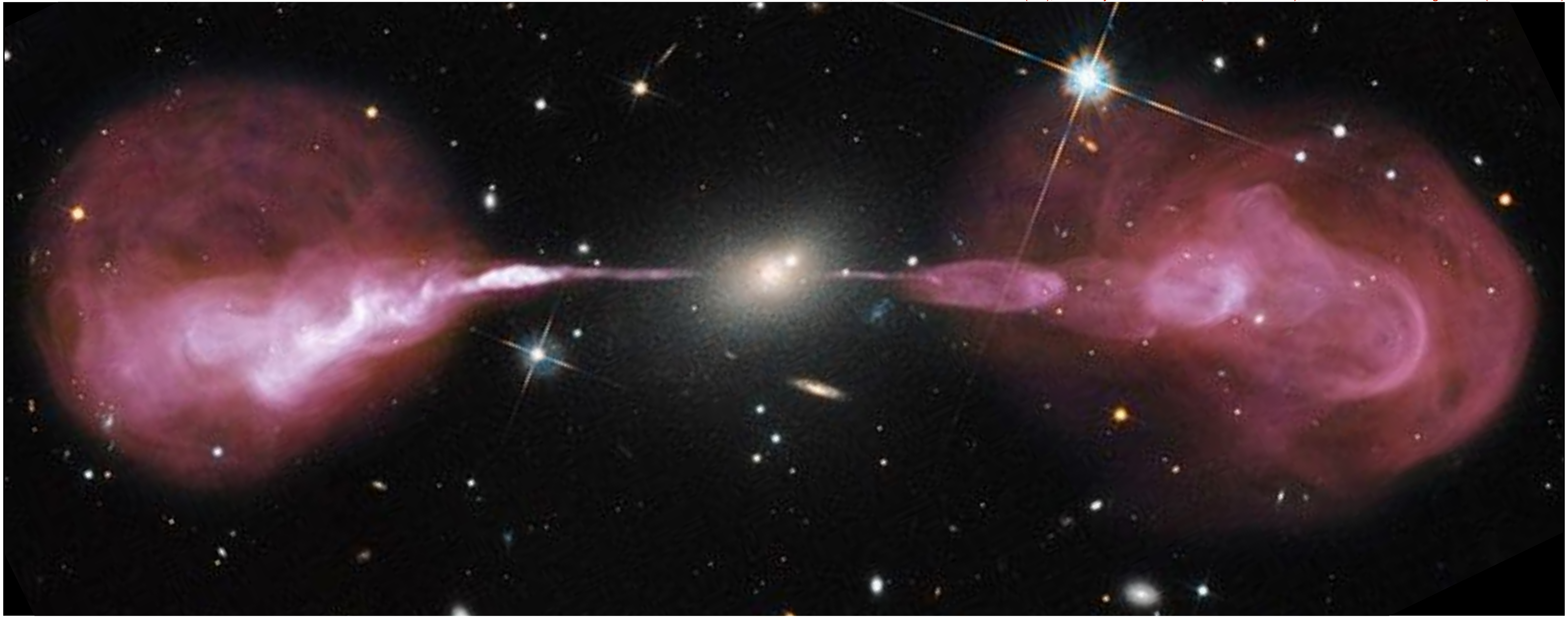
Hercules A - Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)



Self-calibration

European Radio Interferometry School 2022

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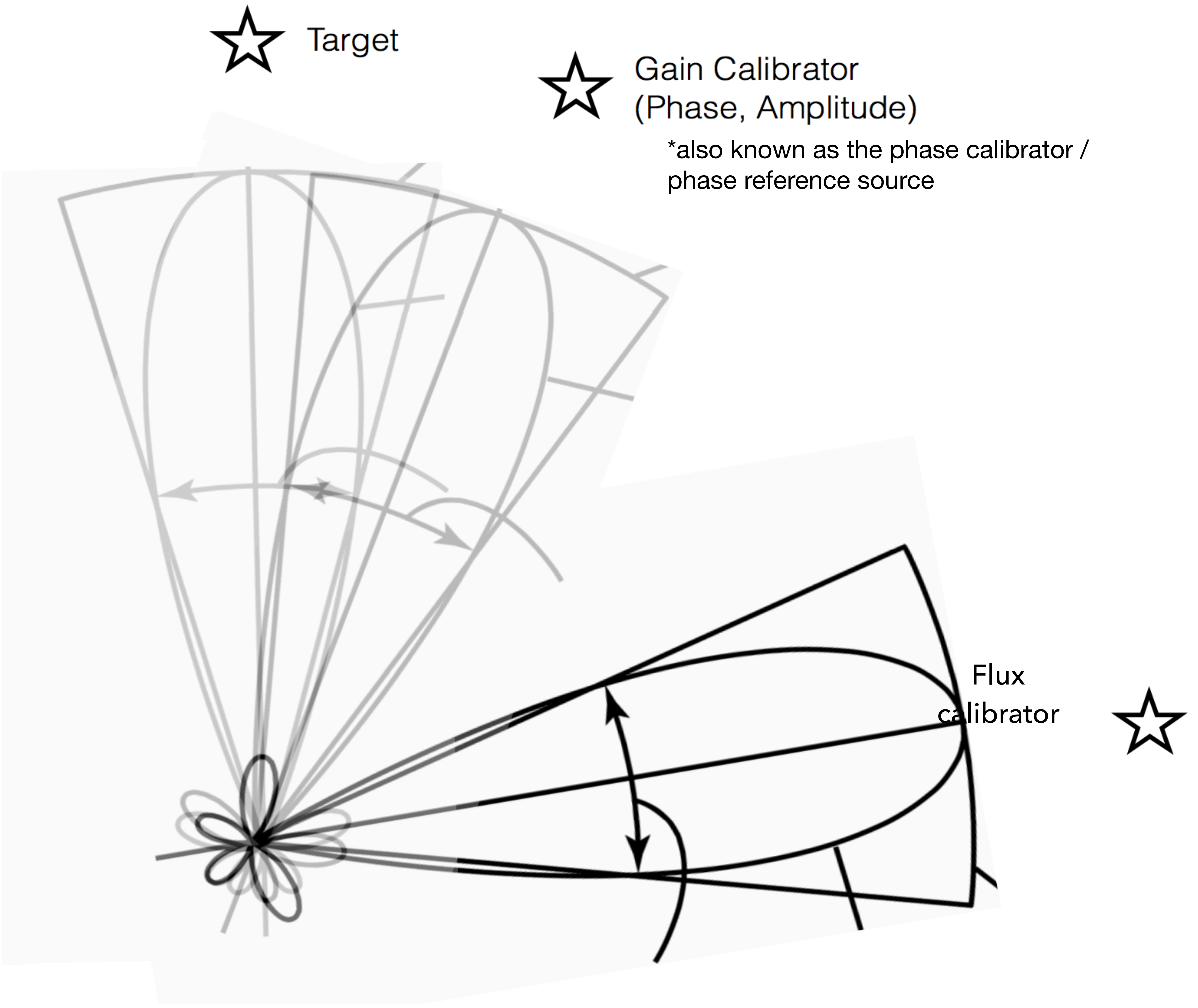
Outline

1. Recap of phase referencing
2. Self-calibration theory
3. Self-calibration in practice

Phase referencing

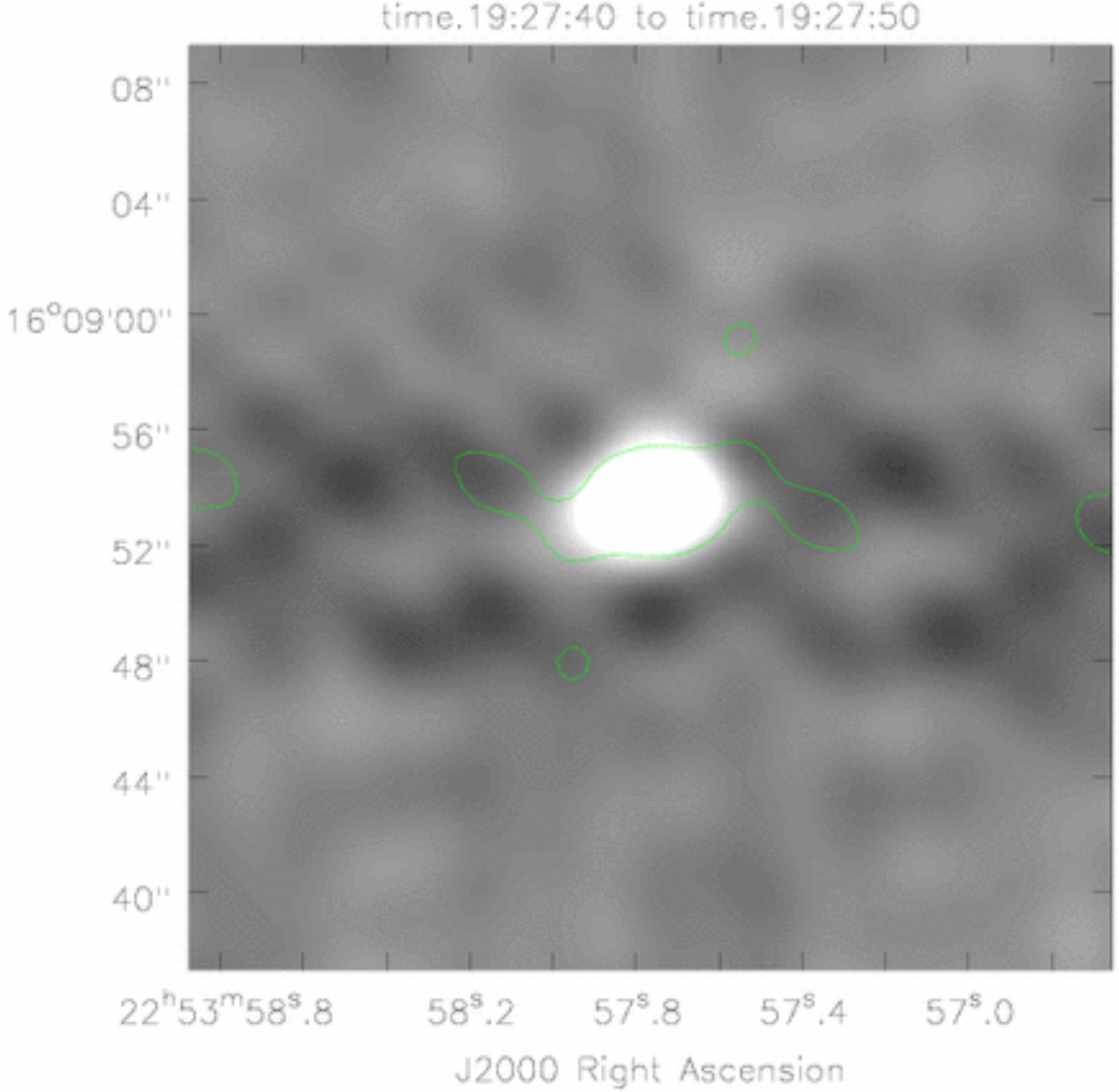
- Apply instrumental corrections
- Edit the data as required
- Apply bandpass, (polarisation) corrections
- Apply phase and (flux-scaled) amplitude corrections derived from phase reference
- Close enough to see similar atmosphere
- Nod on suitable timescale e.g. 10:2min
- Derive time-dependent corrections to make phase-ref visibilities match model
- Apply same corrections to target



The atmospheric contribution

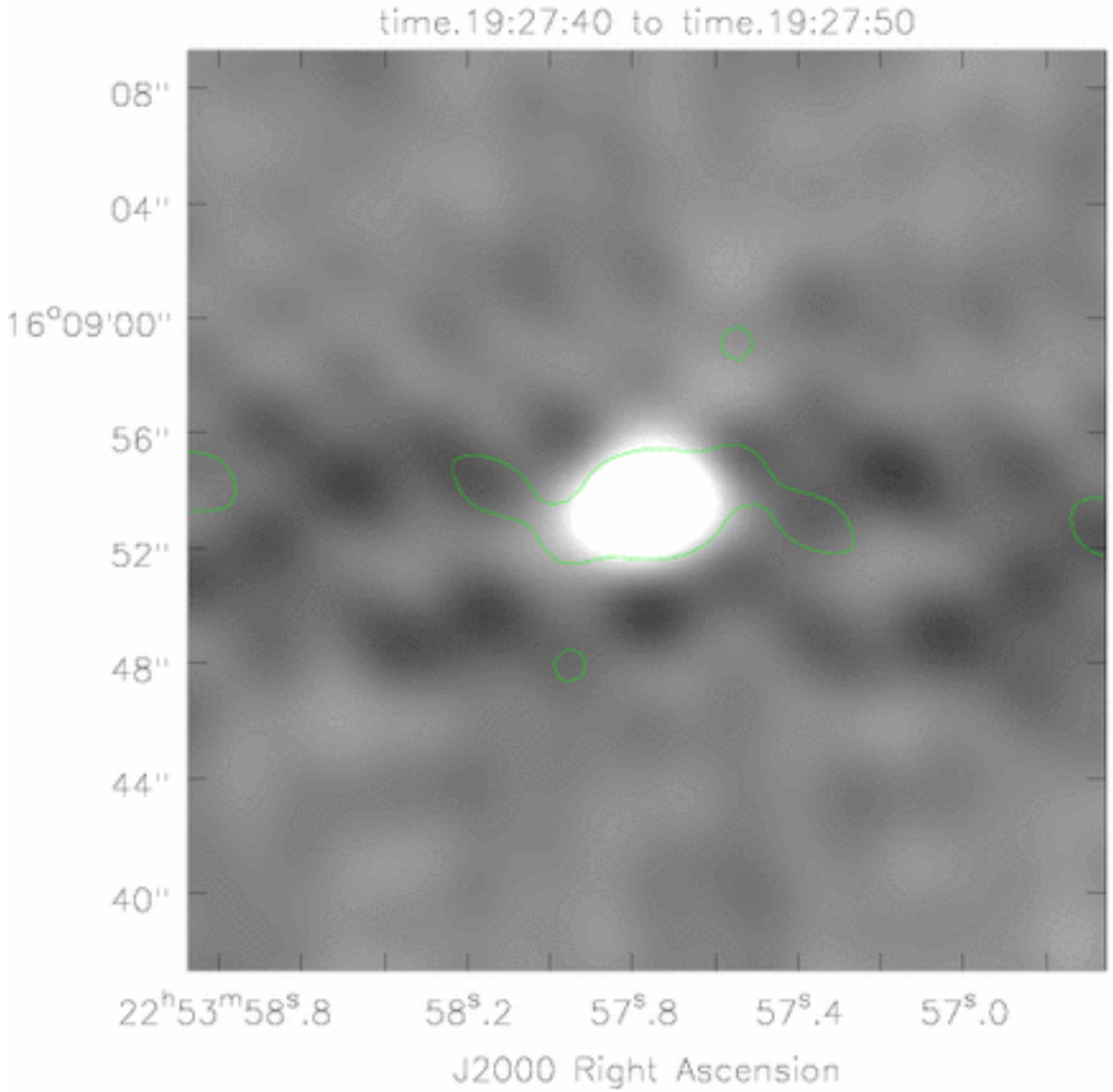
- The atmosphere is similar, not identical, above the target and above the phase-reference source.
- There are offsets in distance and in time.
- Neutral atmosphere contains water vapour
- Index of refraction differs from “dry” air
- Variety of moving spatial structures in the atmosphere.
- Typically worse for low frequencies $\sim 100\text{s MHz}$ (ionosphere) & high frequencies ≥ 20 GHz (water vapour)

