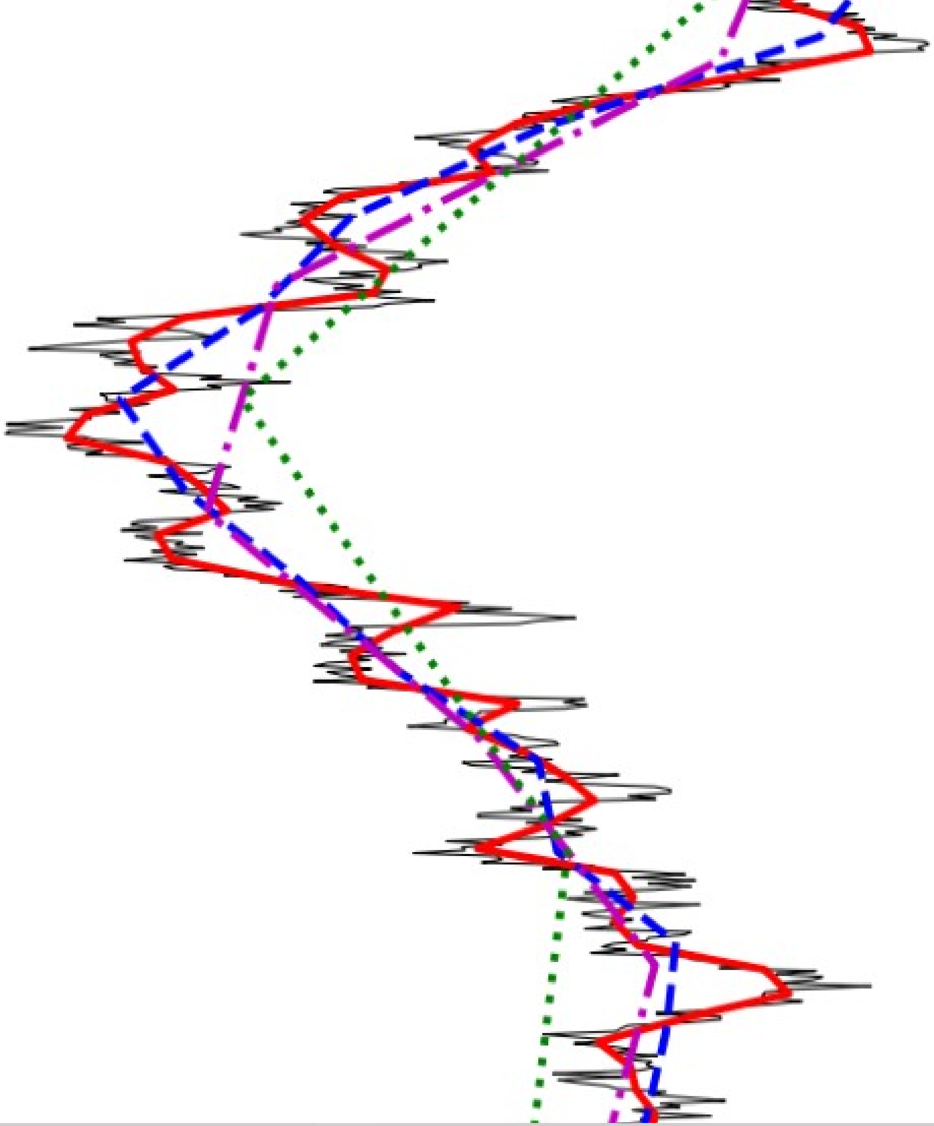

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NRF National Research Foundation | SARAO South African Radio Astronomy Observatory

DARA DEVELOPMENT IN AFRICA WITH RADIO ASTRONOMY

Tailoring calibration

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Summary

- **How do you know what parameters to set, and what do you set them to?**

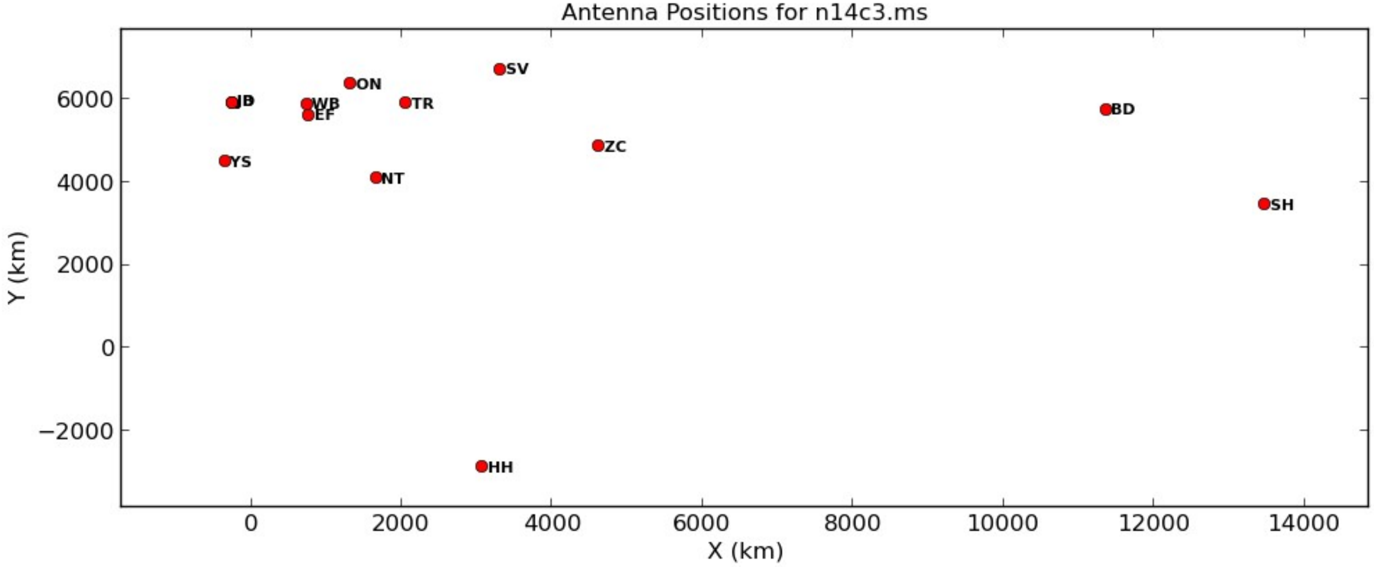
- Some are standard e.g. `vis='?'`, but others e.g. phase reference solution interval can affect calibration profusely!

