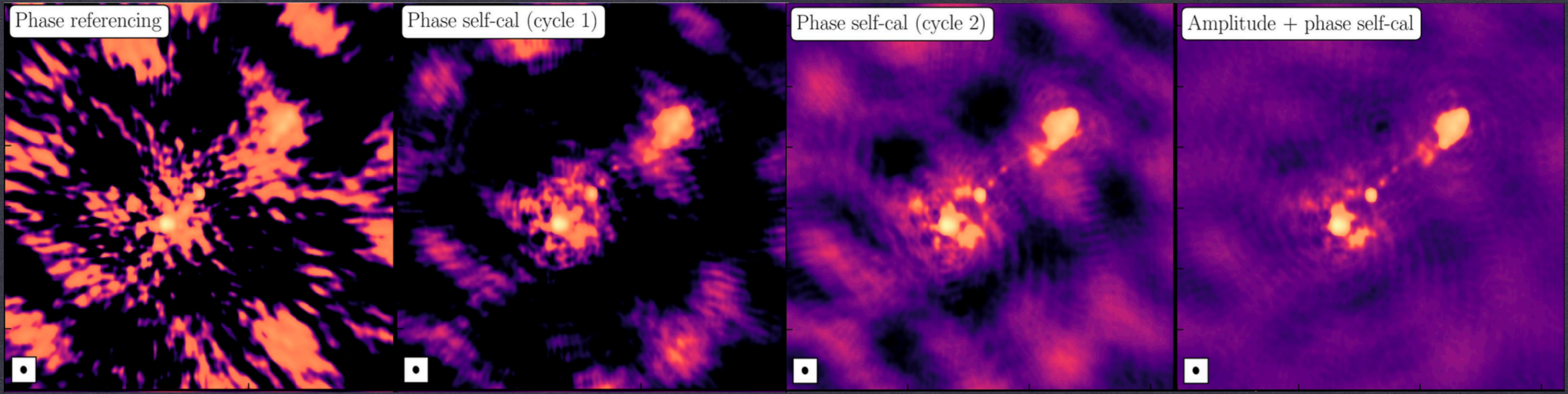

Credit: Jack Radcliffe

SELF-CALIBRATION

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

KATIE HESTERLY
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DARA
UNIT 4

DARA
DEVELOPMENT IN AFRICA WITH RADIO ASTRONOMY

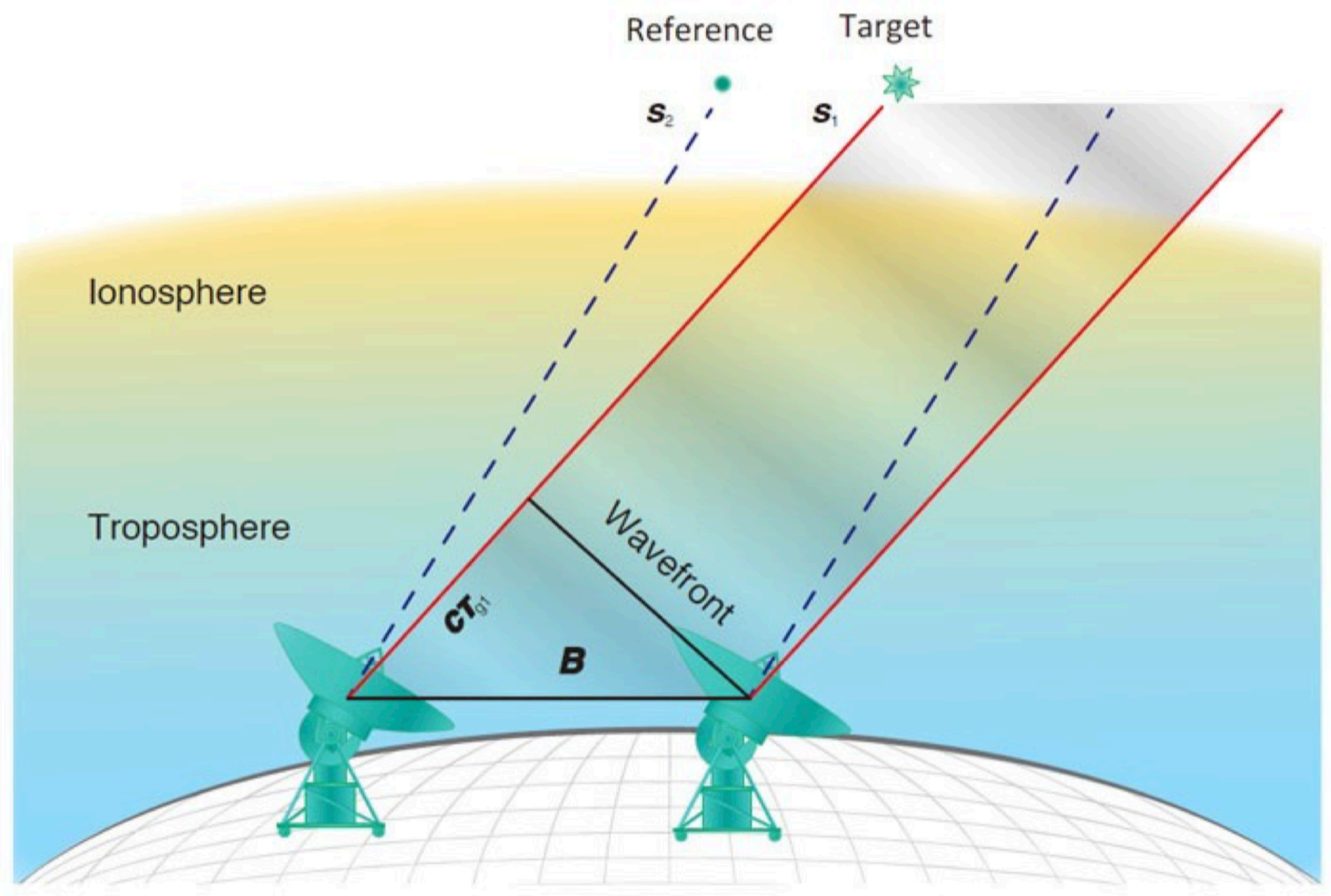
a priori calibration

Summary

Radio telescopes are not perfect and data require correcting.

- **e.g. receiver noise, surface accuracy, T_{sys}, bandpass, atmospheric conditions, radio frequency interference (RFI)**

* Apply instrumental corrections (e.g. T_{sys})
* Edit the data (flag “bad” data such as dropouts, bright spikes from RFI, etc.)