Example 22GHz point source observed with the EVLA



The atmospheric contribution

Example 22GHz point source observed with the EVLA



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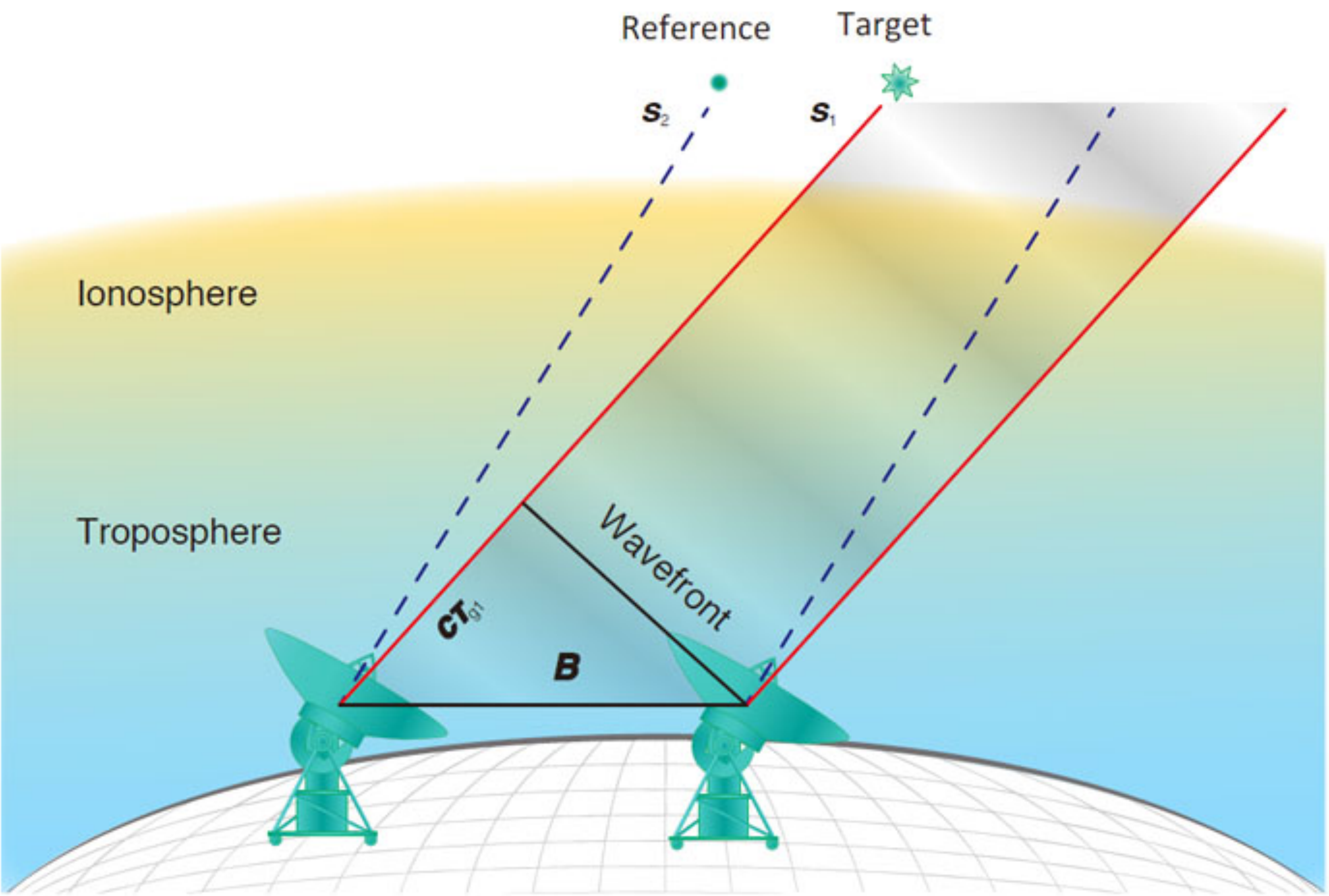
- Neutral atmosphere contains water vapour
- Index of refraction differs from "dry" air
- Variety of moving spatial structures in the atmosphere.
- Typically worse for low frequencies $\sim 100\mathrm{s~MHz}$ (ionosphere) & high frequencies $\geq 20\ \mathrm{GHz}$ (water vapour)

Self-calibration

- The process of self calibration is to primarily correct for complex gain variations between target and phase calibrator positions, typically induced by the atmosphere!
- Only useful for targets where the expected S/N is high - typically >20 for arrays with 6-10 elements or >100 for 20-50 elements
- If you don't expect high enough S/N to self-cal then the only way to improve the dynamic range would be by improving the calibration or removing bad data, reducing confusion etc etc.



Self-calibration - recap of the RIME

- Remember the radio measurement equation

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

  - $\mathsf{V}_{pq}^{\text{obs}}$ - visibility measured between antennas p and q
  - $\boldsymbol{G}_p\boldsymbol{D}_p\boldsymbol{E}_p$ etc. - Jones matrices representing corrupting phenomena along antenna p line of sight or at the antenna.
  - $\mathsf{V}_{pq}^{\text{true}}$ - ‘true visibility i.e. $\iint \mathsf{B}(l, m)\exp\{-2\pi i(ul + vm)\}\,\mathrm{d}l\mathrm{d}m$

This equation is represented in matrix form & the complex gain terms decomposed into Jones matrices which correspond to various sources of error.

Self-calibration

- For self-calibration, we assume that most other effects apart from residual complex gain errors are calibrated therefore we go from:

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

Self-calibration

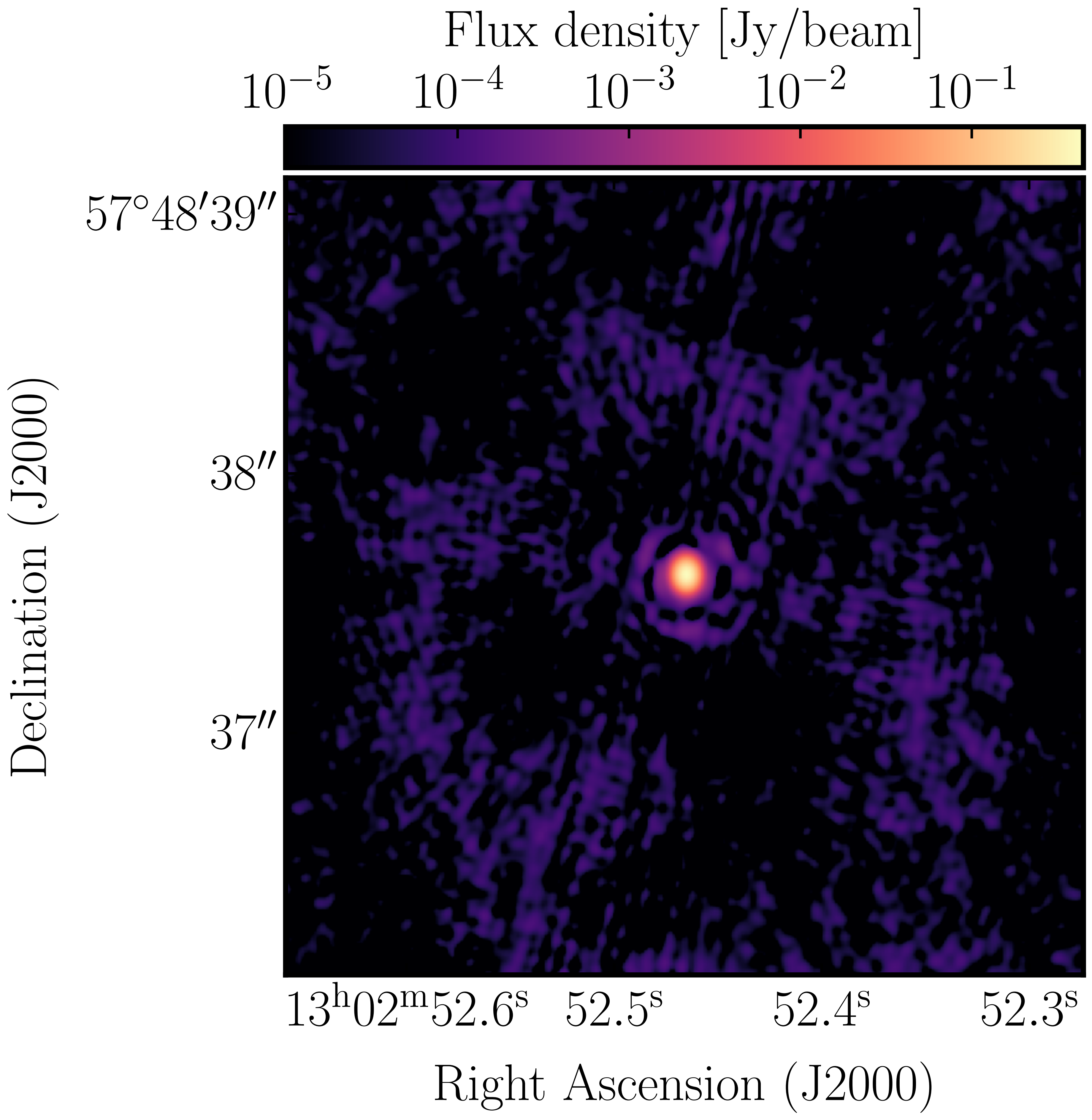
- To,

$$\mathsf{V}_{pq}^{\text{obs}} = \boldsymbol{G}_p \mathsf{V}_{pq}^{\text{true}} \boldsymbol{G}_q^H$$

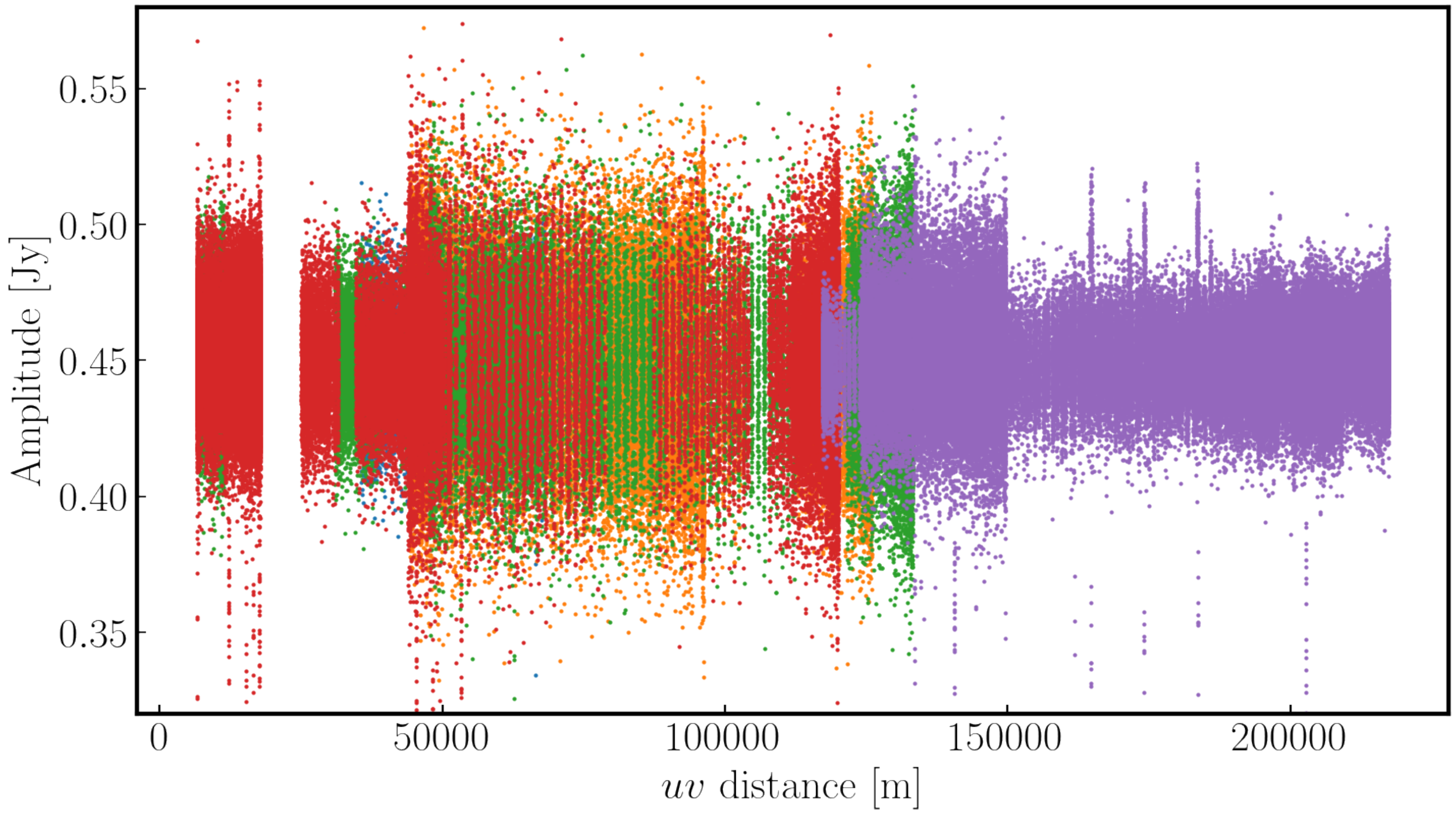
- And we assume that the complex gains are antenna-based (as with standard calibration)
  - Phases - atmosphere above telescope
  - Amplitudes - variable receiver gains etc.

Self-calibration

- Calibration methodology is same as standard calibration **BUT** rather than a point source model, we use a model of the target visibilities (through phase referencing) i.e.