- This lecture should give you some intuition on what to set.

Reference antennas

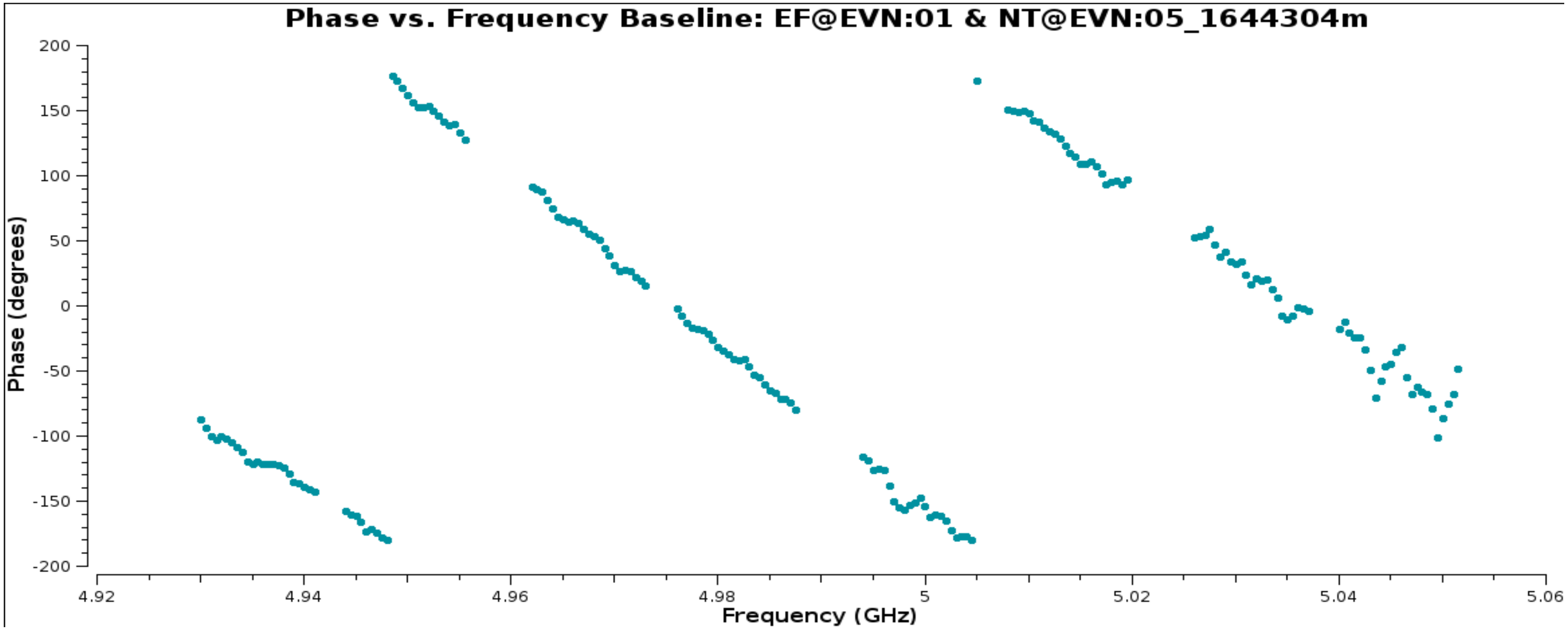
- The reference antenna is the antenna which we compare our solutions too (interferometers only care about relative differences)
- A good reference antenna should be the one that will have the **most good solutions to all other baselines.**
- This means it typically is one or both of:
    - Has a large collecting area
    - Or close to the centre of the array (i.e. lots of short baselines)

Effelsberg is used for the EVN as it's both close to the centre **and** the largest in the EVN (100m)



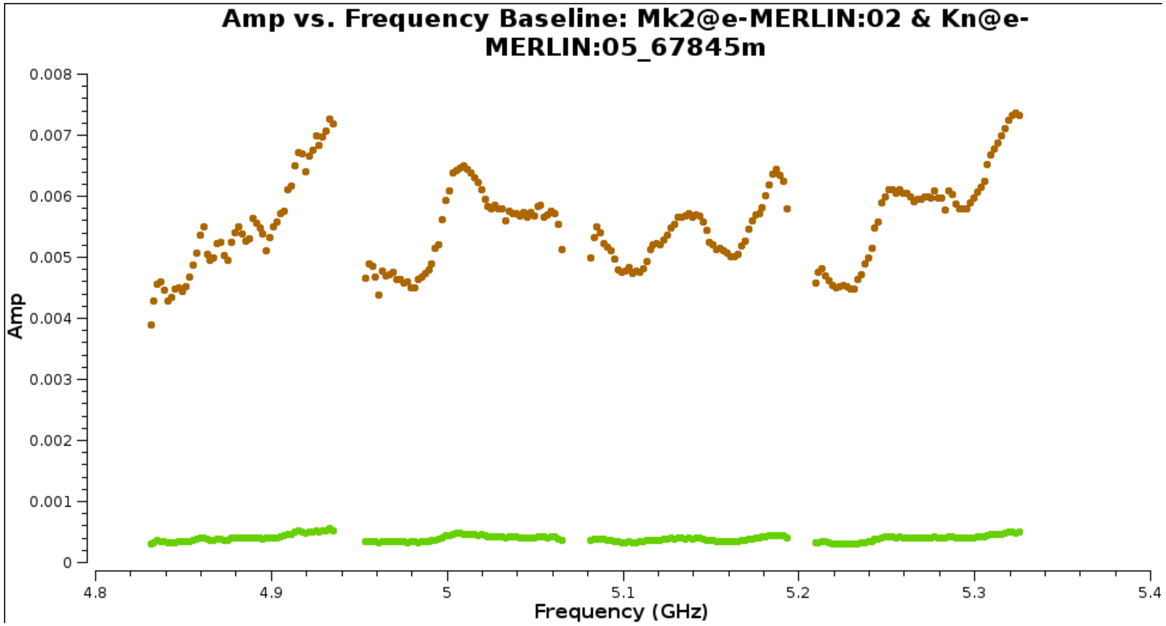
Fringe fitting / delay calibration

- Delay corrections for linear phase gradients: Inspect phase v. frequency
- Always worth correcting for VLBI observations!
- Delays are usually stable for hours but averaging solint limited (~scan) by time-dependent phase stability