* Apply bandpass corrections
* Apply phase and (fluxscaled) amplitude corrections derived from the phase reference
* Apply same corrections to target (should be close enough to phase calibrator to see similar atmosphere)



Credit: Jack Radcliffe, SARAO

a priori calibration

Summary

Radio telescopes are not perfect and data require correcting.

- e.g. receiver noise, surface accuracy, T_{sys}, bandpass, atmospheric conditions, radio frequency interference (RFI)

- **Apply instrumental corrections (e.g. T_{sys}) - often done by the observatory pipeline**
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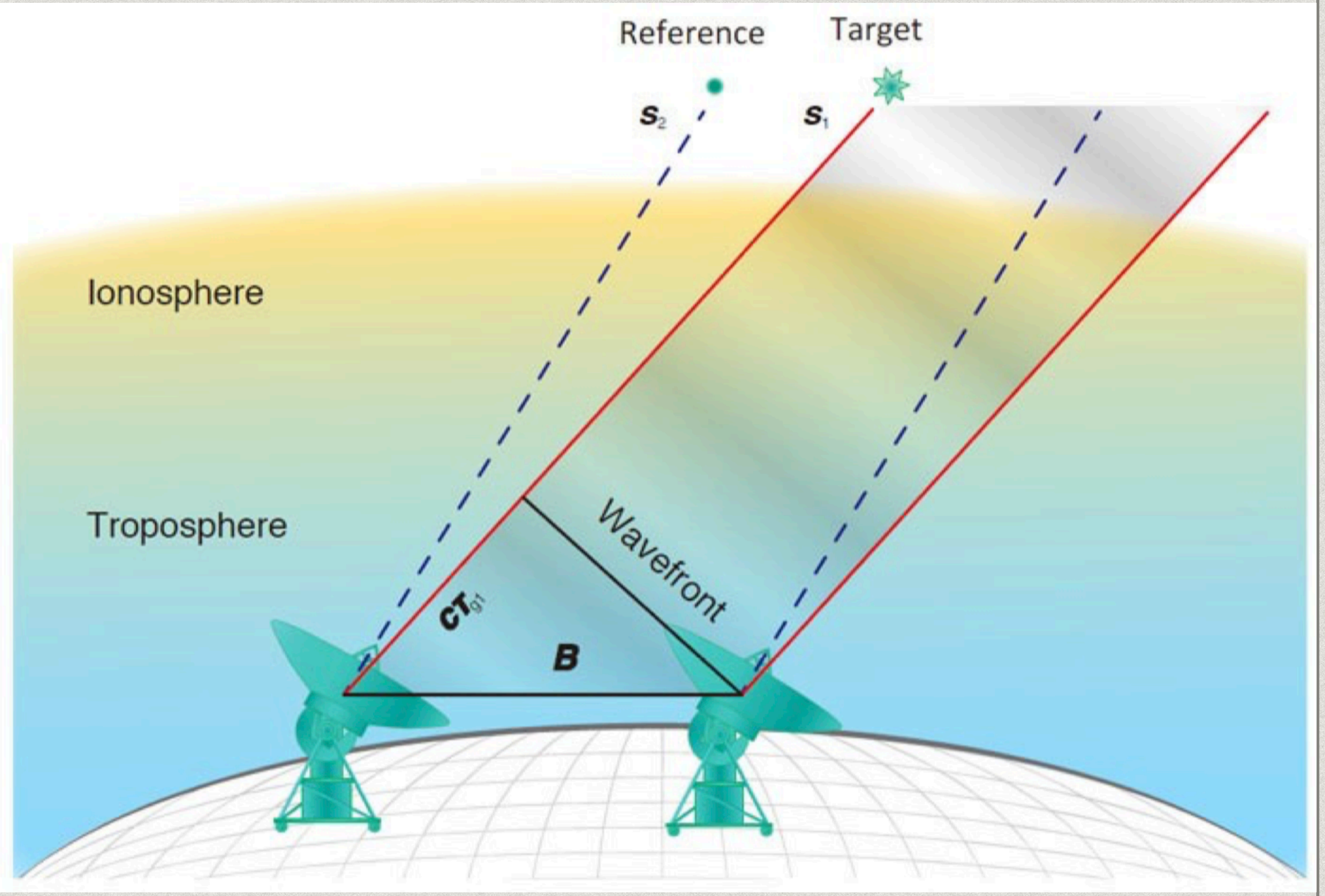