Standard calibration - point source



Self-calibration

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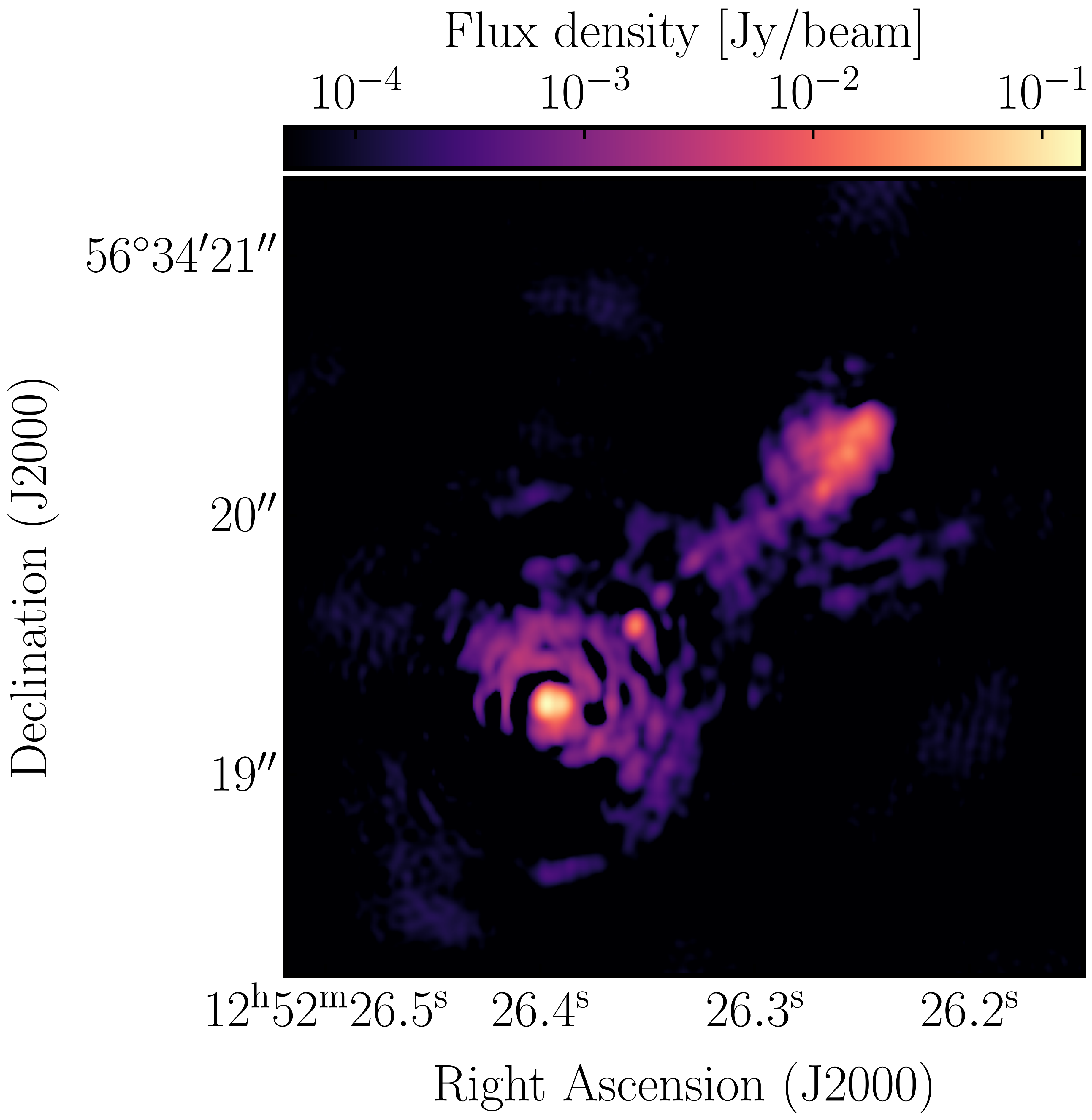
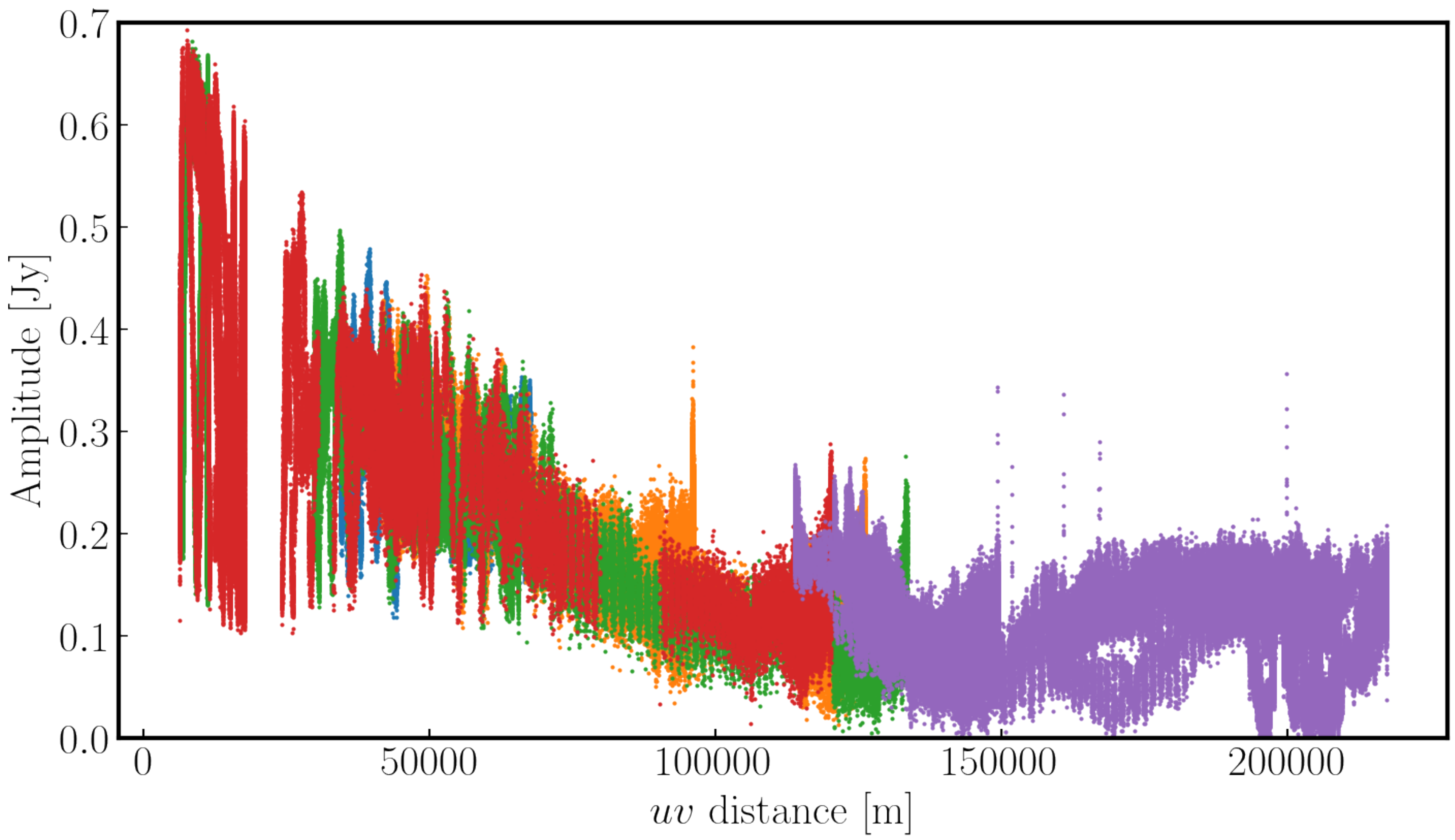
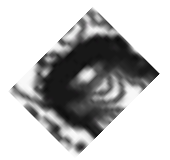


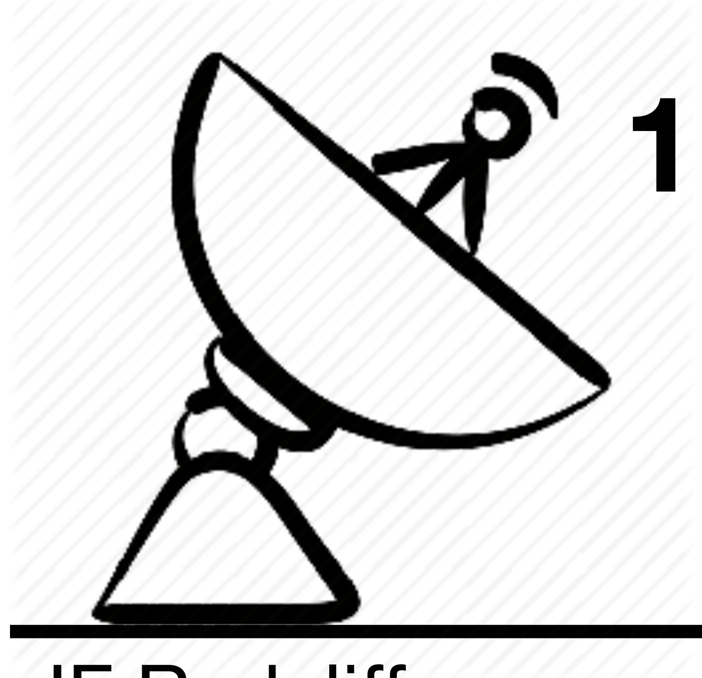
Self-calibration - resolved source



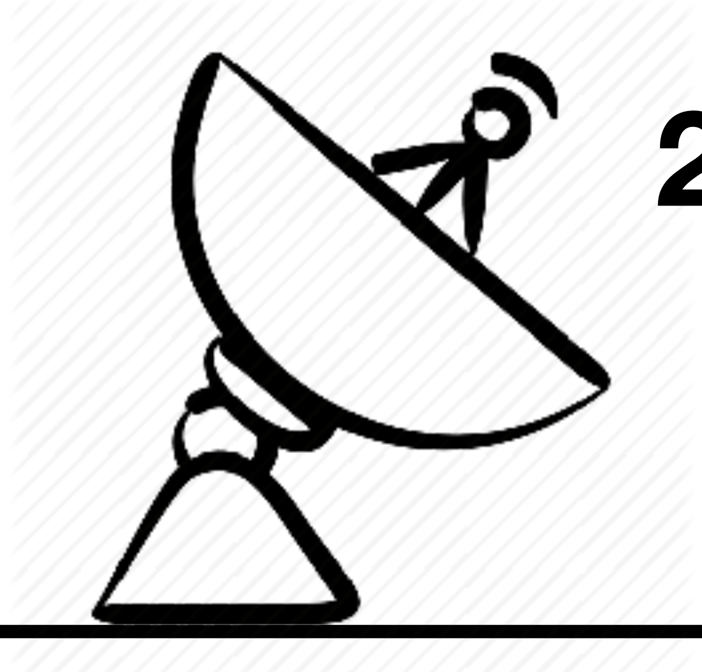
An analogy

An unresolved source

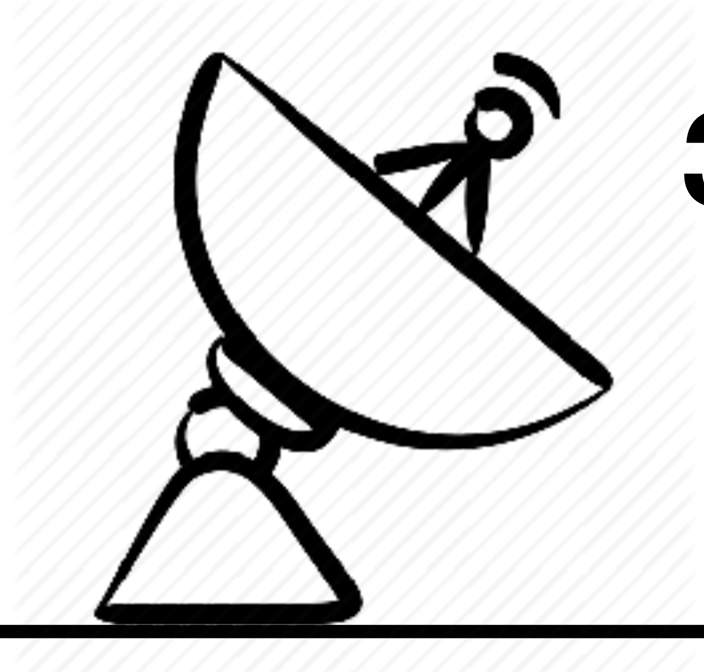




1



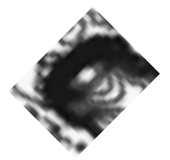
2



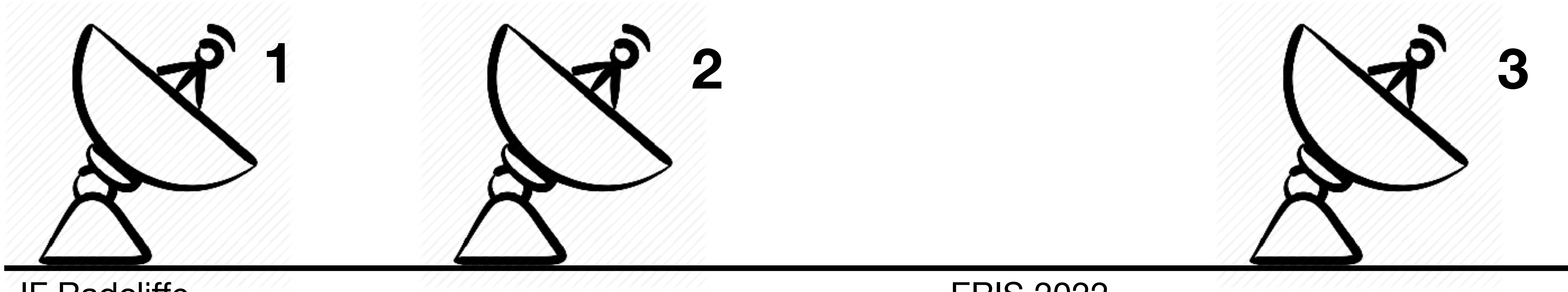
3

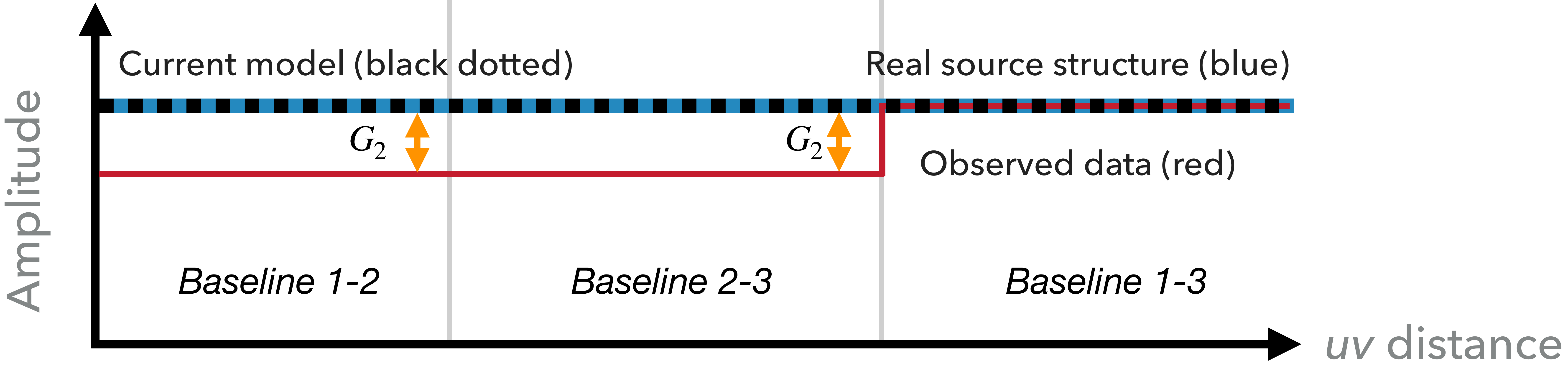
An analogy

An unresolved source

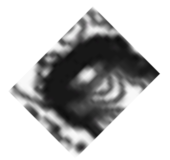


The cosmic cat changes your amplitudes on antenna 2!