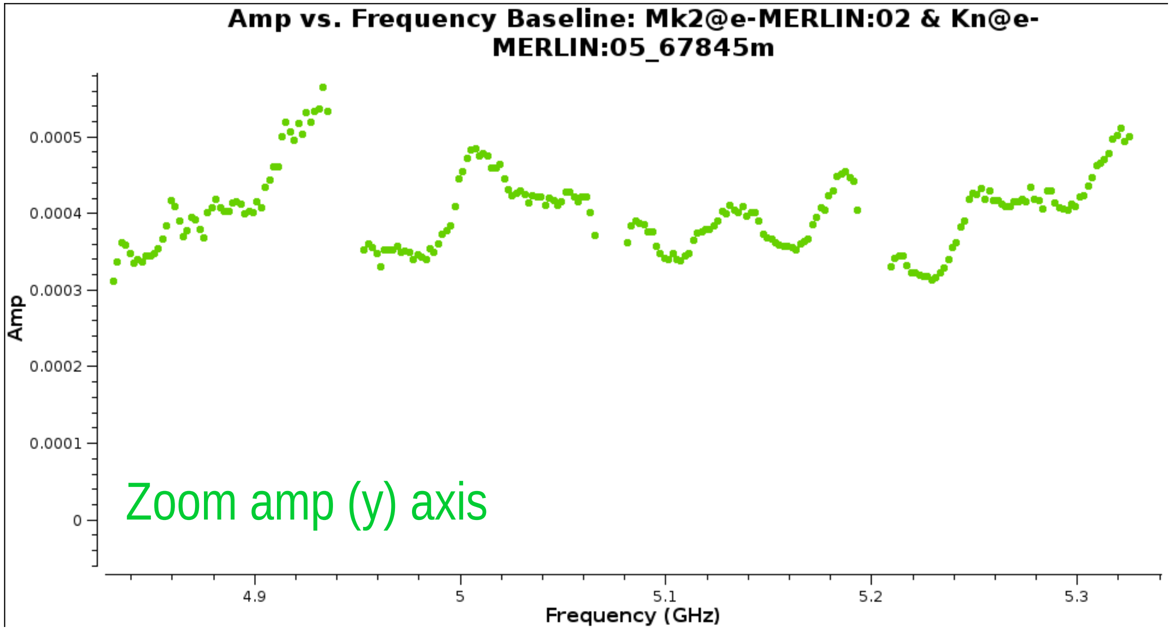


Bandpass calibration

- Correct BP calibrator phase v. time first (see following slides)
- In bandpass, average in time for as long as possible for best S/N per channel
- Example below: Both BP calibrators have same amplitude wiggles
- Could combine, interpolate or use just the one with best S/N?



Bandpass calibration



Additional points

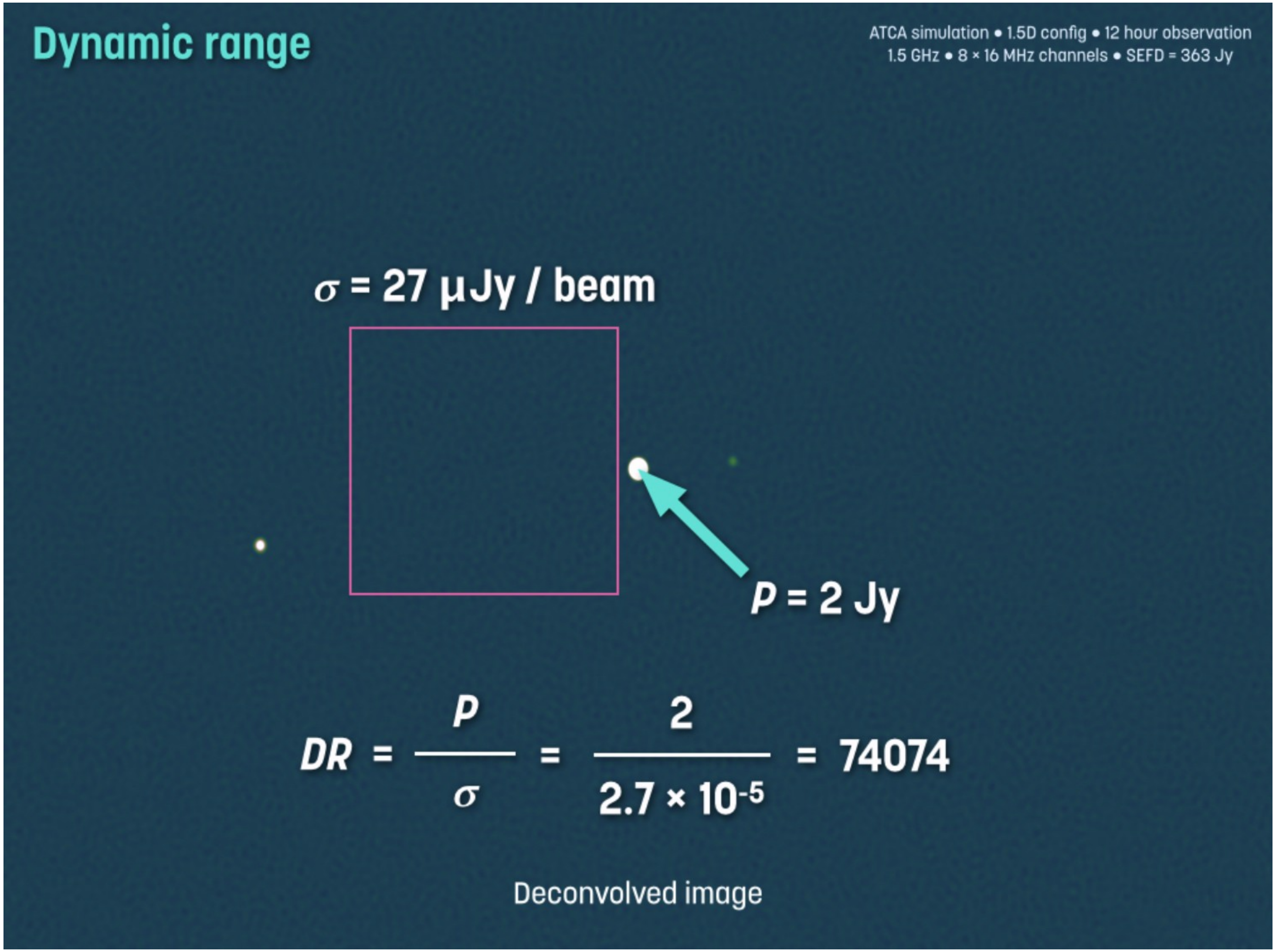
- Normalise bandpass solutions (otherwise flux scale may differ or be unset)
- May need to select timeranges if there's bad data around.

