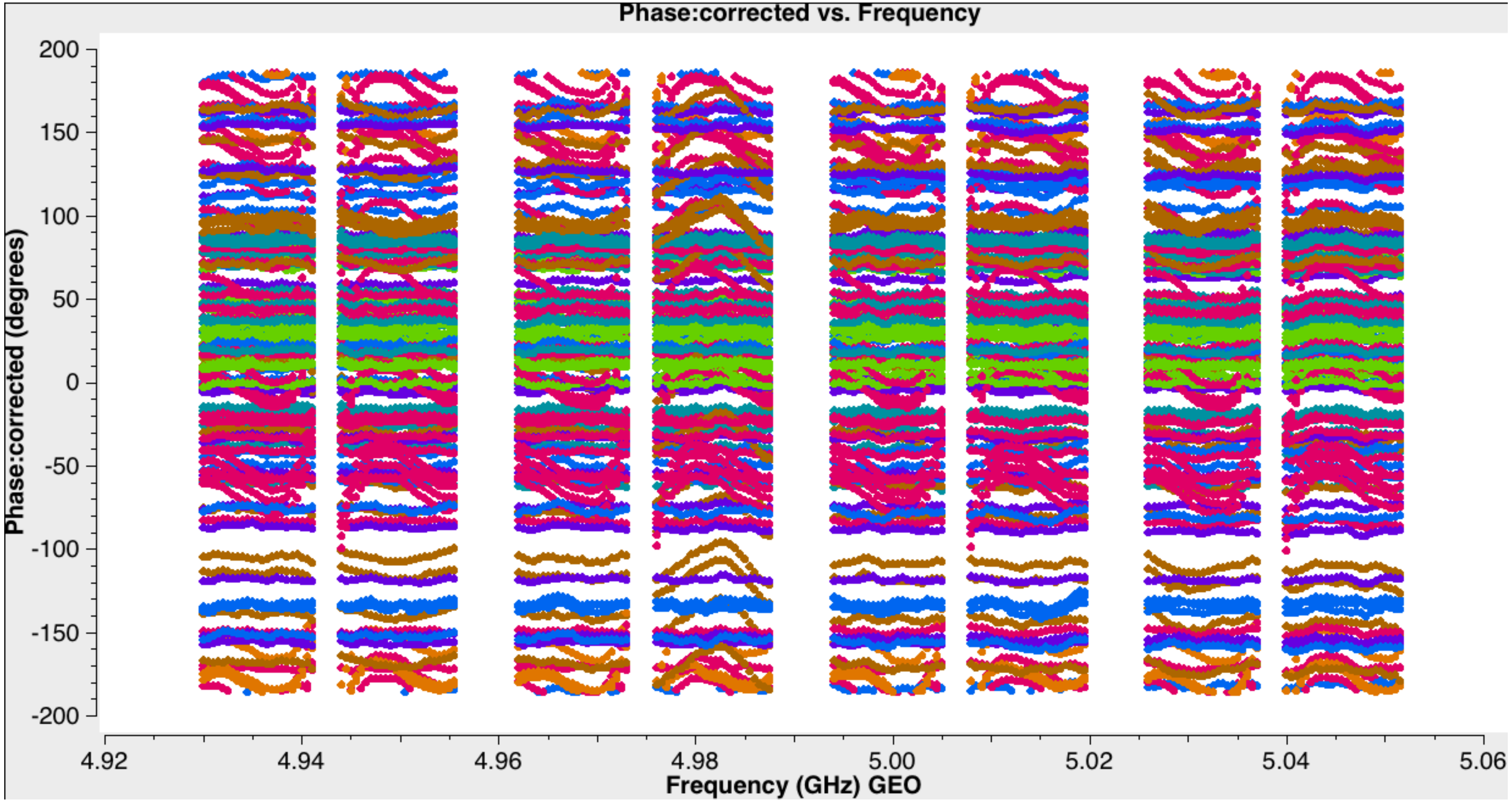
2. **Multi-band fringe-fitting**

- 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)