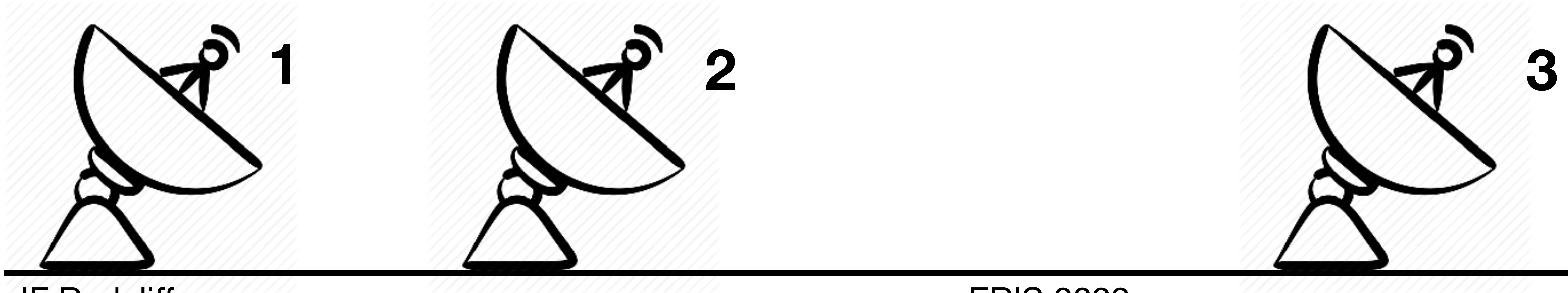


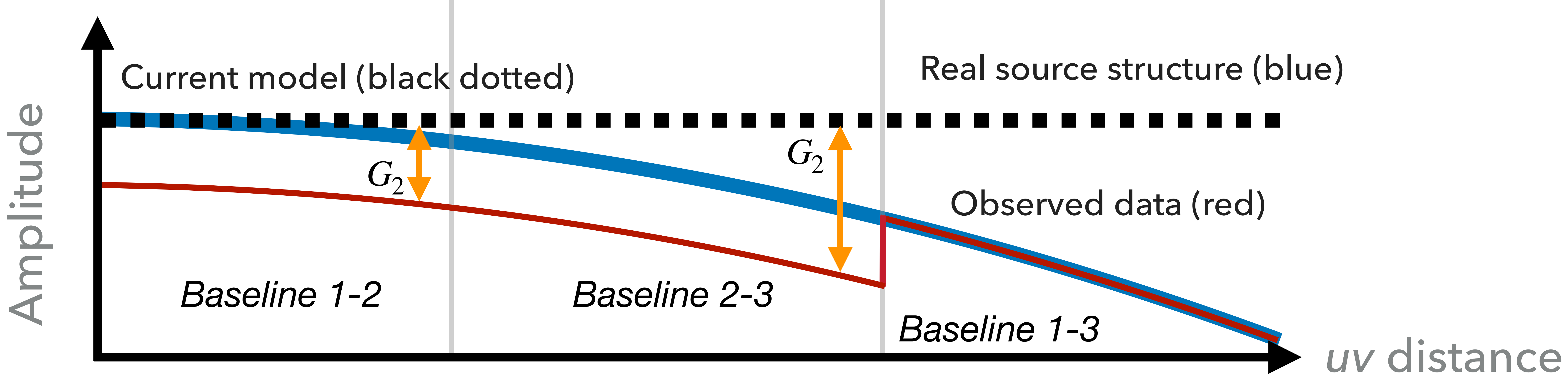
An unresolved 'point' source



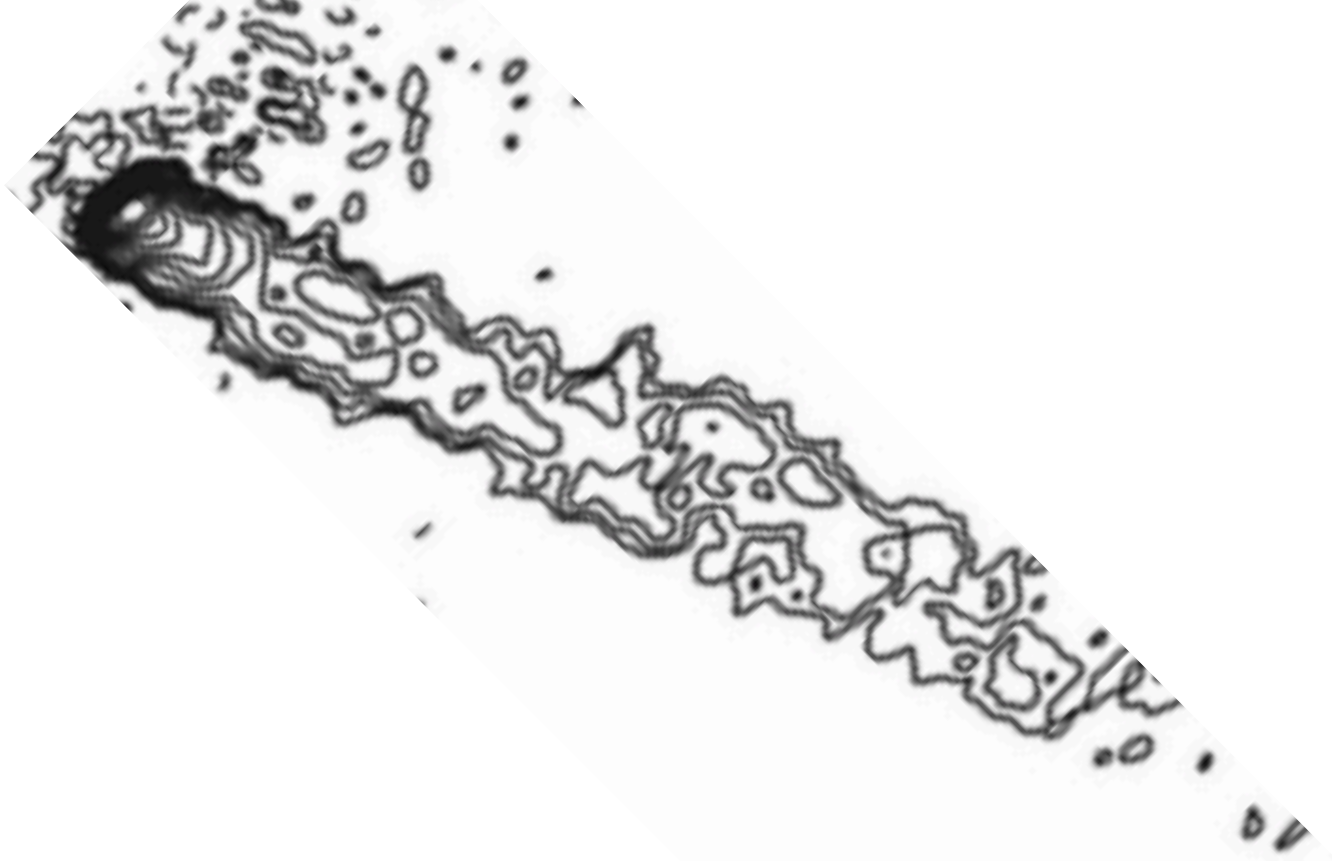
Cosmic cat affects all baselines to antenna 2

Consistent solution for each antenna so solutions **succeed** (ant 1 = 0, ant 2 = cat, ant 3 = 0)





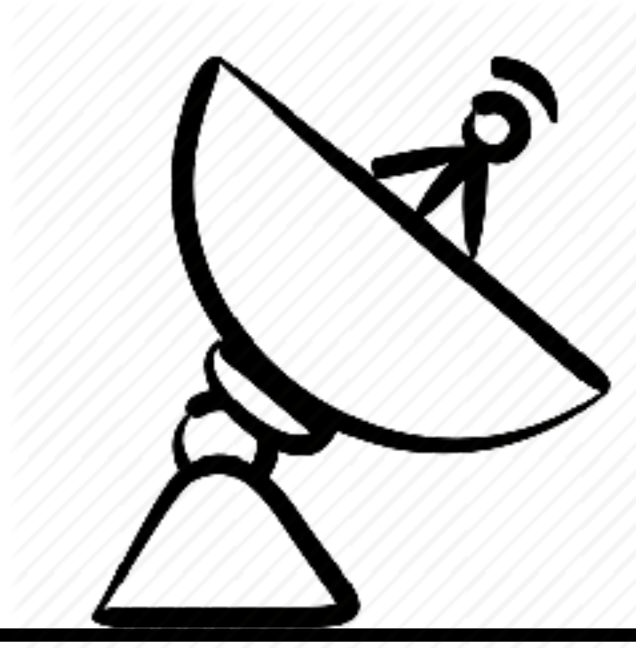
A resolved source!

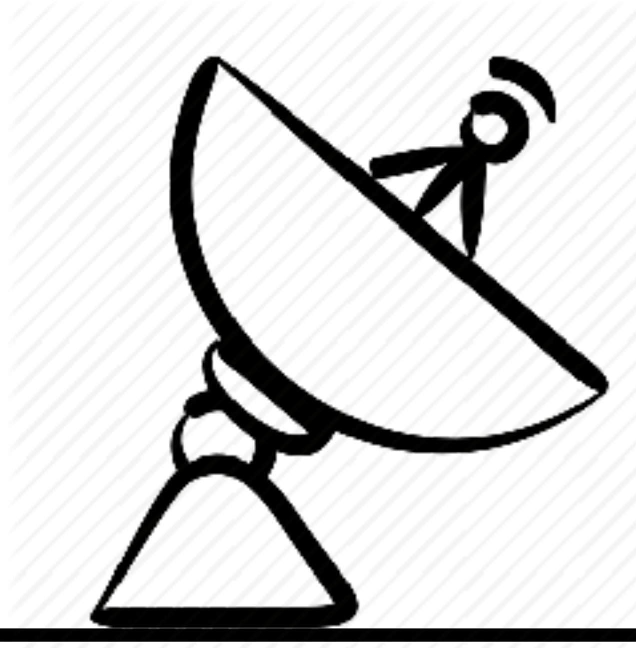


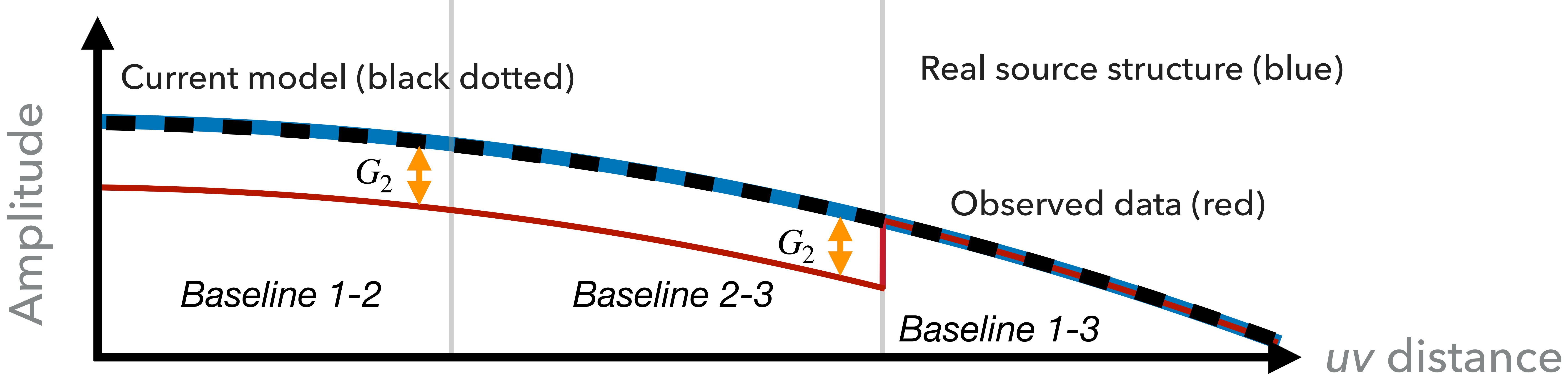
Cosmic cat affects all baselines to antenna 2

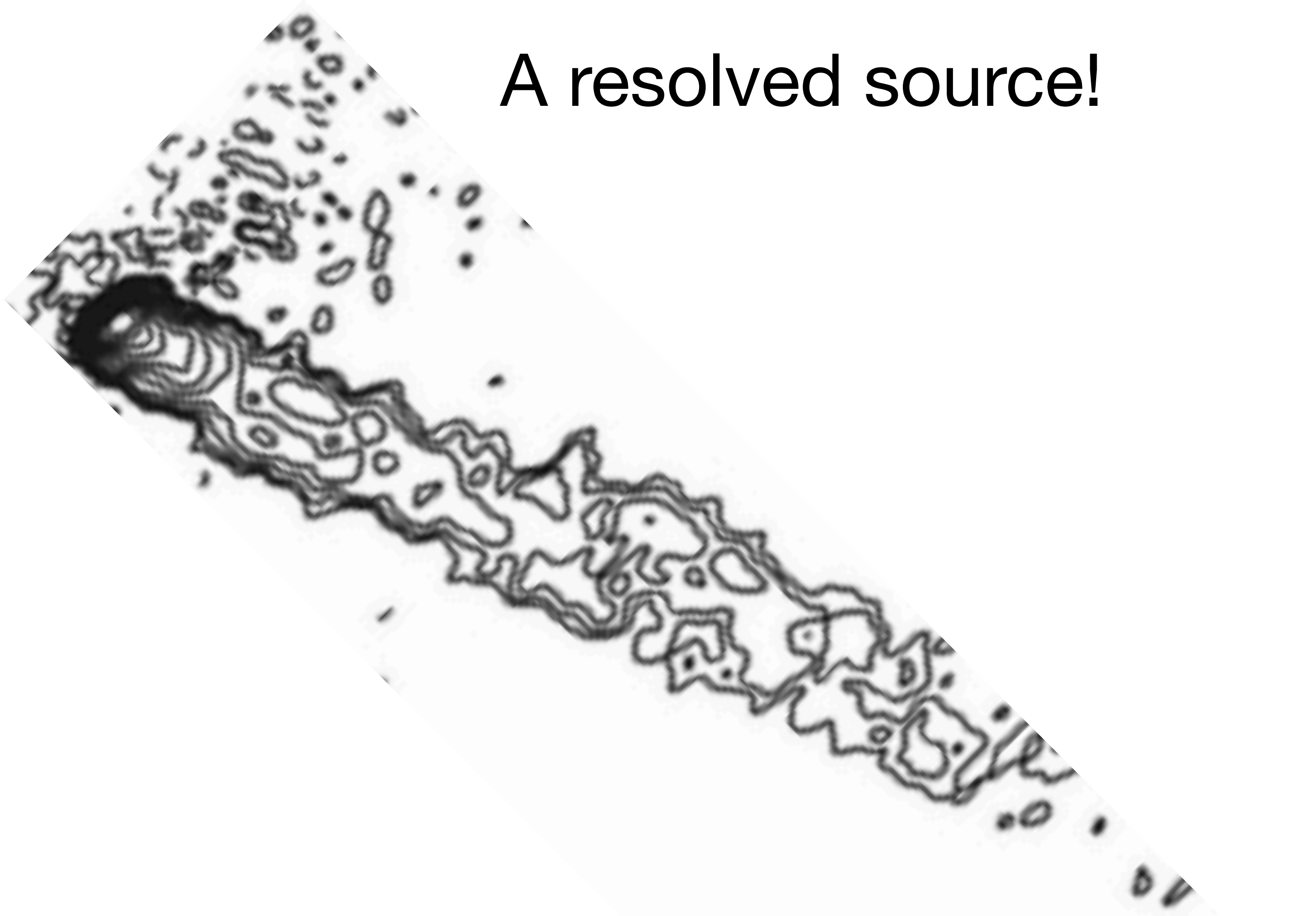
No consistent solution for each antenna so solutions **fail**


1


2


3





A resolved source!