Visibility errors and noise

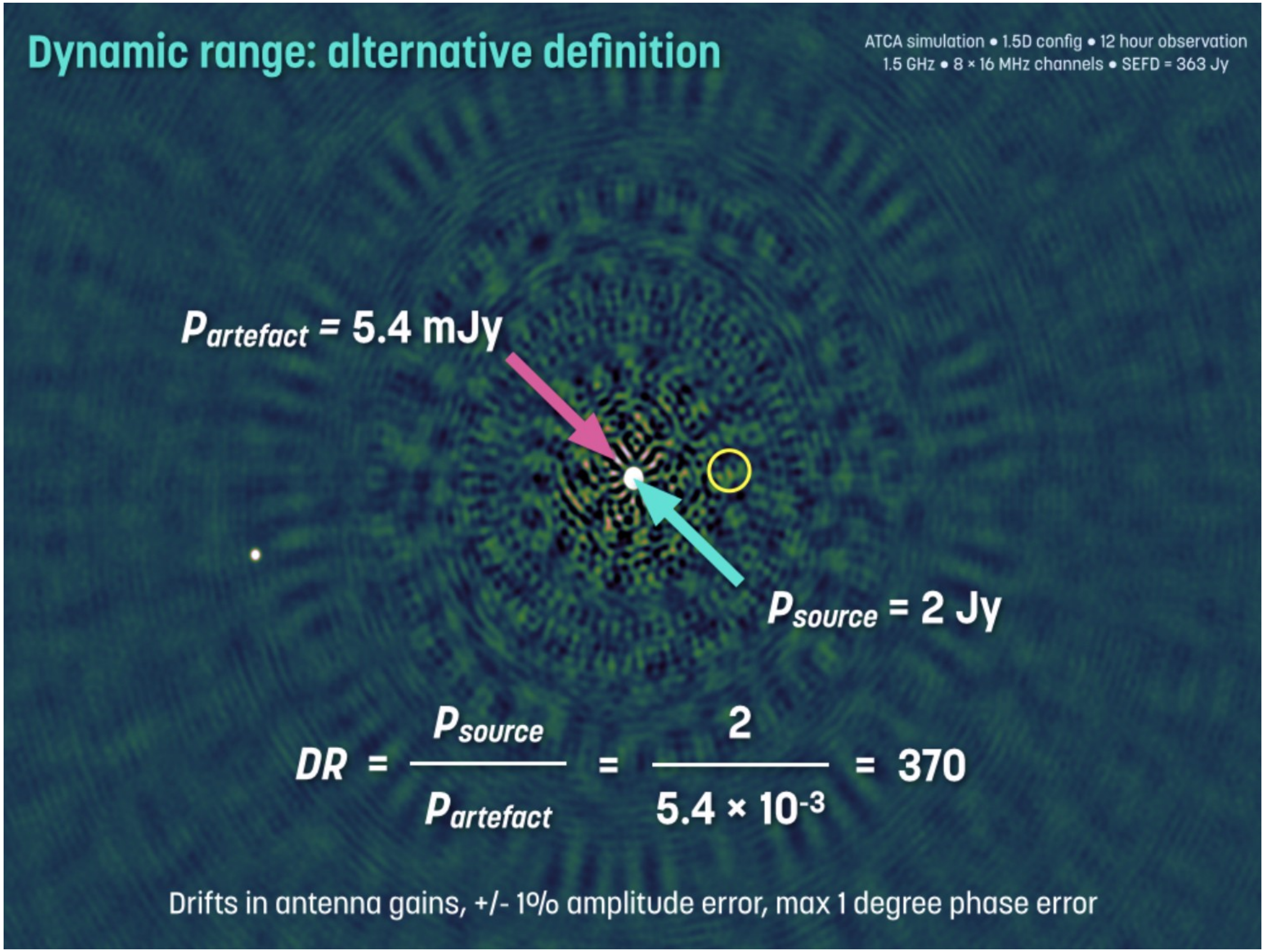
$$\sigma_{\rm sys} = \frac{\langle T_{\rm sys}\rangle}{\eta_{\rm A} A_{\rm eff}\sqrt{(N(N-1)/2)\Delta\nu\Delta t N_{\rm pol}}}$$

- Lowest possible noise is 'thermal' limit based on Tsys (assuming natural weighting):
- Good rule of thumb is that you should **at least reach 3 times the predicted noise floor** (why do you not often reach the noise floor?)
- So you can only improve on this by:
  - Bigger/more efficient antennas ($A_{\rm eff}$,$\eta_{\rm A}$) or more (*N*)
  - Lower noise, $R{\rm X}$ and/or $T_{\rm sky}$ (observing conditions)
  - Observe for longer/wider bandwidth