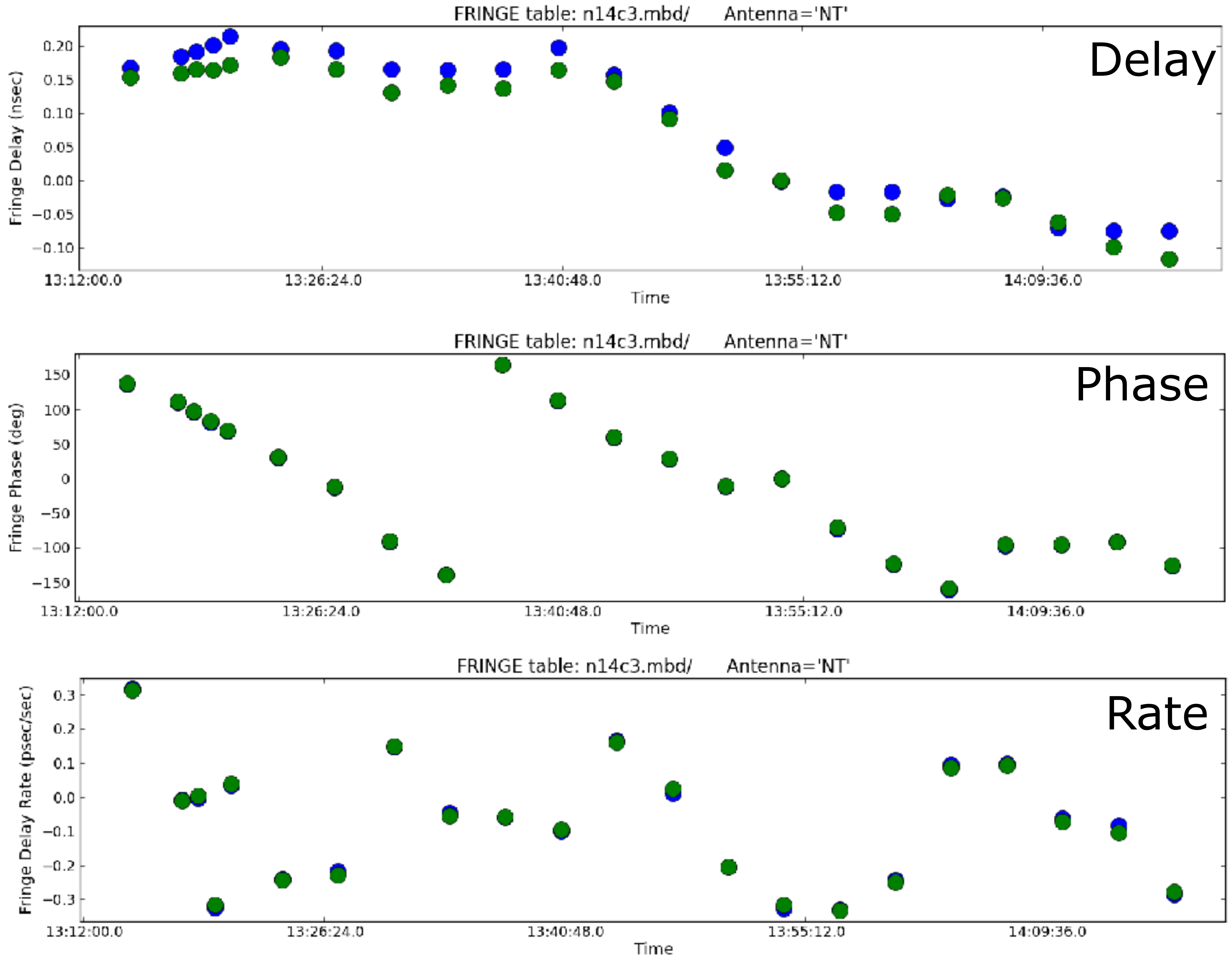


Fringe-fitting in practice

Multi-band fringe-fitting

Multi-band delay solutions

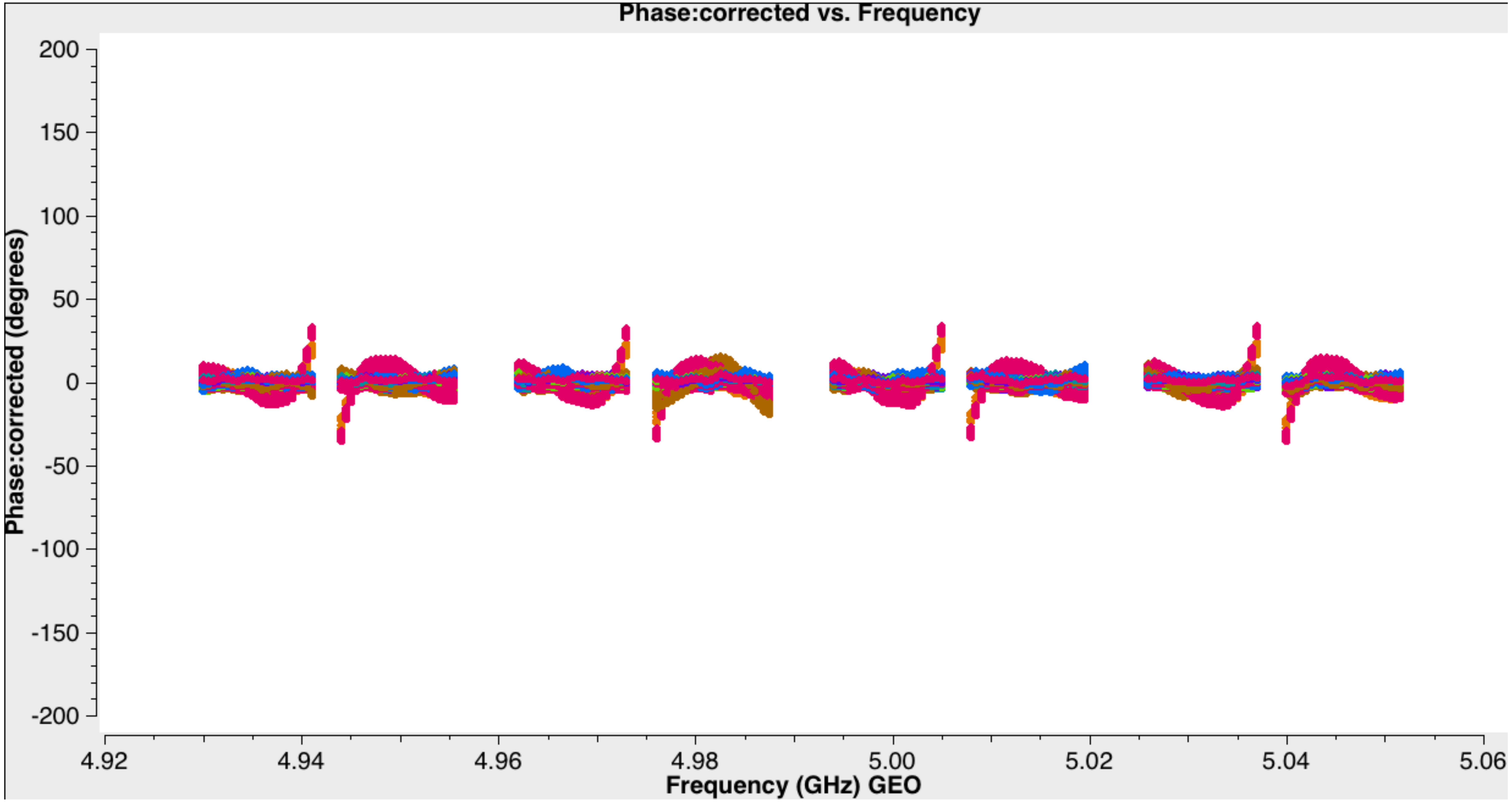
- Noto telescope only shown here
- One solution per scan and spw combined
- Delay, phase, rate solutions primarily due to atmosphere