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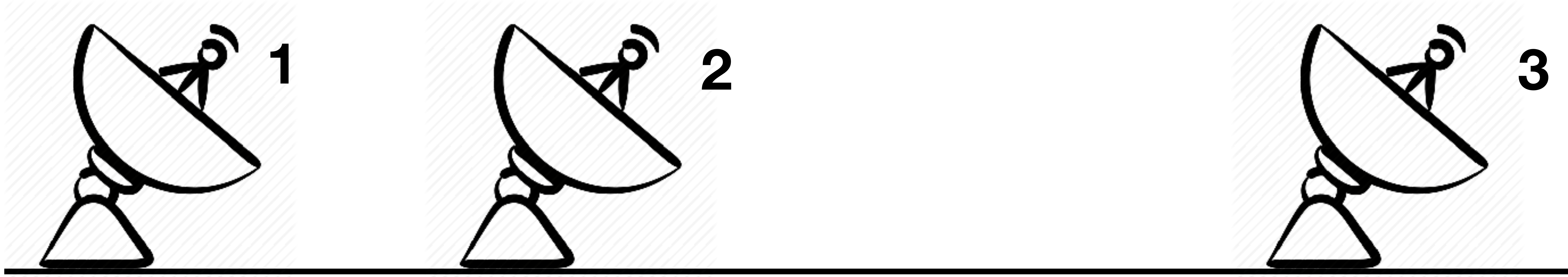
Consistent solution for each antenna so solutions **succeed** (ant 1 = 0, ant 2 = cat, ant 3 = 0)

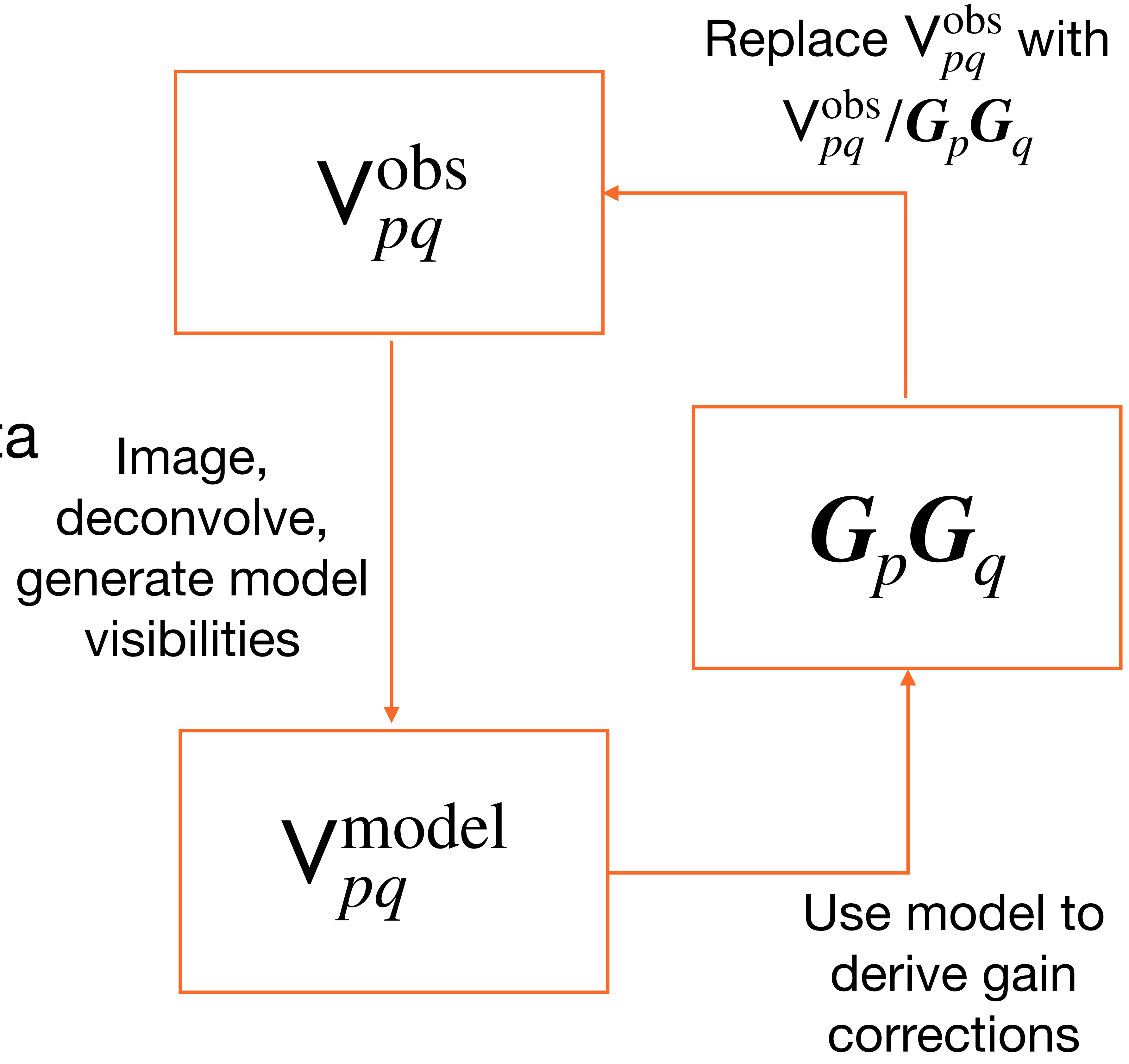


Self-calibration principles

- Use *target* visibilities and allow the antenna gains to be free parameters.
- If all baselines correlated, there are N complex gain errors corrupting the $N(N-1)/2$ complex visibility measurements for a given time & frequency.
- Therefore there are $(N(N-1)/2)-N$ complex numbers that can be used to constrain the true sky brightness distribution.
- Even after adding the degrees of freedom from the antenna gains, the estimation of an adequate model of the target brightness is still overdetermined - need a model to constrain!
- The improved model created from constraining these parameters can then be used to constrain the visibilities & remove residual phase & amp errors.

Self-calibration methodology

1. Create an initial source model, typically from an initial image (or else a point source)
   - Use full resolution information from the model image NOT the restored image (i.e., CLEAN + residuals)
2. Find antenna gains
   - Using “least squares” fit to visibility data
3. Apply gains to correct the observed data
4. Create new model visibilities (V_{pq}^{model}) from the corrected data
5. Go to (2), unless current model is satisfactory
   - shorter solution interval, different *uv* limits/weighting
   - phase → amplitude & phase



Self-calibration in practice

1. Apply phase referencing corrections
2. Image target
   - Model image generated when imaging (tclean *.model files)
3. Fourier Transform model into measurement set to create model visibilities (V_{pq}^{model})
   - Done automatically in tclean through parameter savemodel='modelcolumn'
4. *(optional)* Compare model with visibilities (using a plotting tool). Differences due to either/both:
   - Deficiencies in the model
   - Atmospheric or other errors affecting visibilities

Self-calibration in practice

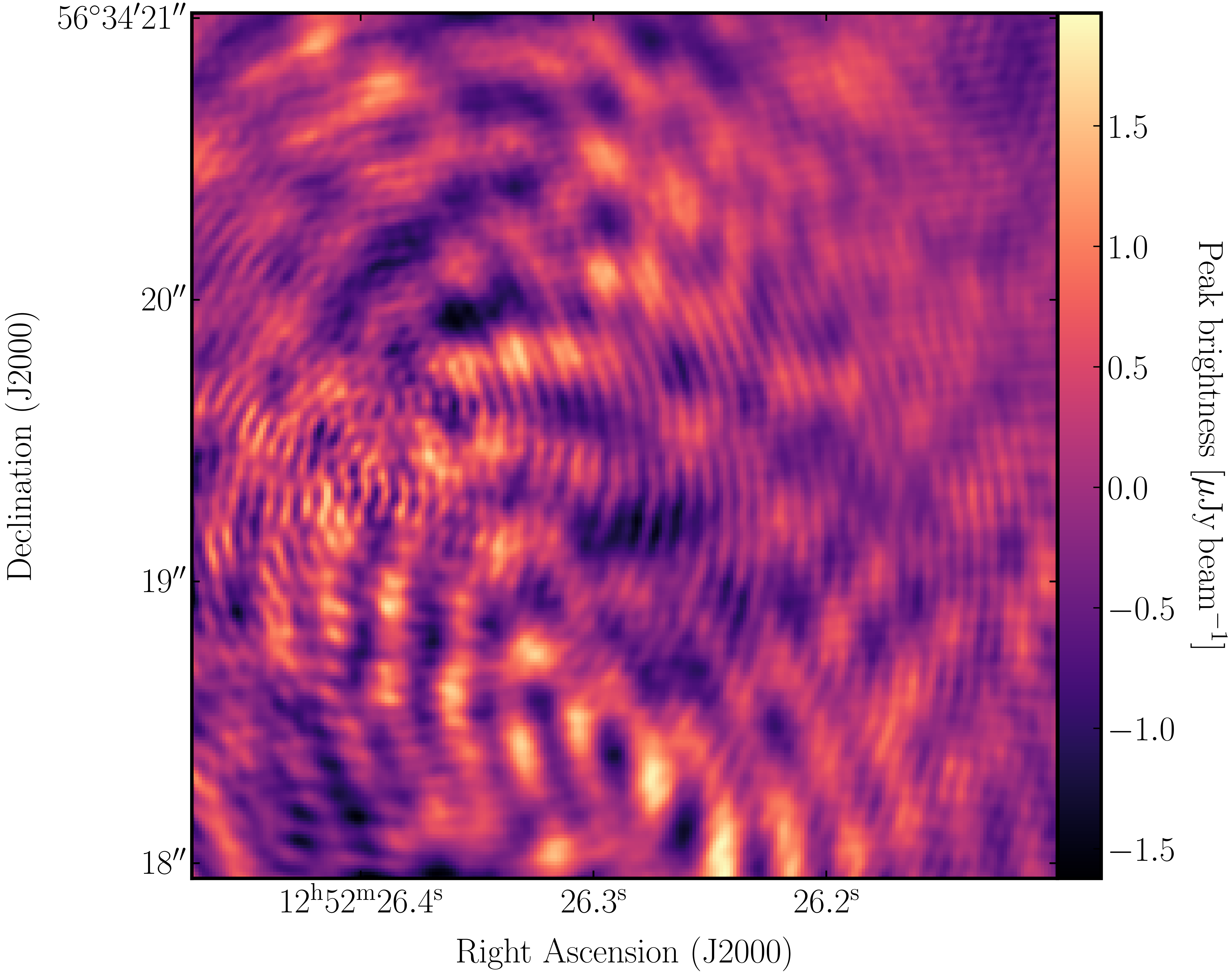
5. Estimate solution intervals for subsequent calibration
    - Use plotting tool (e.g., plotms) and average to see
6. Estimate corrections for phase visibility errors
    - Use task gaincal with calmode='p'.
6. Apply and make another image (with higher signal-to-noise)
    - This should provide an improved model
7. Repeat until phase corrections converge then do an amplitude & phase self calibration.
    - Use task gaincal with calmode='ap'.

Target without phase referencing

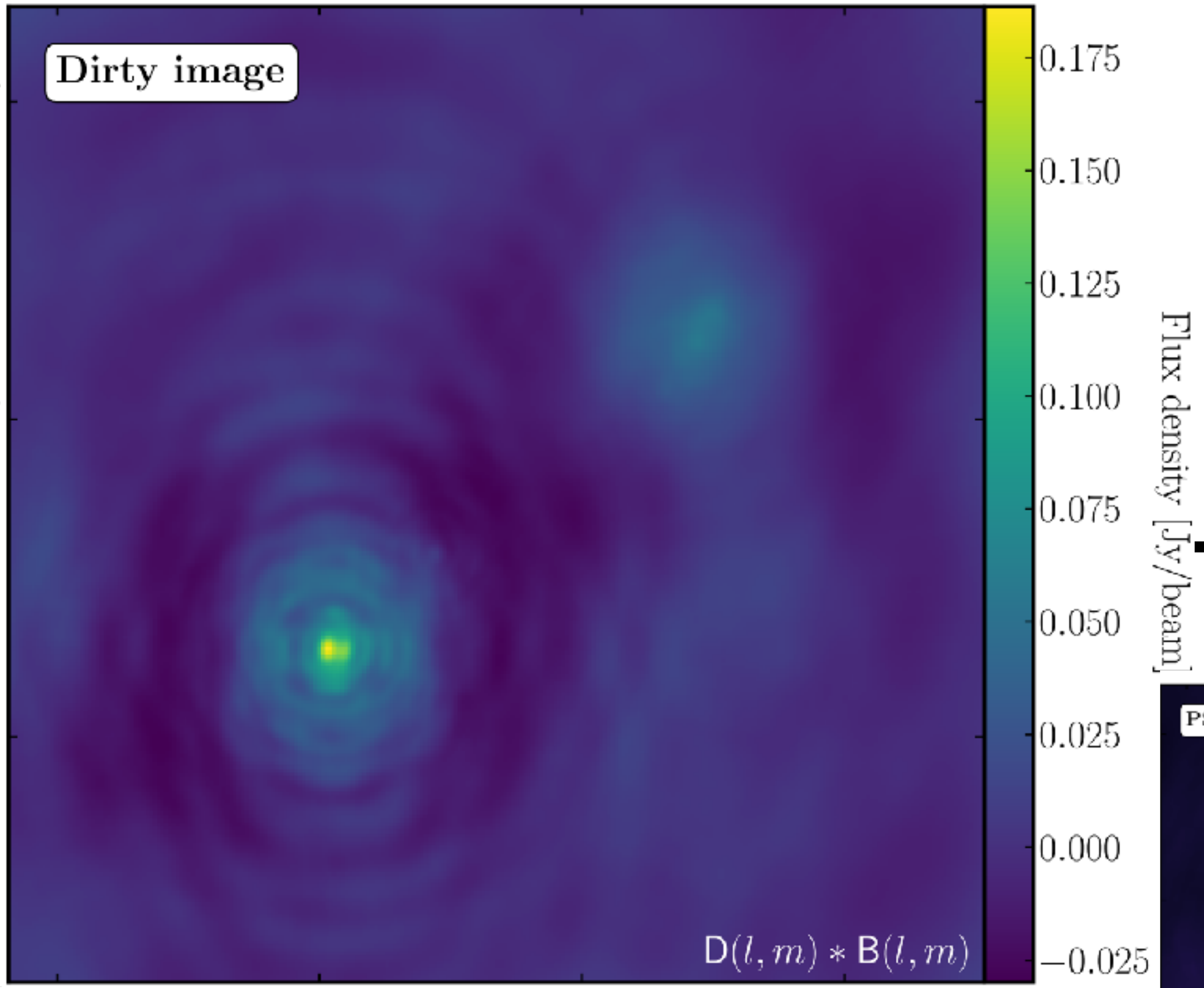
Dirty map

- Raw phase (not corrected)
- Holes and smearing
- No peaks

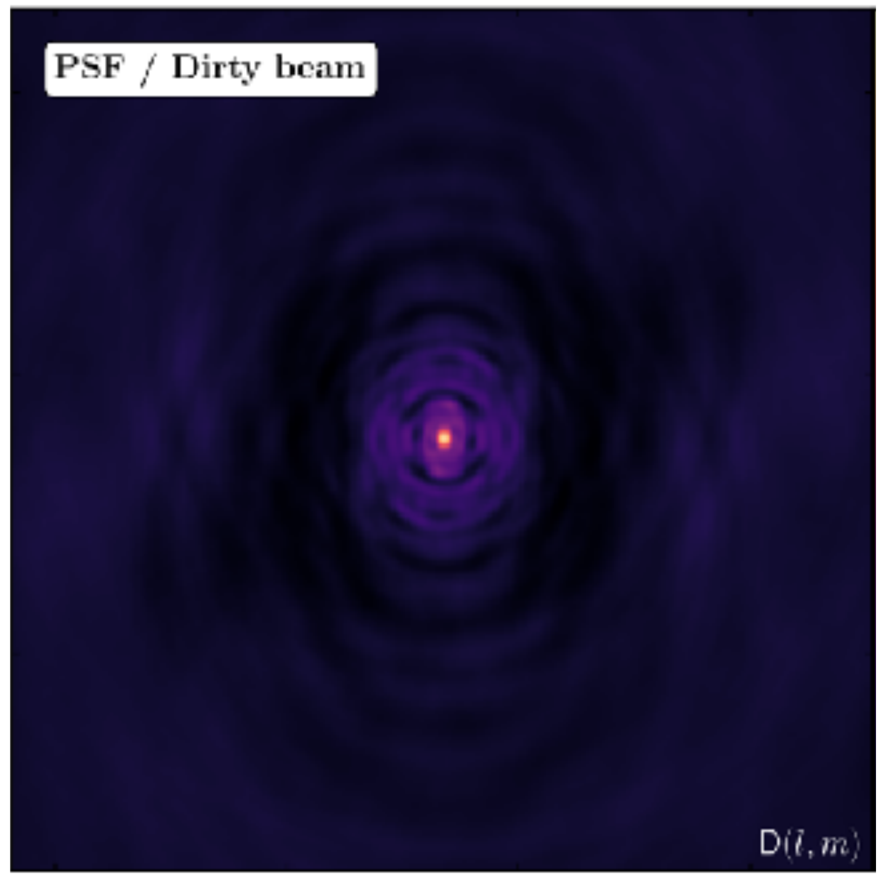
Apply phase referencing corrections to visibilities and Fourier Transform to image plane to get….