Dynamic range



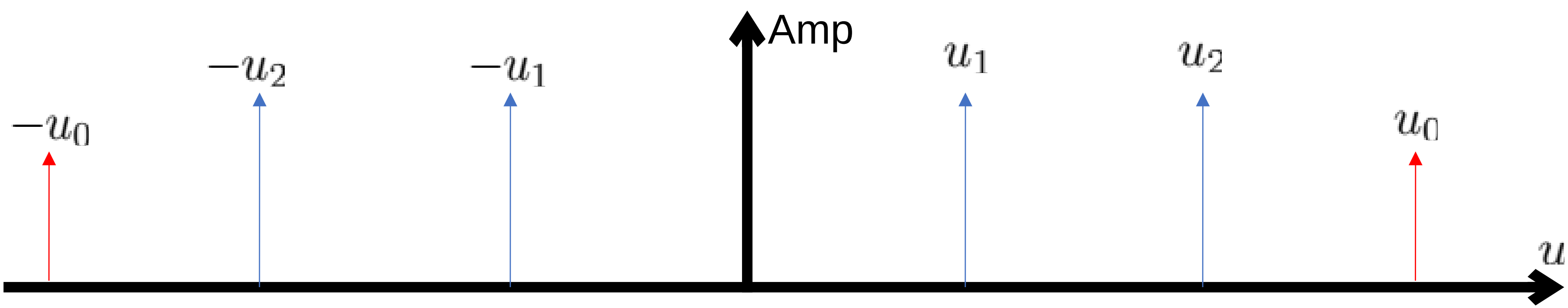
Dynamic range



Phase errors and dynamic range

- Let's take a simplified array - flat, linear array, *N* antennas
- Single integration observation of a point source - *N*(*N*-1)/2 visibilities
- Direction such that we only need to consider *u* axis
- Each baseline visibility is a δ spike in the *uv* plane
- All but one are 'perfect' (unit amplitude, zero phase)
- These have $V(u) = \delta(u - u_k)$ for the *k*th baseline.
- Phase error on baseline length u_0 of ϕ_ϵ radians so

$$V(u) = \delta(u - u_0)\exp(-i\phi_\epsilon)$$



Phase errors and dynamic range

- Image is formed by Fourier Transform:

$$I(l) = \int V(u) \exp(i2\pi ul) \mathrm{d}u$$

Each baseline contributes at position u_k and complex conjugate $-u_k$ in the visibility plane.

- Evaluating the term for each $(N(N-1)/2)-1$ good baselines gives us $2\cos(2\pi u_k l)$
- However single bad baseline gives $2\cos(2\pi u_0 l - \phi_\epsilon)$
- Which, assuming small ϕ_ϵ gives: $\approx 2[\cos(2\pi u_0 l) + \phi_\epsilon \sin(2\pi u_0 l)]$
- So the image integral now becomes:

$$I(l) = 2\phi_\epsilon \sin(2\pi u_0 l) + 2 \sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k l)$$

Phase errors and dynamic range

- The synthesised beam is (in this case):

$$B(l) = 2 \sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k l)$$

- Deconvolution is the subtraction of the beam from the image which leaves the residual error i.e.

$$R(l) = I(l) - B(l) = \left[2\phi_\epsilon \sin(2\pi u_0 l) + 2 \sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k l) \right] - 2 \sum_{k=1}^{N(N-1)/2} \cos(2\pi u_k l)$$

$$= 2\phi_\epsilon \sin(2\pi u_0 l)$$

- This is an ‘odd’ sinusoidal with amplitude $2\phi_\epsilon$ and period $1/u_0$

Phase errors and dynamic range

- Therefore for a small phase error ϕ_ϵ, and large N, the ratio of peak to noise residual is:

Dynamic range – $D_{\mathrm{B}}(\phi_\epsilon) \sim I(l)/R(l) \sim N^2/\sqrt{2}\phi_\epsilon$

- Amplitude error on a single baseline has the effect of $V(u) = (1+\epsilon)\delta(u-u_0)$ leading (via a cos function) to

Dynamic range – $D_{\mathrm{B}}(\phi_\epsilon) \sim I(l)/R(l) \sim N^2/\sqrt{2}\epsilon$

Therefore:

- **A phase error of 5° is as bad as a 10% amplitude error**

- **Phase errors are sin (odd), amp are cos (even)**

Phase errors and dynamic range

So far considered just one-baseline error, one integration:

- **All** baselines to one antenna affected by same error:
  - $(N-1)$ bad baselines (~*N* for large *N*)
  - $D_{\rm ant} = D_B/(N-1) = [N^2/(N-1)]/\sqrt{2}\phi_\epsilon \sim \mathbf{N}/\sqrt{\mathbf{2}}\phi_\epsilon$
- If **all** baselines are affected by **random noise**,
  - $D_{\rm all} = D_{\rm B}/\sqrt{N(N-1)/2} = \sqrt{N(N-1)/2)}/\phi_\epsilon \sim \mathbf{N}/\phi_\epsilon$

These expressions are valid if errors are correlated in time, e.g. single phase-ref scan, not much change in *u* (or *v*)

- For *M* periods (scans?) between which noise is uncorrelated:

  Dynamic range is increased -

$$D_{\rm all} \sim \sqrt{M}N/\phi_\epsilon$$

Phase errors and dynamic range

- Using this, lets take **10 antenna** array and **12 independent** scans
- All phase referencing applied, and well edited for RFI

- Typical residual phase scatter ~20^{o} → $D_{\mathrm{all}} \sim \sqrt{M} N/\phi_{\epsilon} \sim 100$

Can we improve on this?