Fringe-fitting in practice

Multi-band fringe-fitting

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

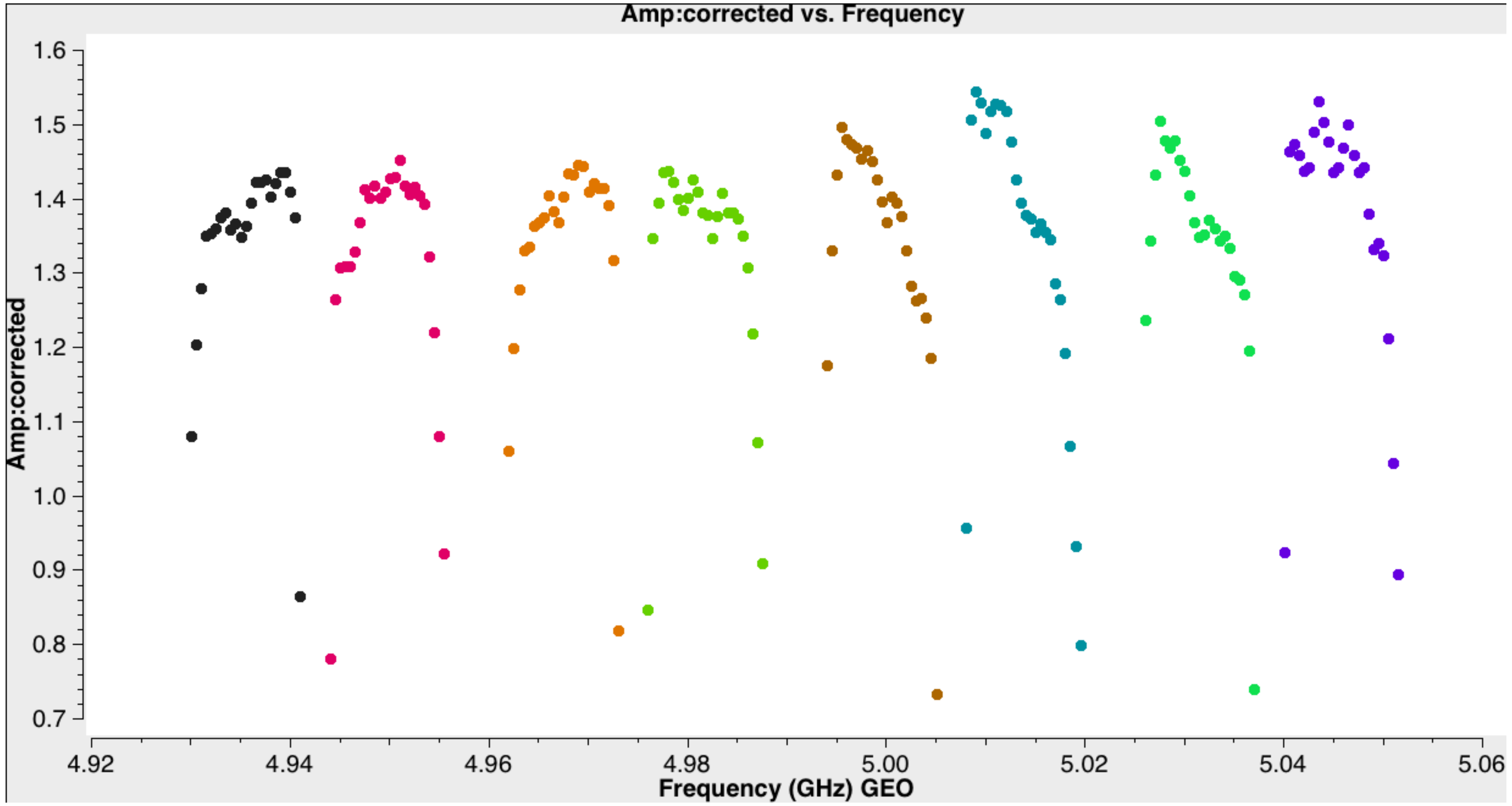


Bandpass correction

- Bandpass is the frequency-dependent sensitivity across the observed frequency range.
- Variations are due to filters, receiver sensitivity variations & signal processing artefacts.
- Note you need to calibrate the phases & amplitudes first!
- Often done on the same scan that the sub-band delay is done on (corrected for phases & amps)

$$\mathrm{V}_{pq}^{\mathrm{obs}} = \boldsymbol{M}_p \boldsymbol{B}_p \boldsymbol{F}_p \boldsymbol{G}_p \boldsymbol{D}_p \boldsymbol{E}_p \boldsymbol{P}_p \boldsymbol{T}_p \mathrm{V}_{pq}^{\mathrm{true}} \ldots$$

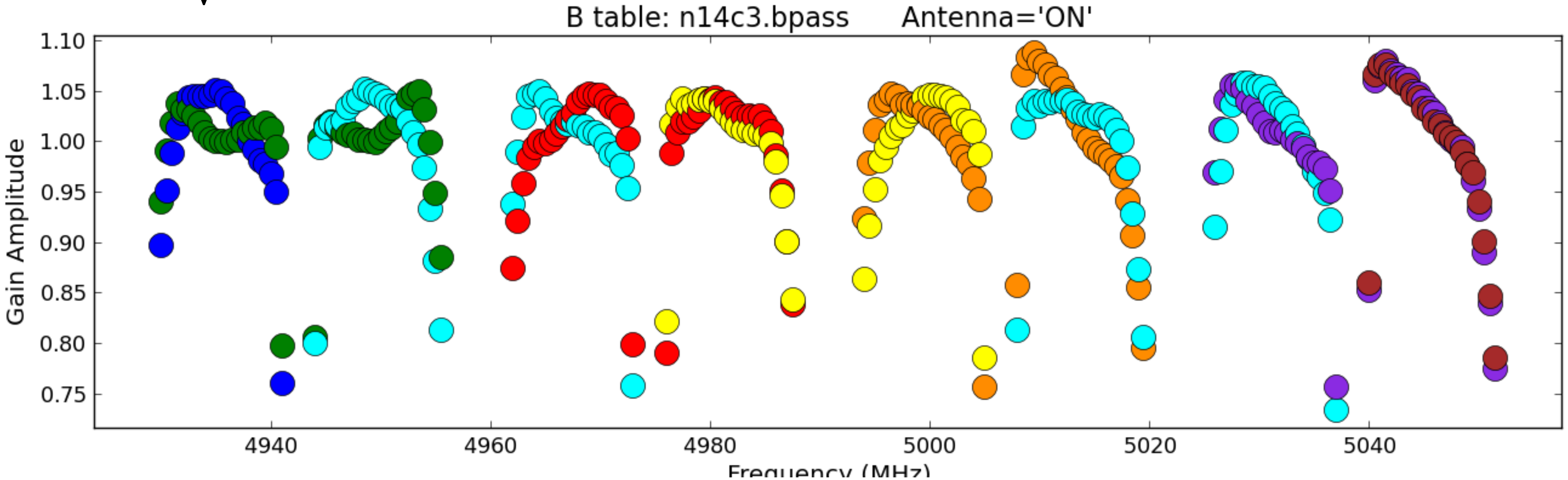
Baseline Effelsberg & Onsala (LL polarisation only)