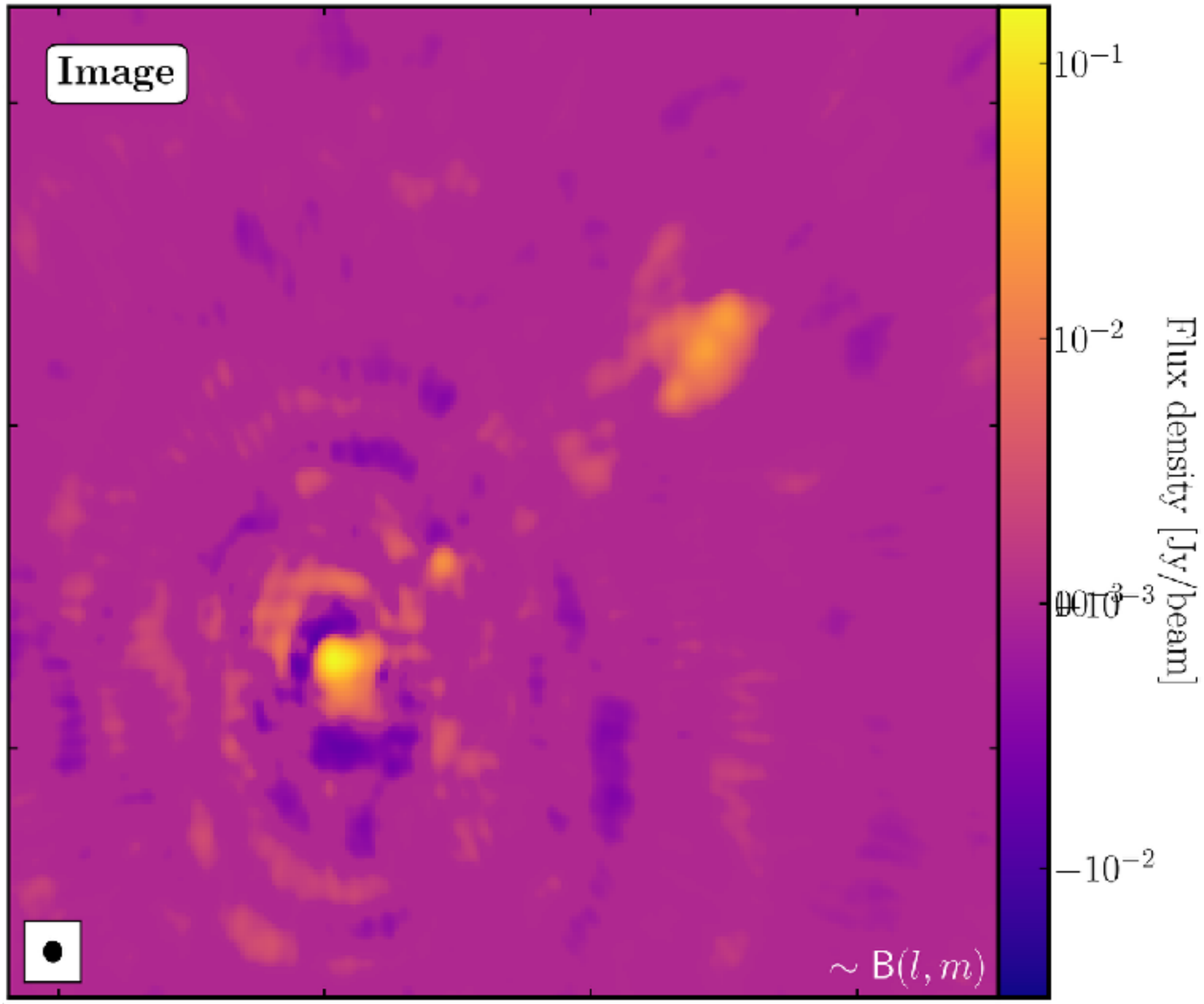


Phase-referenced target image



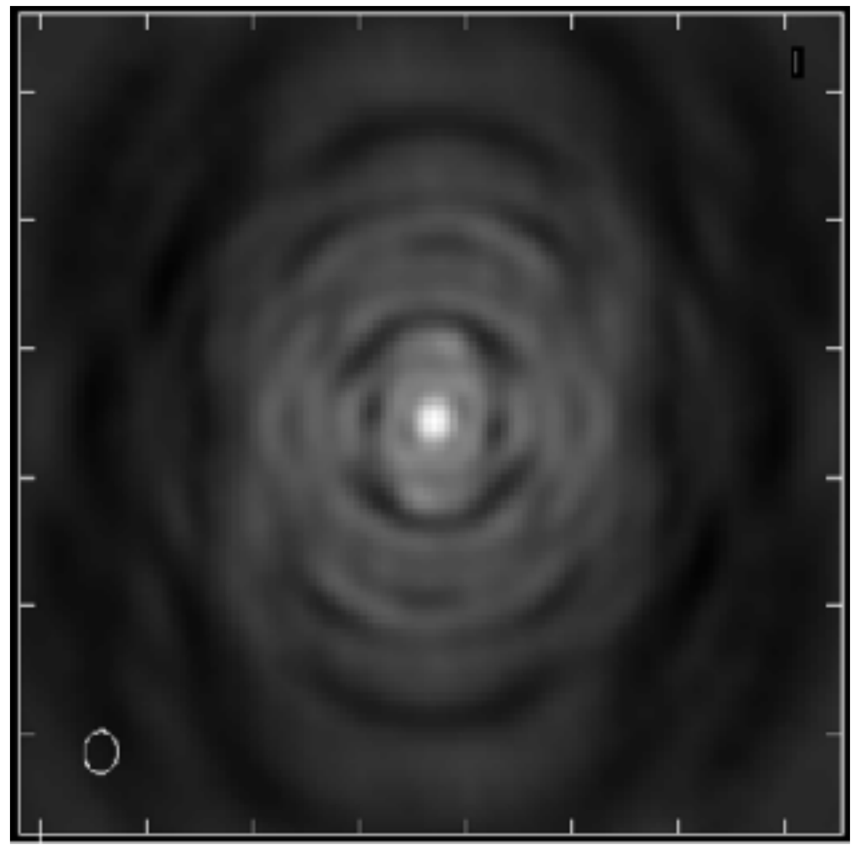
Deconvolve iteratively

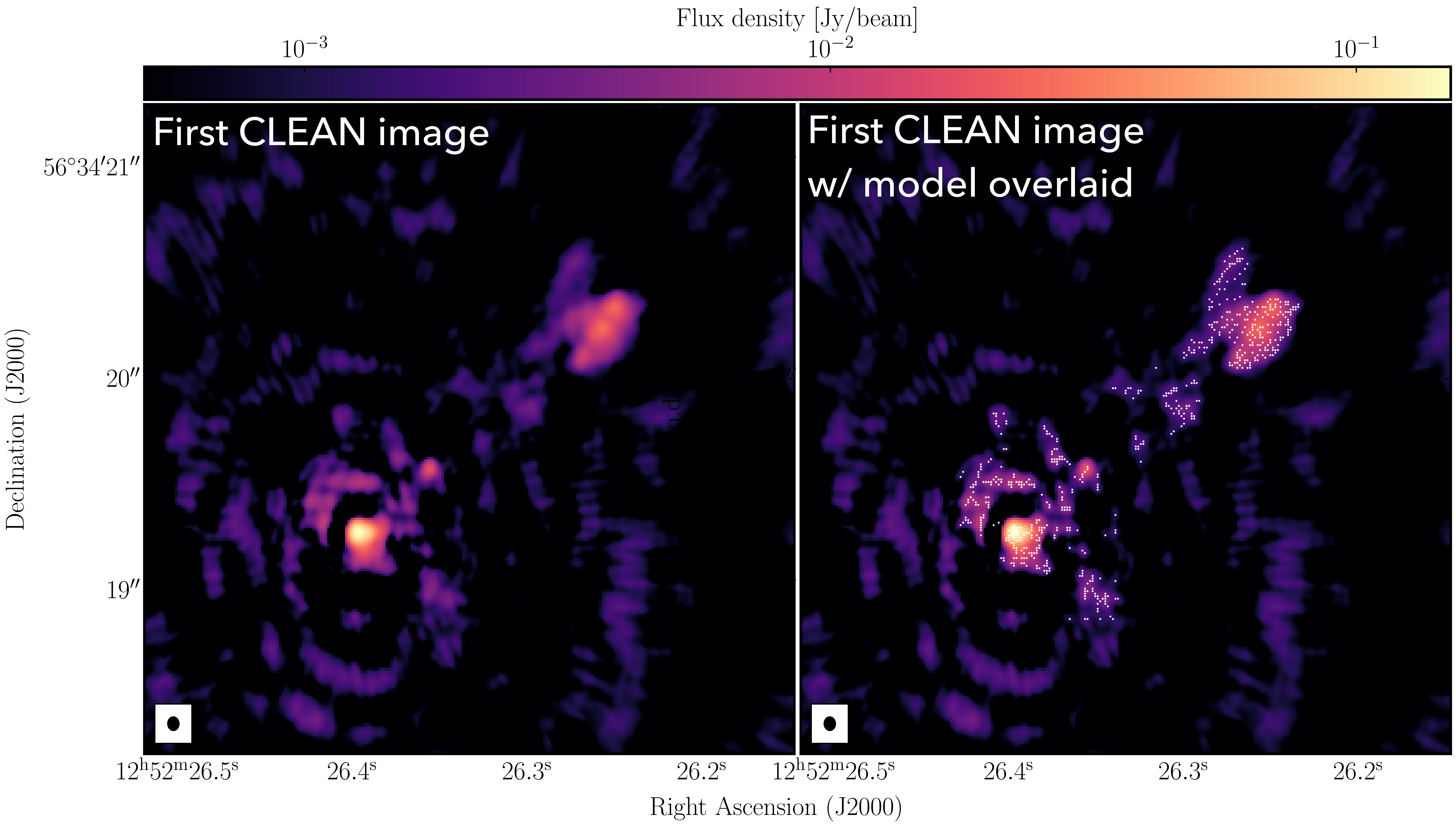




Model generation

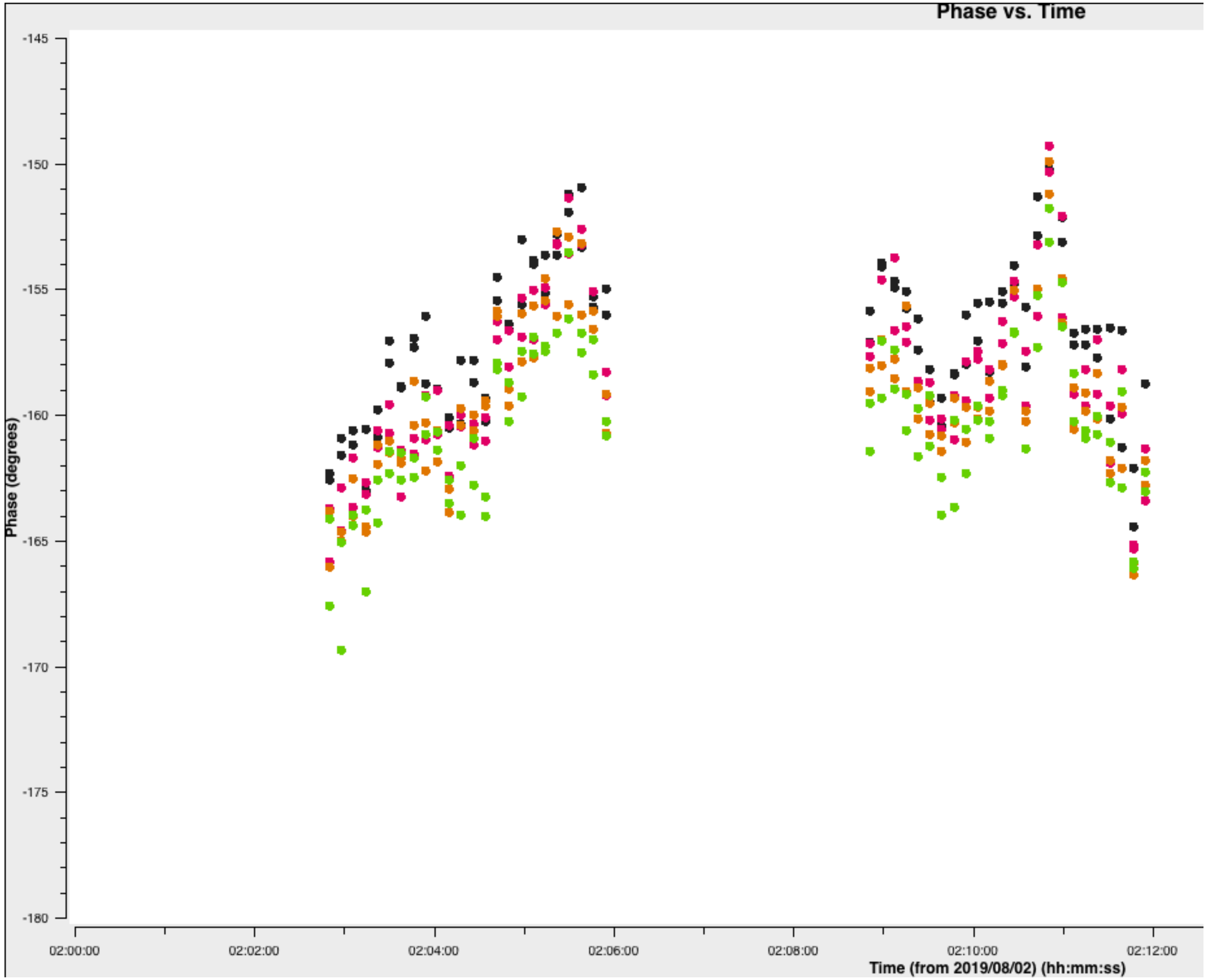
- FT of CLEAN components / model image will be used as model
- Plot PSF to help avoid cleaning sidelobes