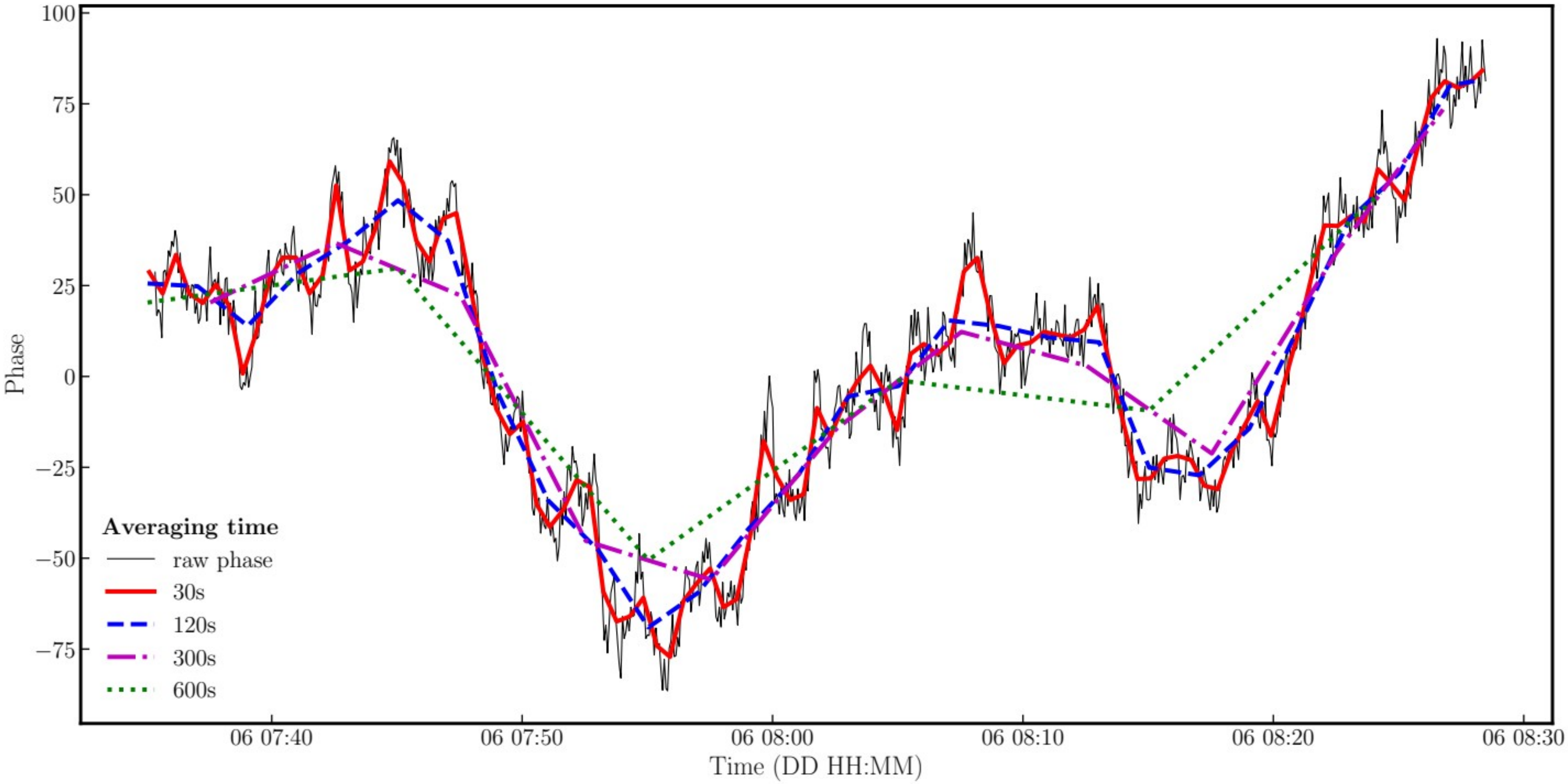
- If map noise is near the T_{sys} limit and remaining errors noise then no!

- If noise is non-Gaussian and shows errors and well above T_{sys} limit then telescopes imperfectly calibrated so:
  - Use self-calibration per antenna, per scan (or longer) to get enough S/N so that the phase errors get below 20^{o}

Solution intervals

Example phase variation across time

- Solution interval too long – lose phase structure
- Solution interval too short – not enough S/N unless very bright source



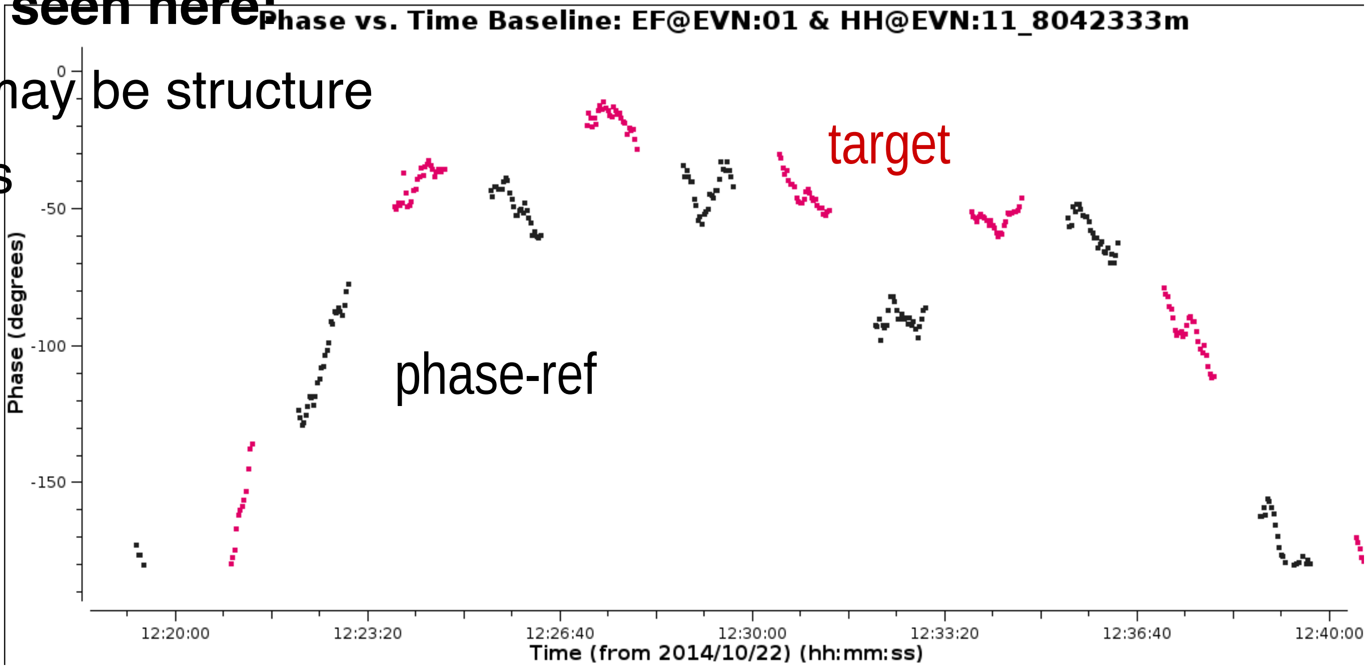
Time dependent phase calibration

Phase reference source:

- Need to interpolate solutions to target
- Does the phase-ref phase track the target phase?