Bandpass correction

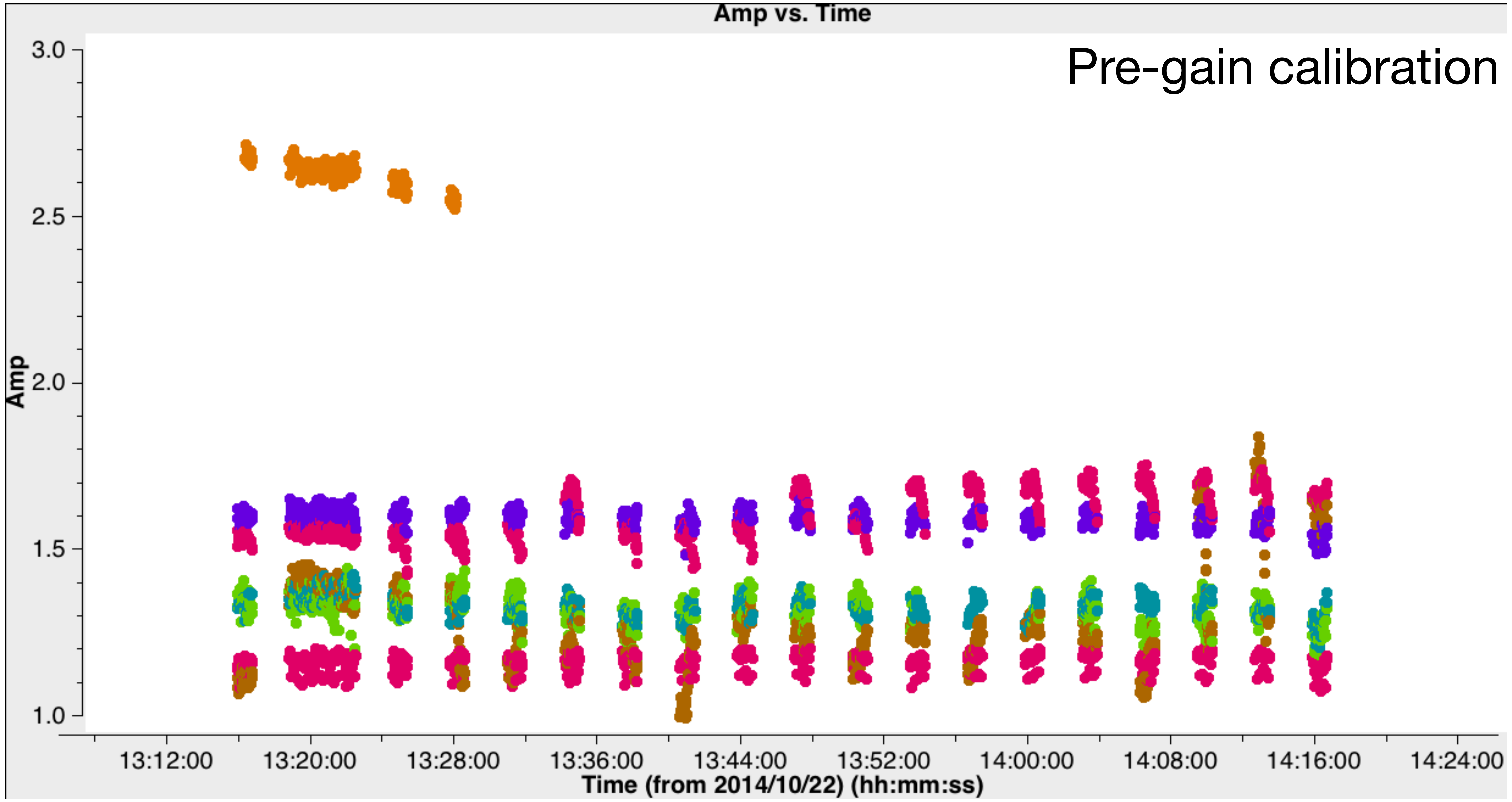
- Bandpass correction derives the amplitude and phases **per** antenna.
- Each antenna will have a distinctive amp vs frequency shape which can be derived from all baselines to that antenna! (It’s a bunch of lots of simultaneous equations)
- Bandpass calibrators **must** be extremely bright (so can use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