Determining a solution interval

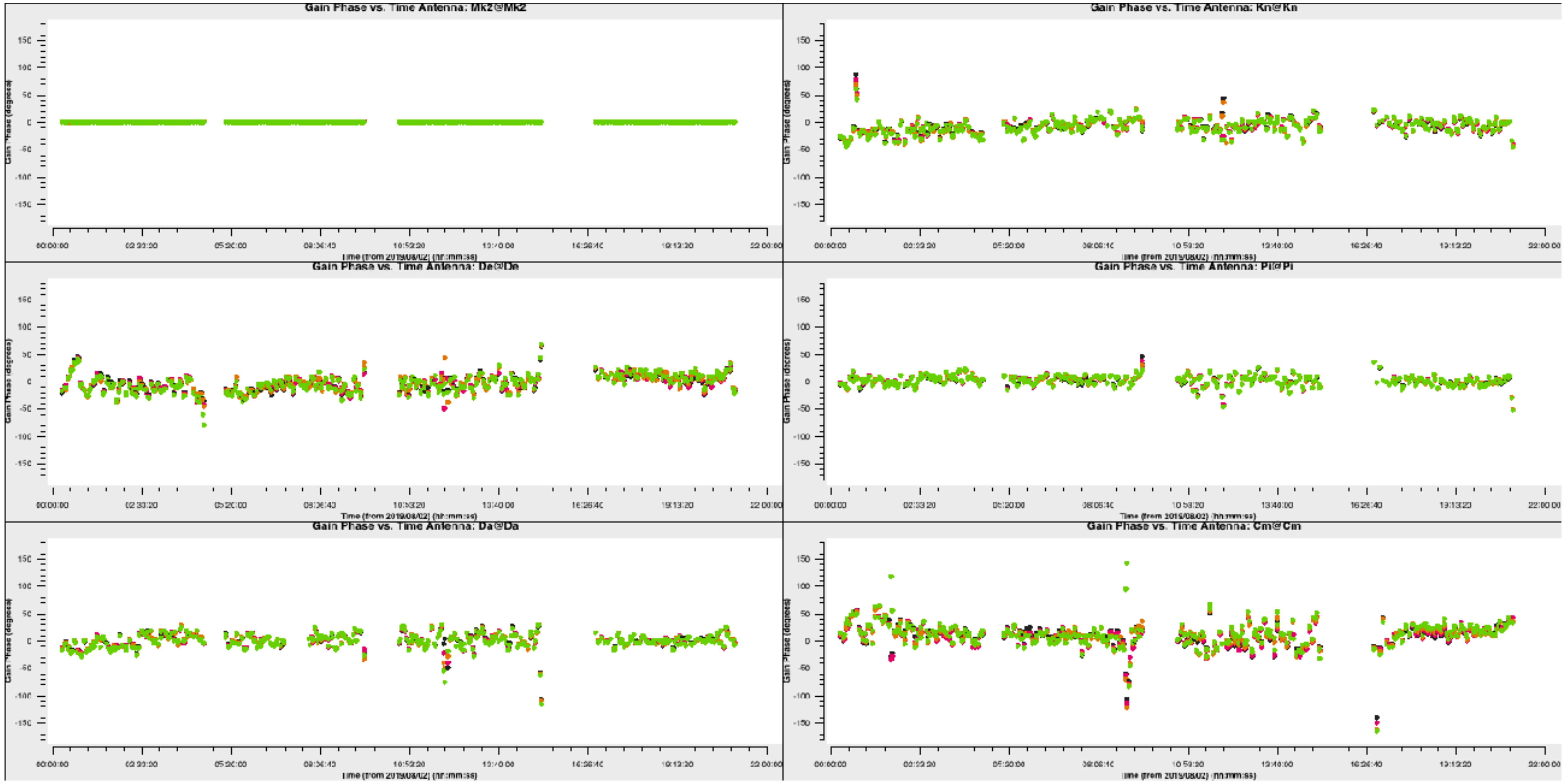
- Look at a few scans
- Note different timescales - thermal noise ~integration to integration and atmosphere ~30-60s
- Experiment with averaging to establish trade-off between thermal noise and atmospheric fluctuations
- Chosen solution interval should also ideally fit an integral number of times into each scan.
- Good idea not to use too short a solution interval for the first model. This is because the model may not be very accurate, so you don't want to constrain the solutions too tightly.



Phase self-calibration

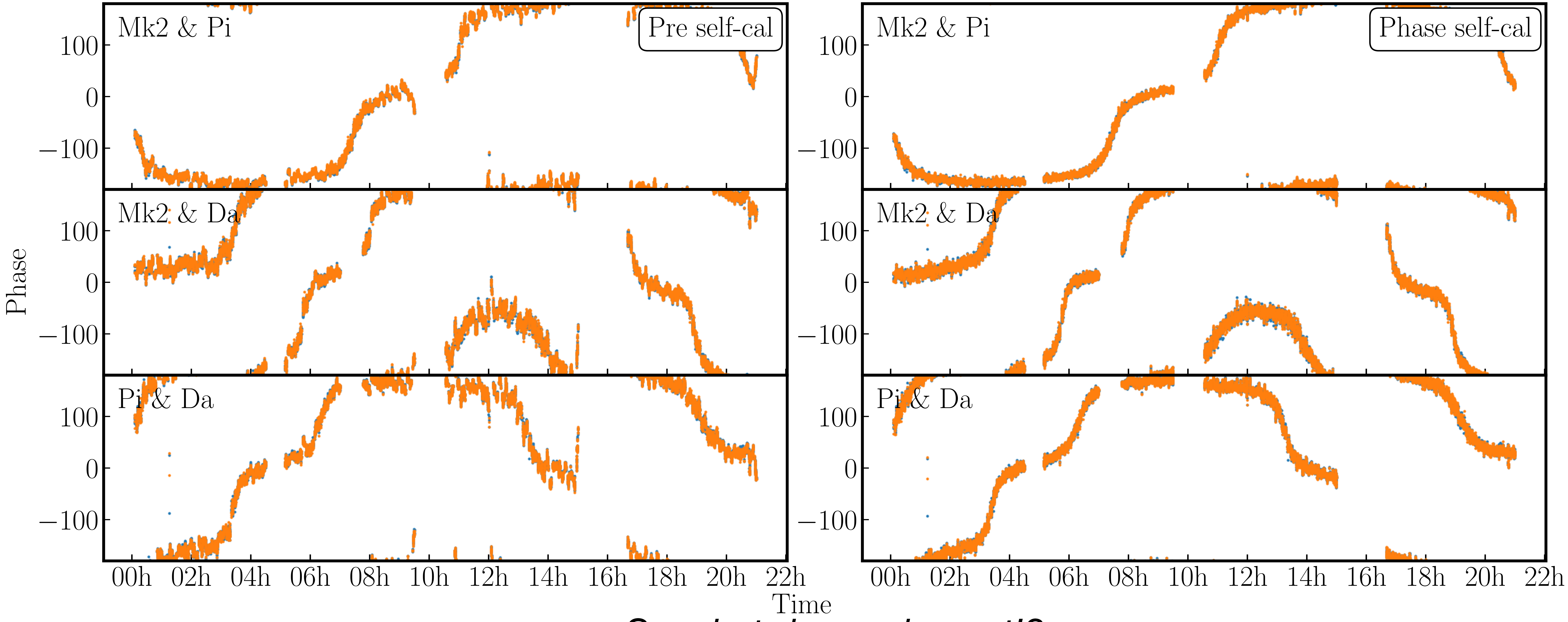
- FT of model image are stored (‘model' column in CASA tclean).
- Obtain phase solutions contained in a calibration file - (**gaincal** in CASA compares model with target visibility data)

Phase solutions



Phase self-calibration

- Apply calibration file (containing self-cal solutions) to the observed visibilities (CASA task **applycal)**
- Much improved and smoother target phases - reduced scatter!



So what do we do next!?

Iterative self-calibration

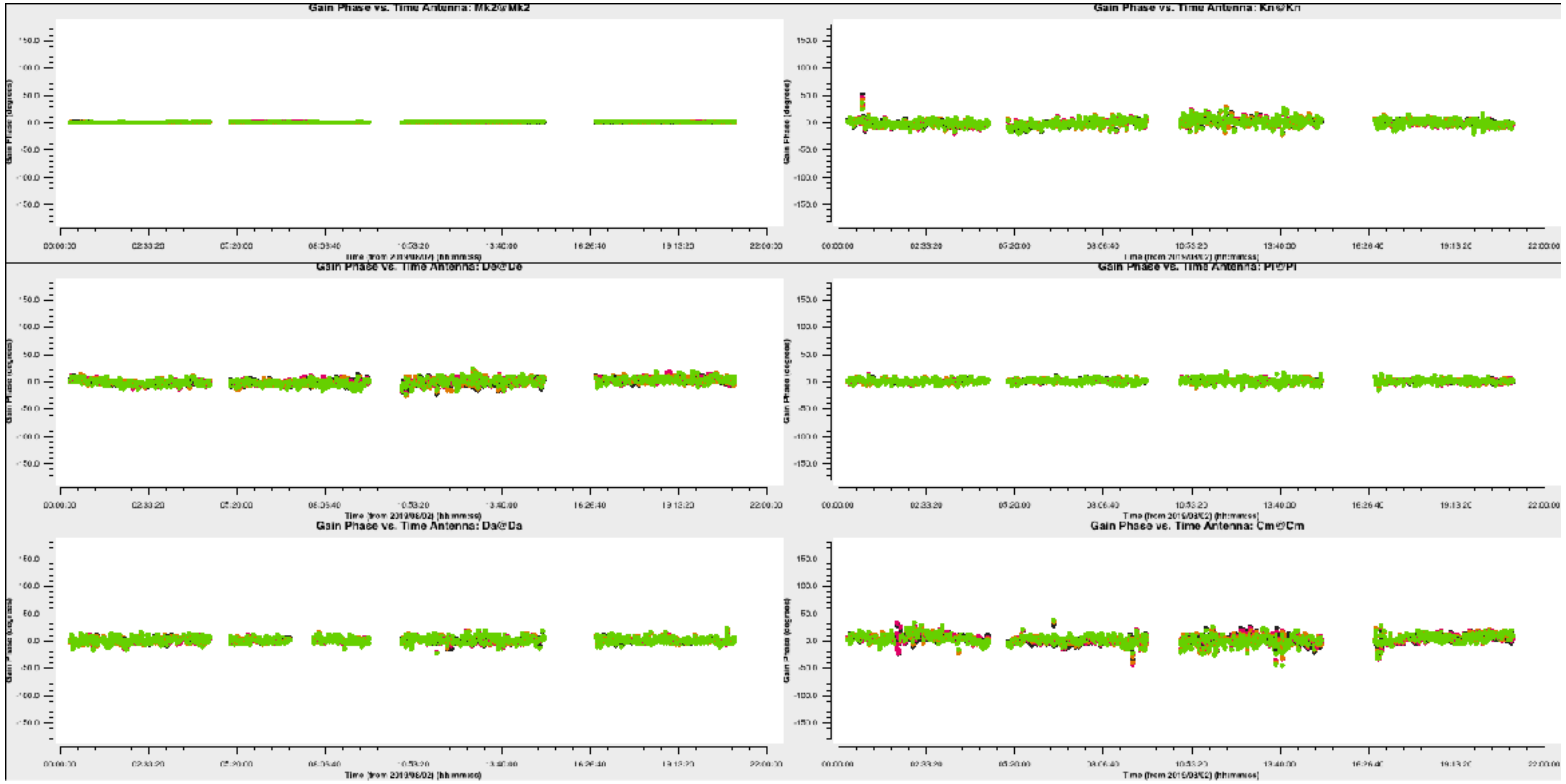
- Solutions have been applied so we image again!

  Note that in CASA:

  - The old model column is overwritten!
  - Use task ft (with previous model image) if you want to go back to a previous CLEAN model.

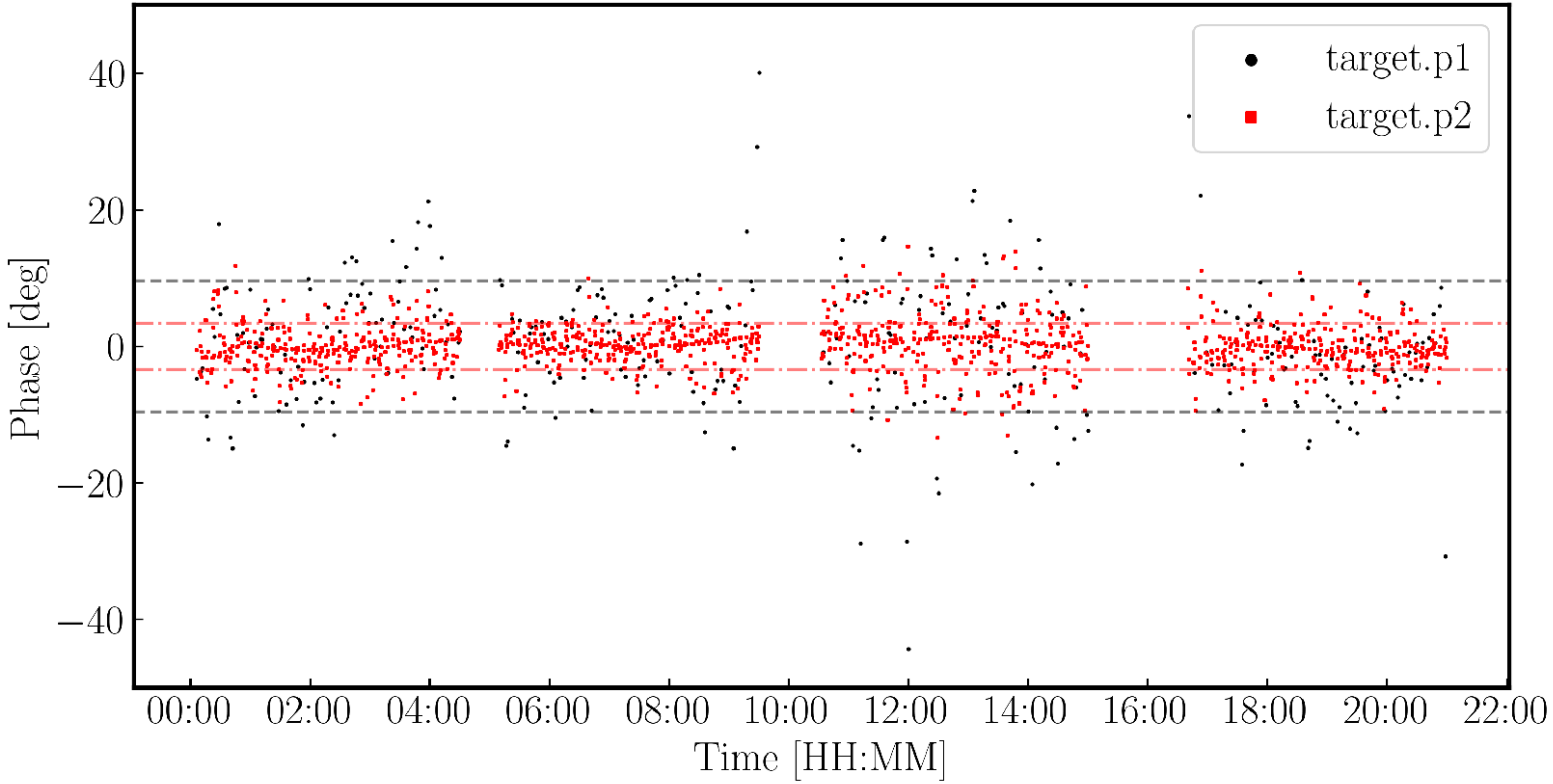
- Repeat this process until residual phase solutions converge on zero.