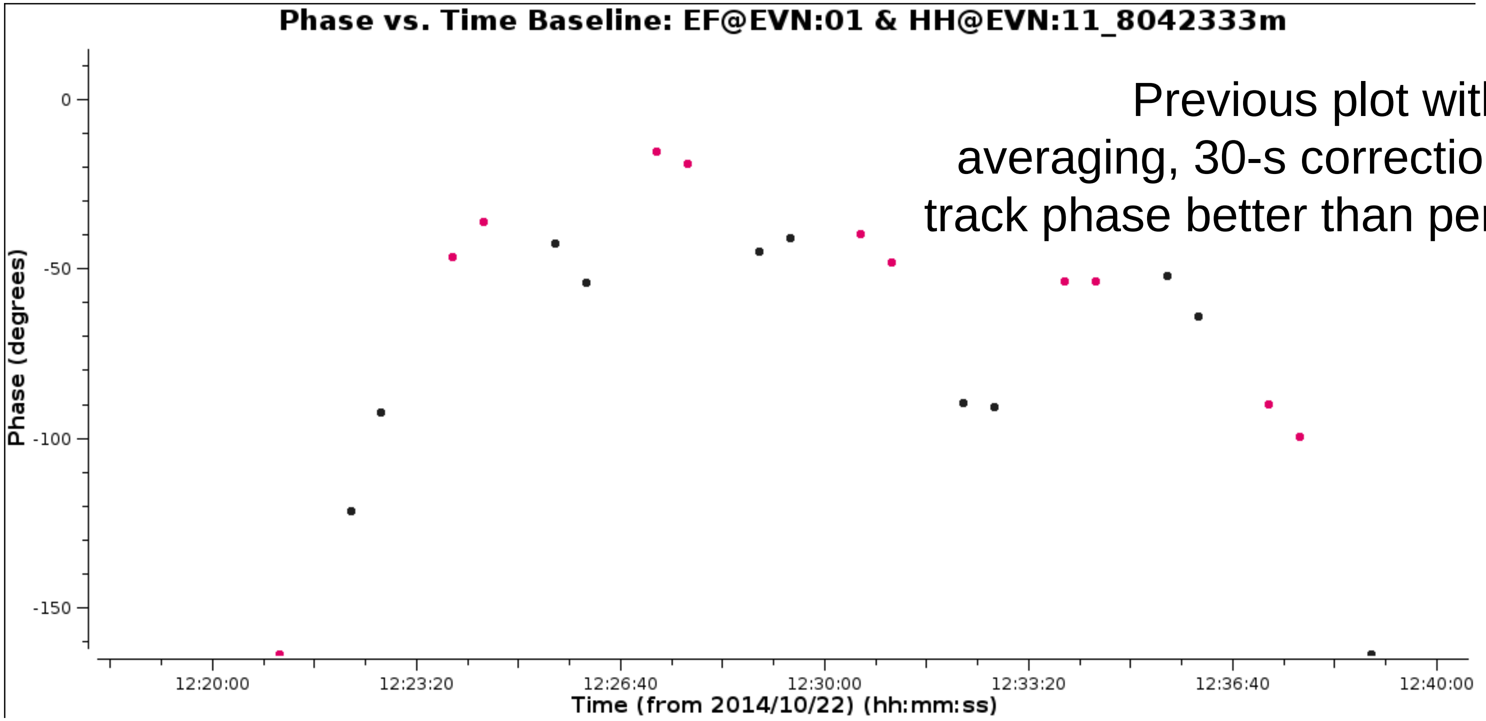
Consistent trend seen here:

- Target wiggles may be structure
- Some deviations



Time dependent phase calibration

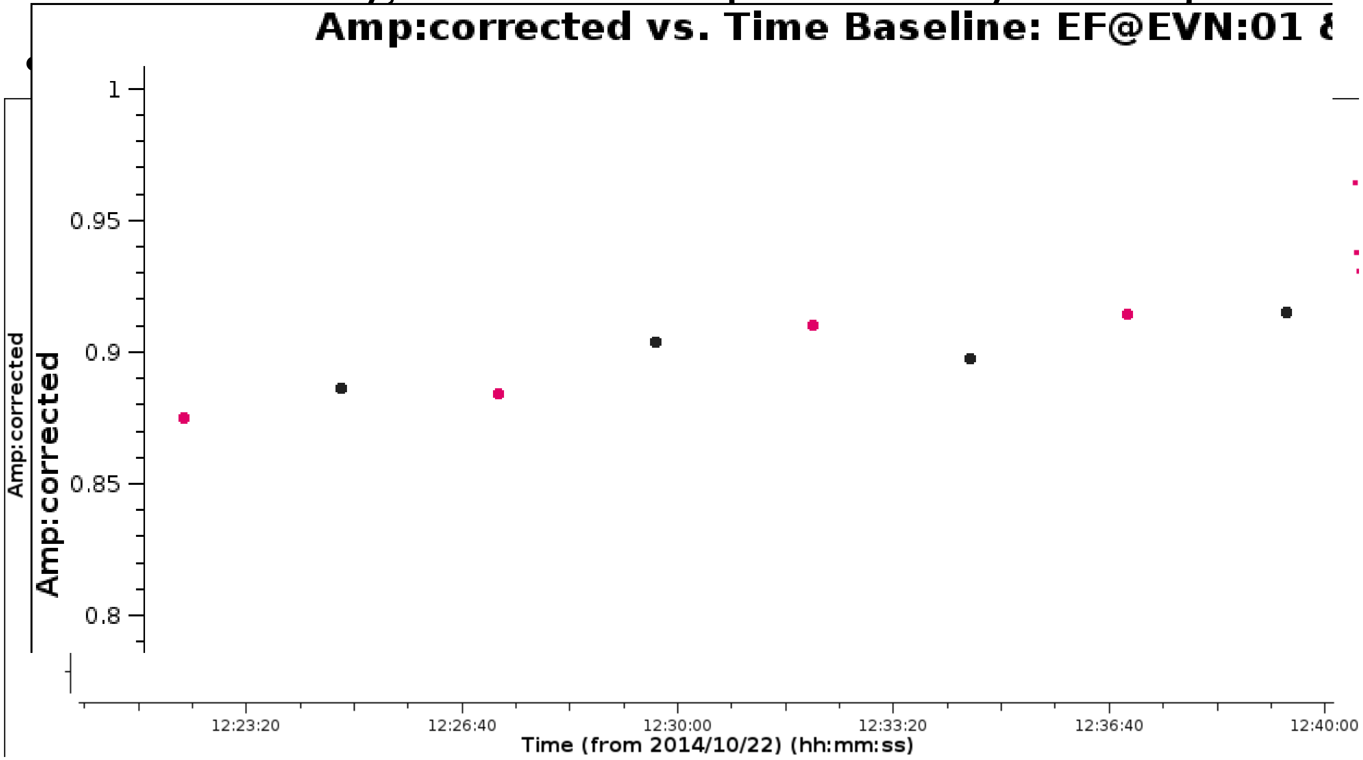
- Need to interpolate phase-ref solutions to target
- Ideally no more than 2 solutions per phase-ref scan
- Check enough S/N in e.g. half scan
- Seeing low scatter by eye is OK!