(remember $\sigma_S = \frac{2kT_{\rm sys}}{A_{\rm eff}\sqrt{N(N-1)\Delta\nu\tau}}$)?



Phase referencing - amplitude

- The nodding between phase calibrator and target allows us to also track the amplitude variations, often caused by variable gains in the antenna system.



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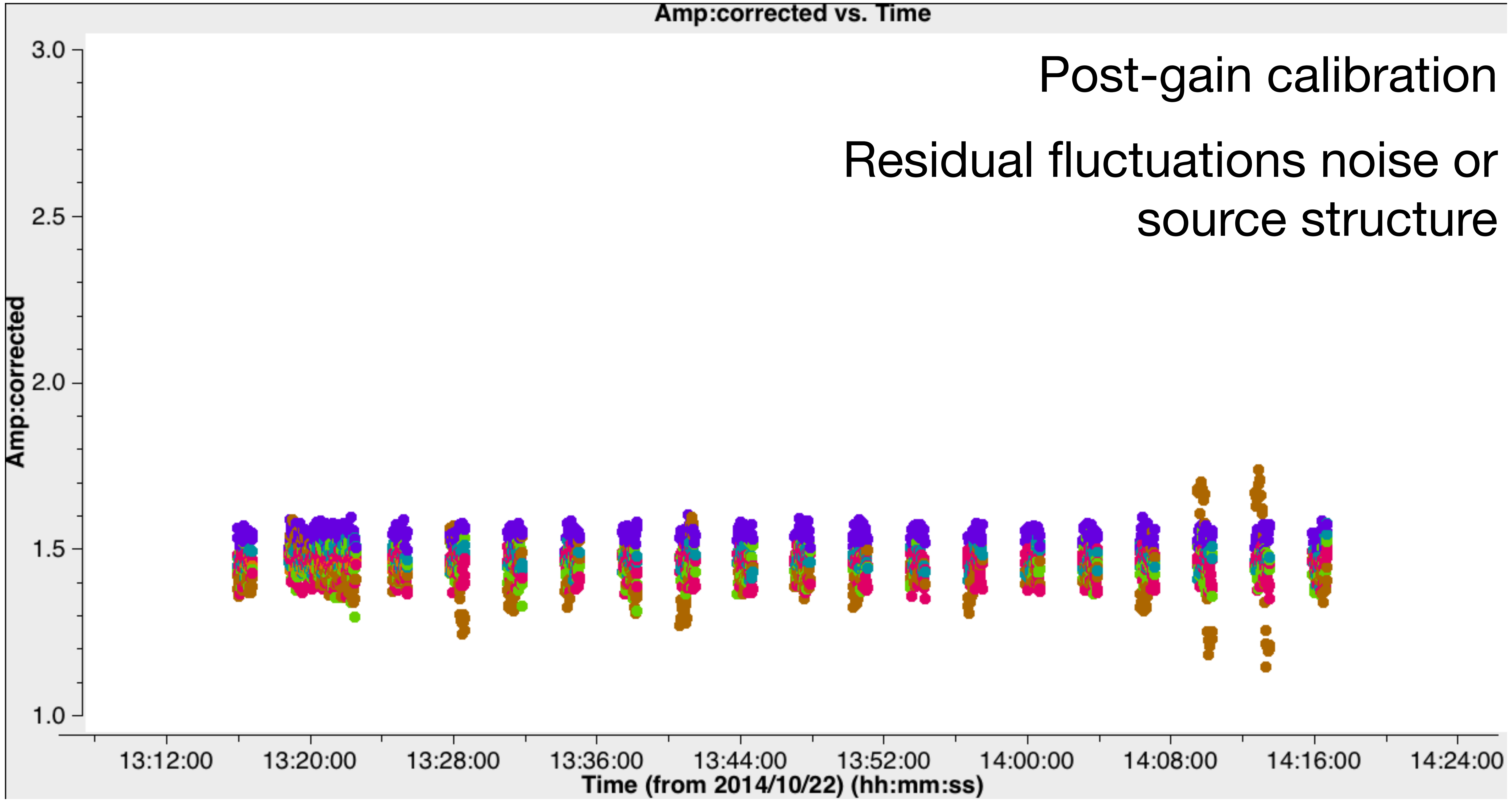
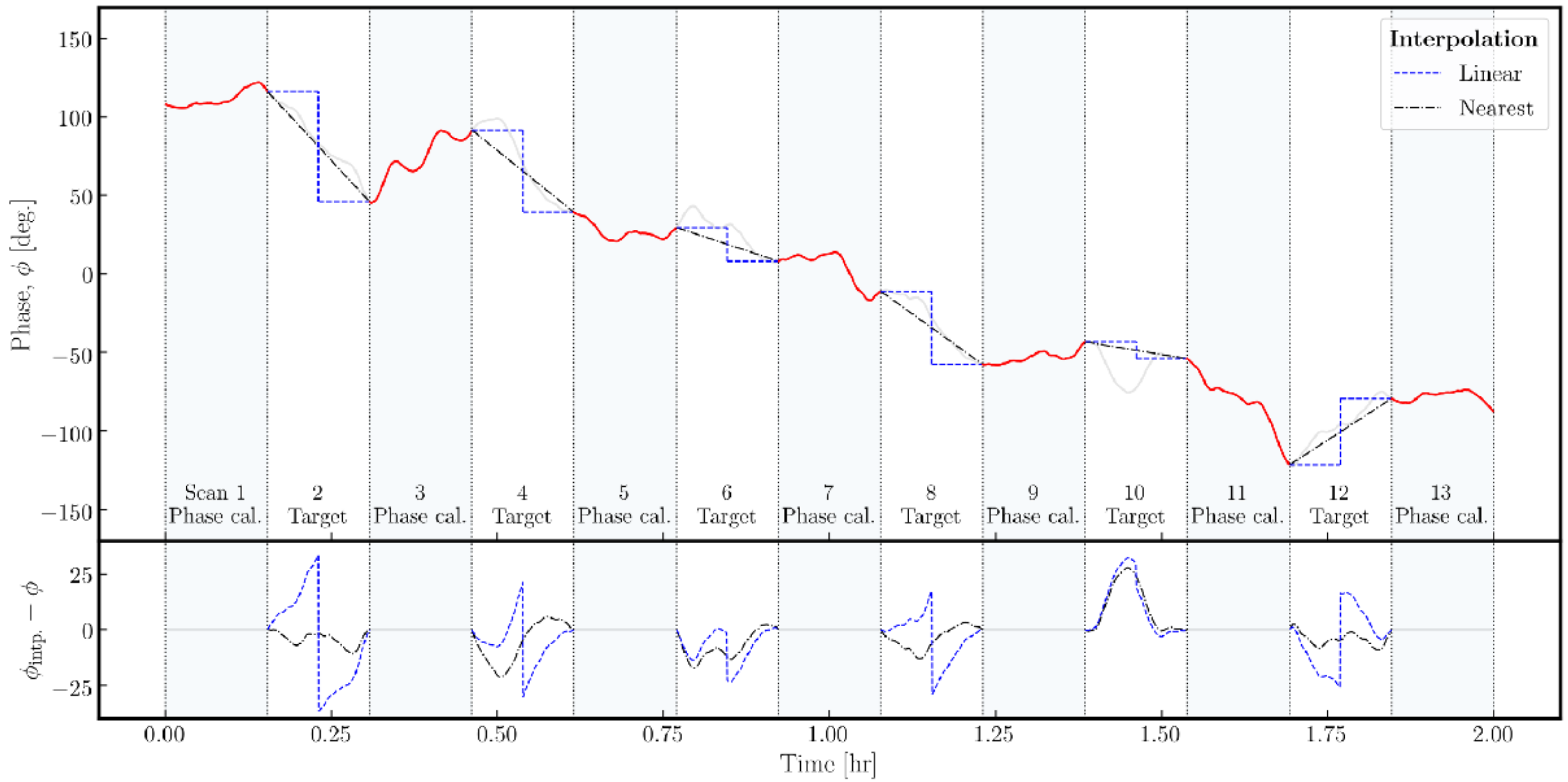
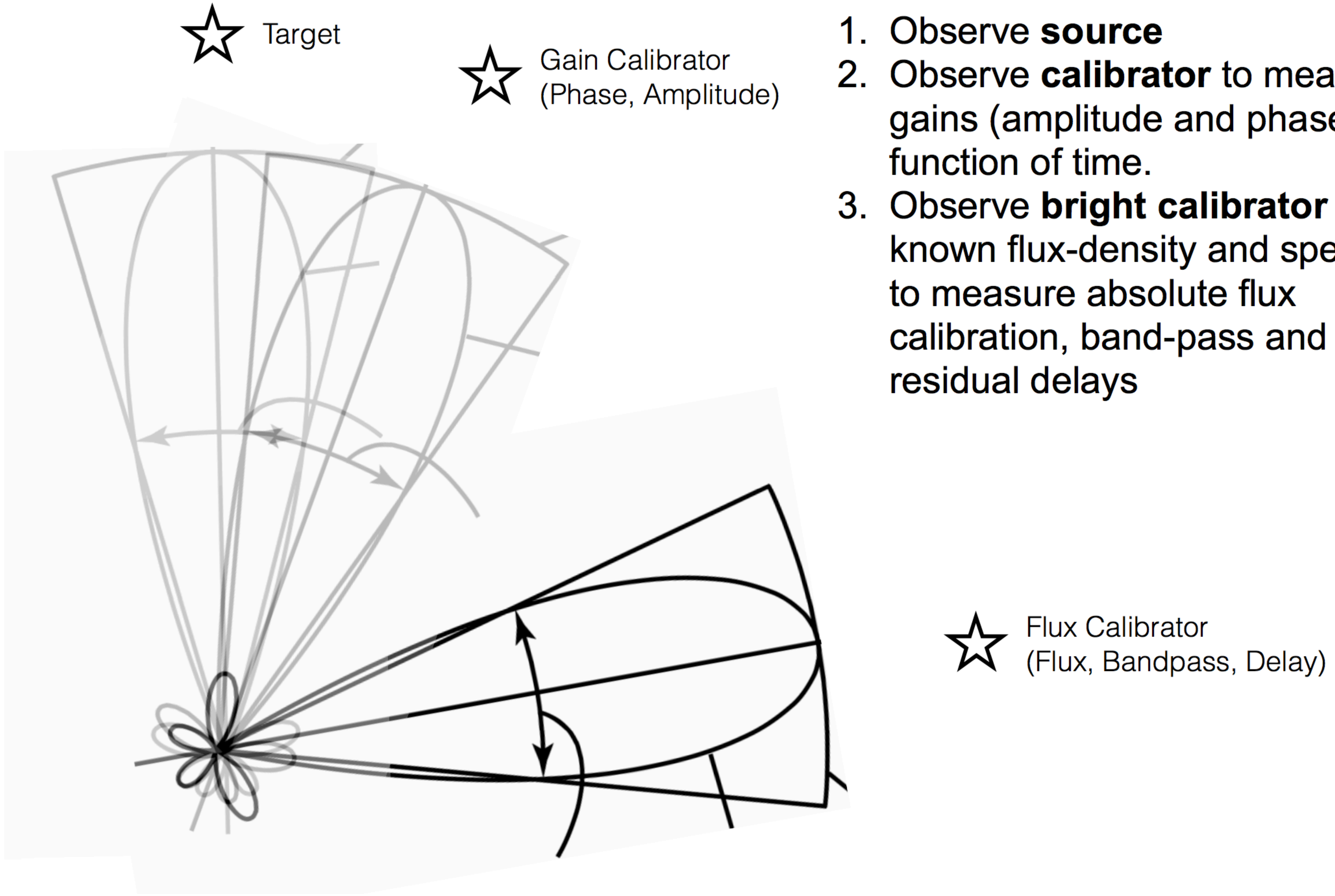


Transferring solutions

- As we are deriving various values with the various calibration techniques, we then need to interpolate these values in time and frequency to our target field!
- The solutions are not 100% correct just yet (e.g. the atmospheric paths are not the same) - but we will explain in the self-calibration lectures.



Putting it all together - observing 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

**Remember to constantly look for bad data throughout!*

1. Apply a priori calibration first (e.g., gaincurves, $T_{\rm sys}$, TEC, EOPs)
2. Sub-band fringe-fitting calibration on bright source - remove instrumental delays.
3. Bandpass correction on same bright source
4. Multi-band fringe fitting on all phase reference (near to the target) sources — removes time dependent phase errors (e.g., atmospheric errors)
5. Amplitude gain correction (using self-calibration)
6. Apply to target
7. Self-calibrate on target — if bright enough.
8. Science!

And remember this works on the assumption that your phase calibrator is a point source at the phase centre! i.e. flat in amp and 0 in phase (unless you do self-calibration)