Second phase self-calibration solutions



We expect small residual phase solutions from next gaincal

Comparing subsequent solution tables



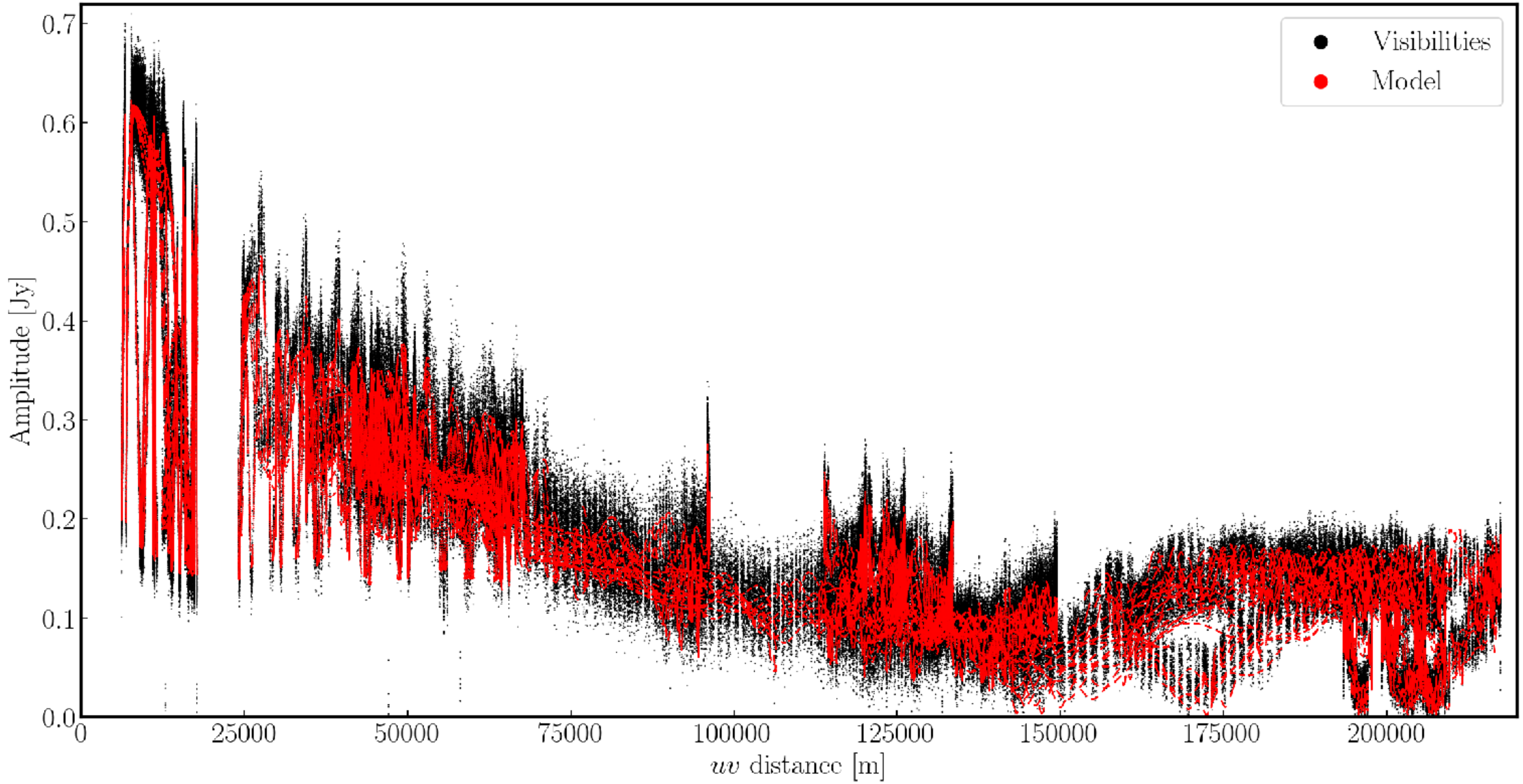
Iterative self-calibration

- A good iterative self-cal cycle to follow is outlined below. The phase calibration increases the model S/N enough for amp cal in future iterations.
- You should aim to change parameters e.g. solution interval at each round to generate the improvements
- In CASA, you should apply your previous self-cal solutions when deriving new calibration tables

First image
↓
Self-cal phases
↓
Shallow deconvolution
(to avoid CLEAN bias)
↓
Self-cal. phase
↓
Deep CLEAN
↓
Self-cal. amplitude + phase
(amp. solutions should be near 1!)
↓
Deep CLEAN

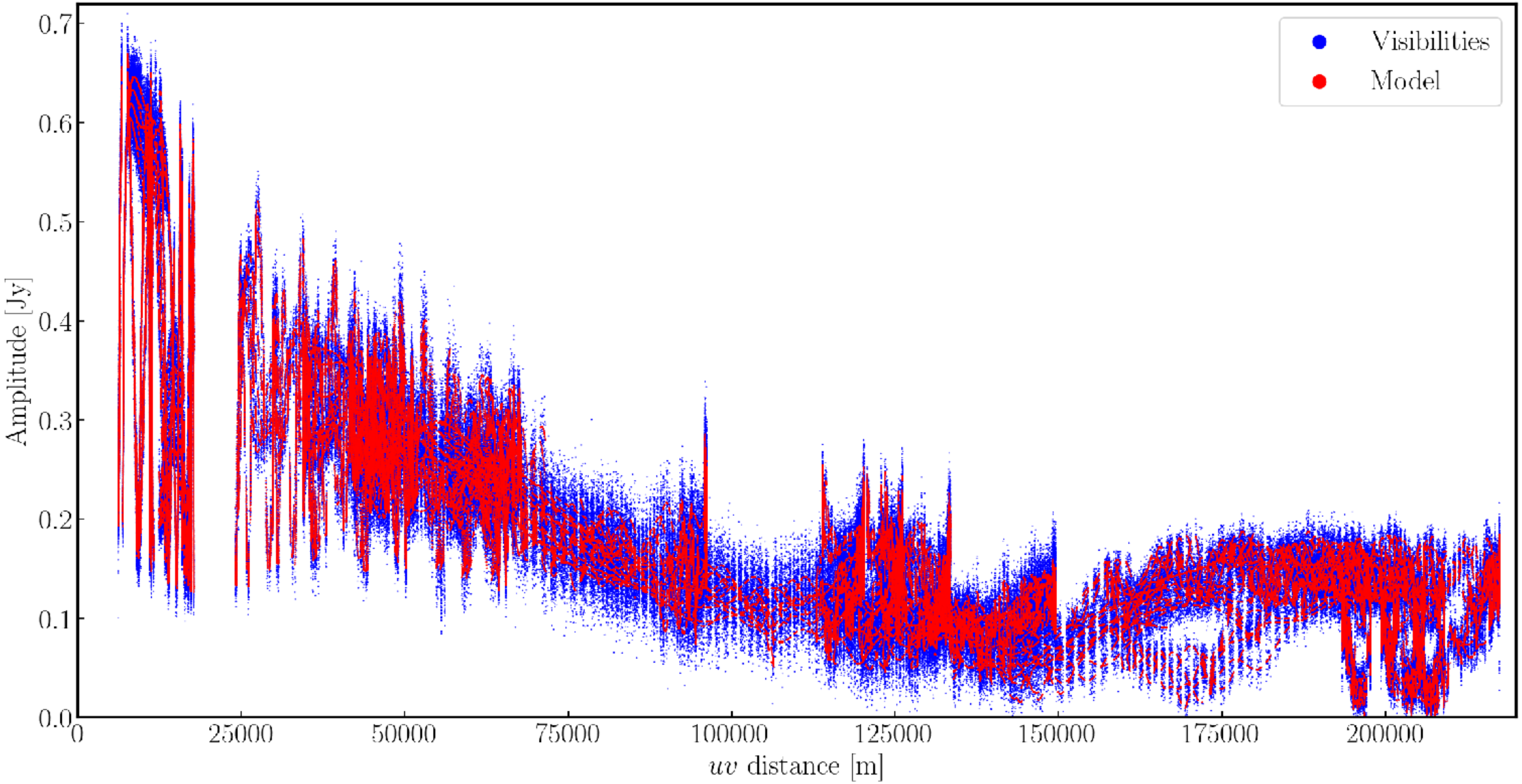
Self-calibration improvements

- And your visibilities change from this… (phase referencing only)



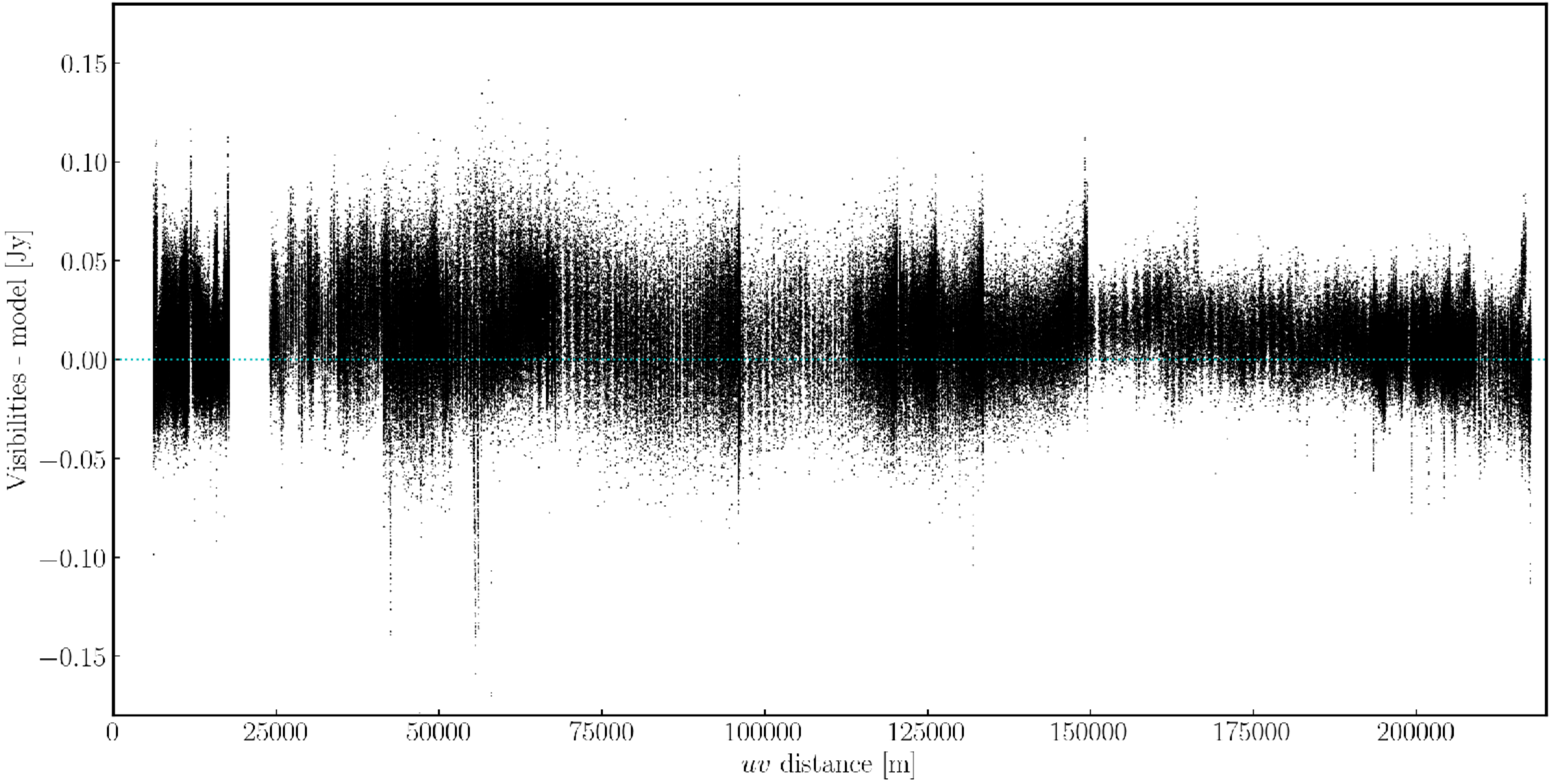
Self-calibration improvements

- To this… (phase referencing + self calibration)



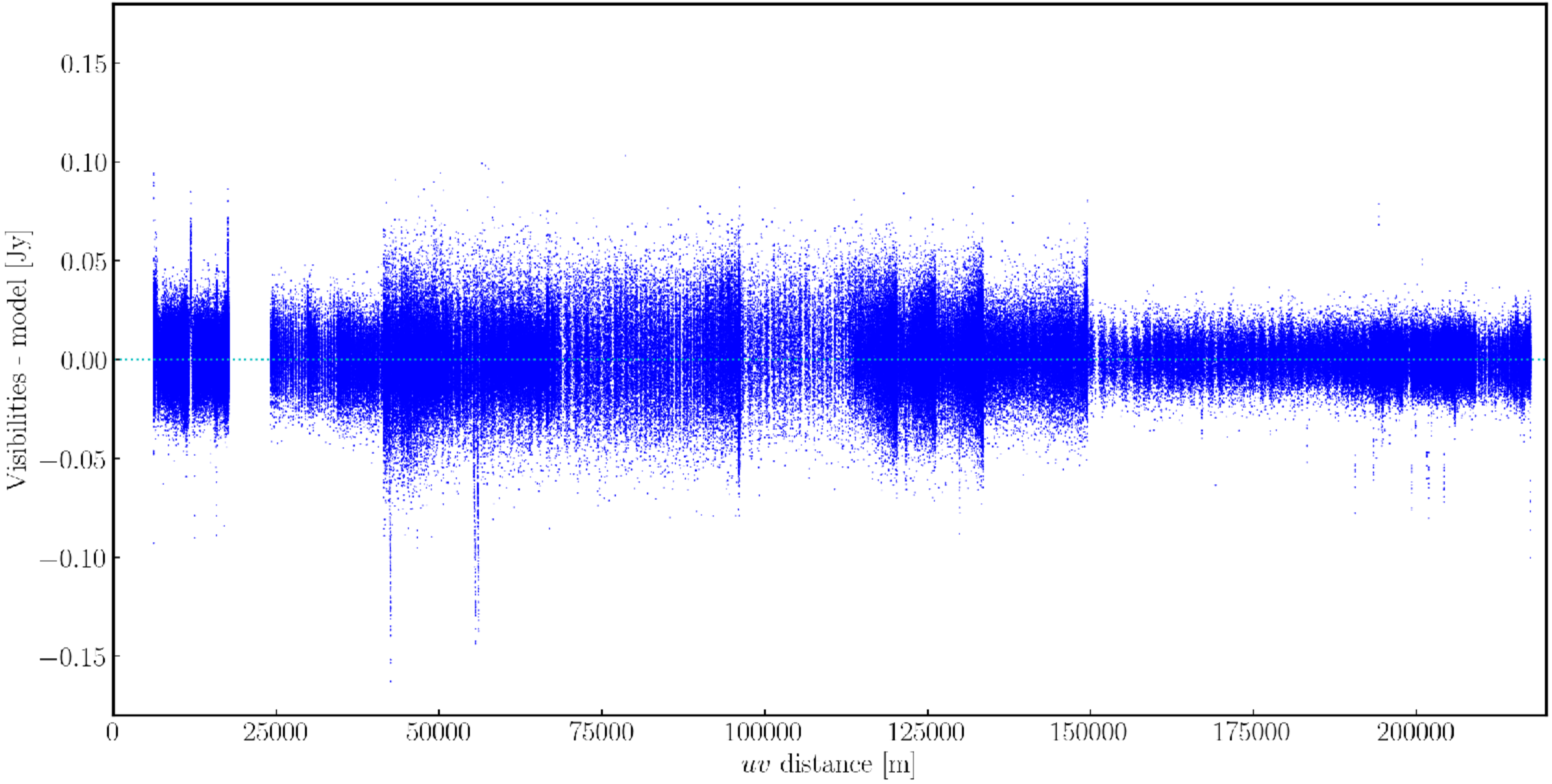
Self-calibration improvements

- Or looking at residuals - before



Self-calibration improvements

- Or looking at residuals - and after



Summary

- After rounds of self-calibration, you get a vastly improved image with increased signal to noise:

- Phase referencing calibration not perfect due to offset between target and calibration (often)
- Self-calibration uses the initial model (non-resolved source) gained from phase referencing to determine gain errors
- Iterative process required and can result in drastically improved S/N and detection of faint structures