Previous plot with 30-s averaging, 30-s corrections will track phase better than per-scan

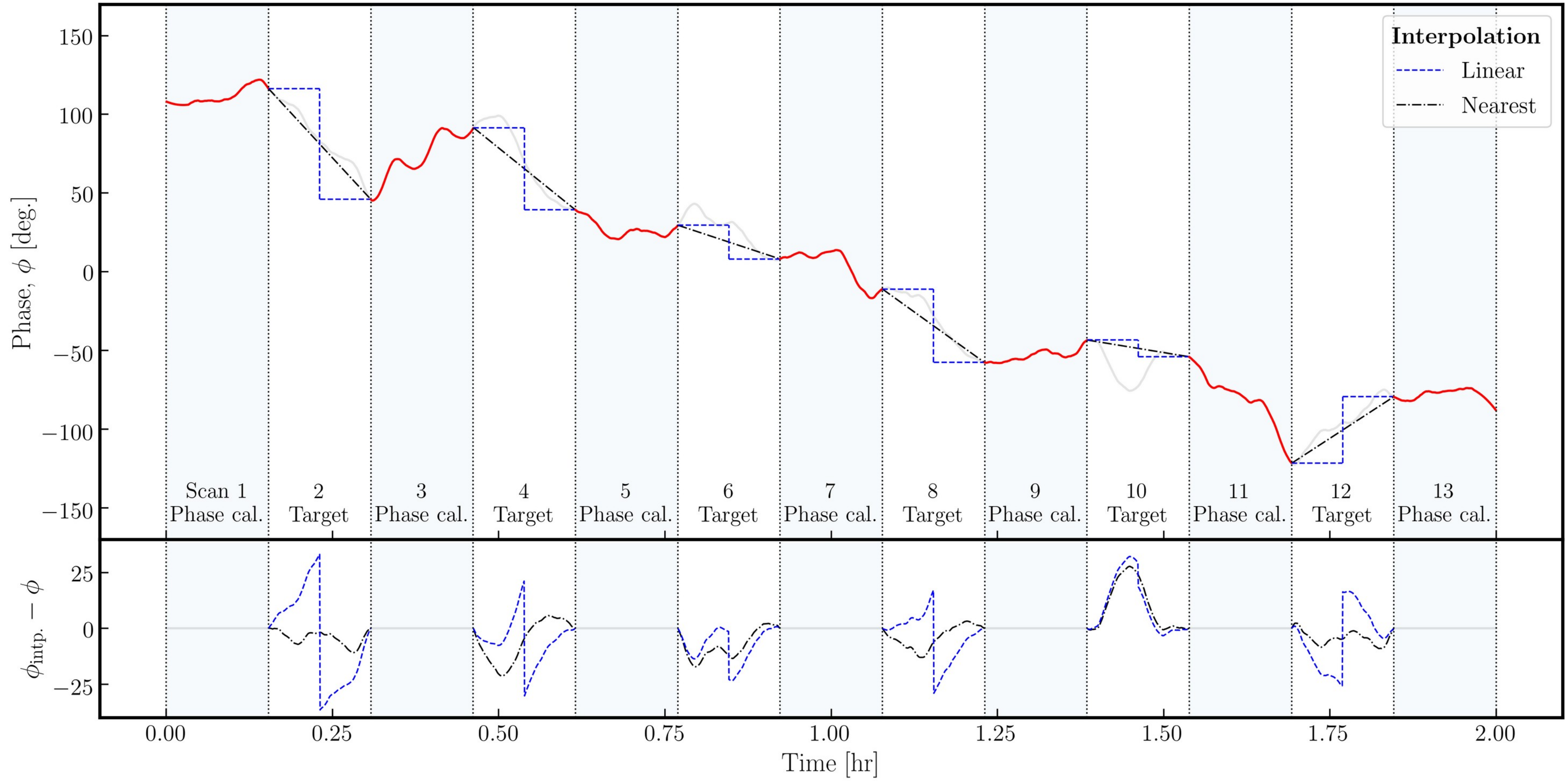
Time dependent amplitude calibration

- Apply phase solutions first to allow longer solint for amplitude calibration
- Avoid decorrelation
- If necessary, use shorter phase-only solint just for this



Interpolating solutions

- Interpolation chosen can increase calibration errors
- Linear is often better when extrapolating across scans



Conclusions

- “Good” calibration solution depend on the conditions of the observation and science goals
- Identify a good reference antenna
- Bandpass and amplitude solution intervals can be as long as possible to get best S/N
- Best solution interval for phase solutions depends, but almost always shorter than a single scan
- Want the best dynamic range possible – self calibration shall be shown to be very helpful in this respect!

Thanks to Anita Richards & Joe Callingham for slide ideas