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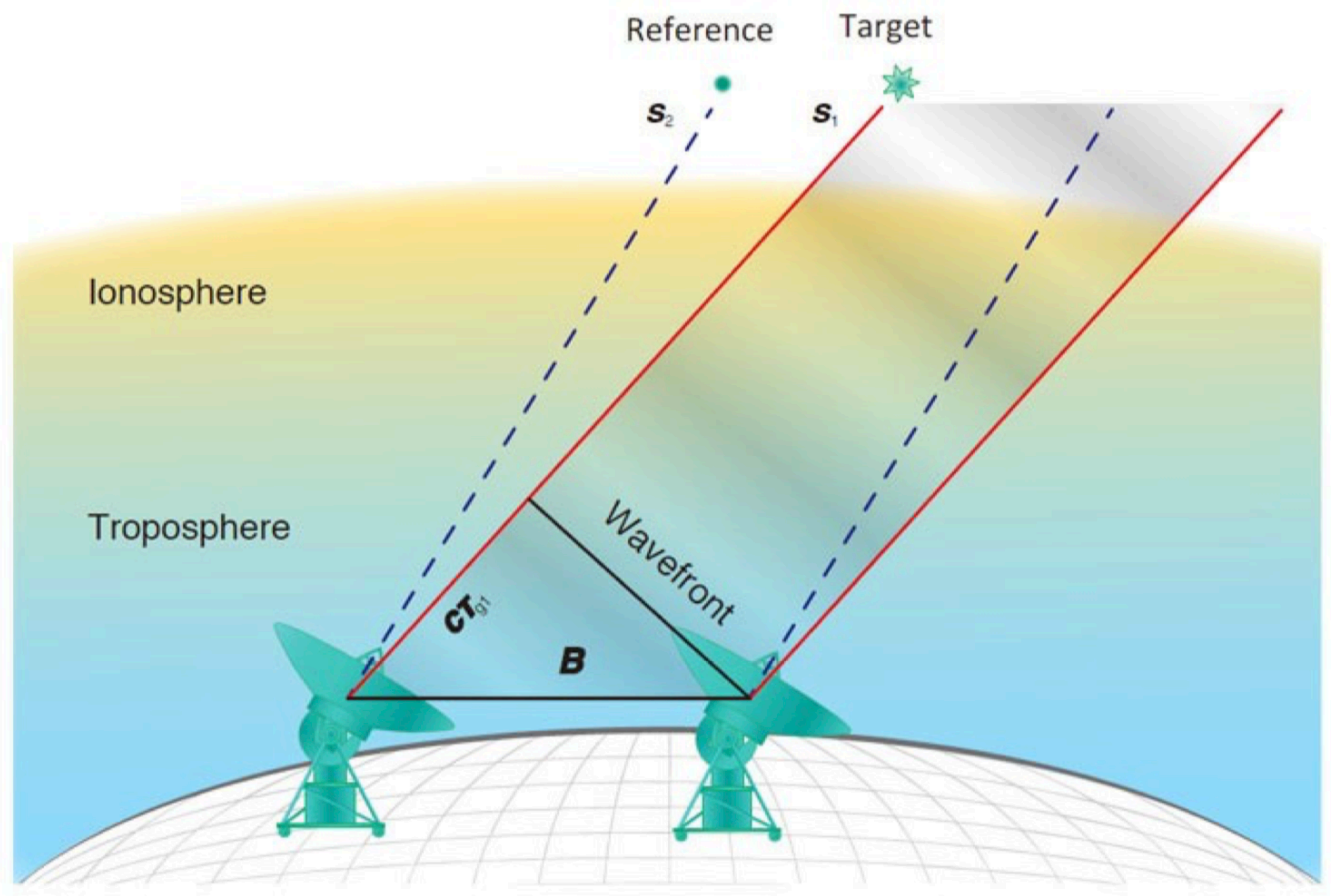

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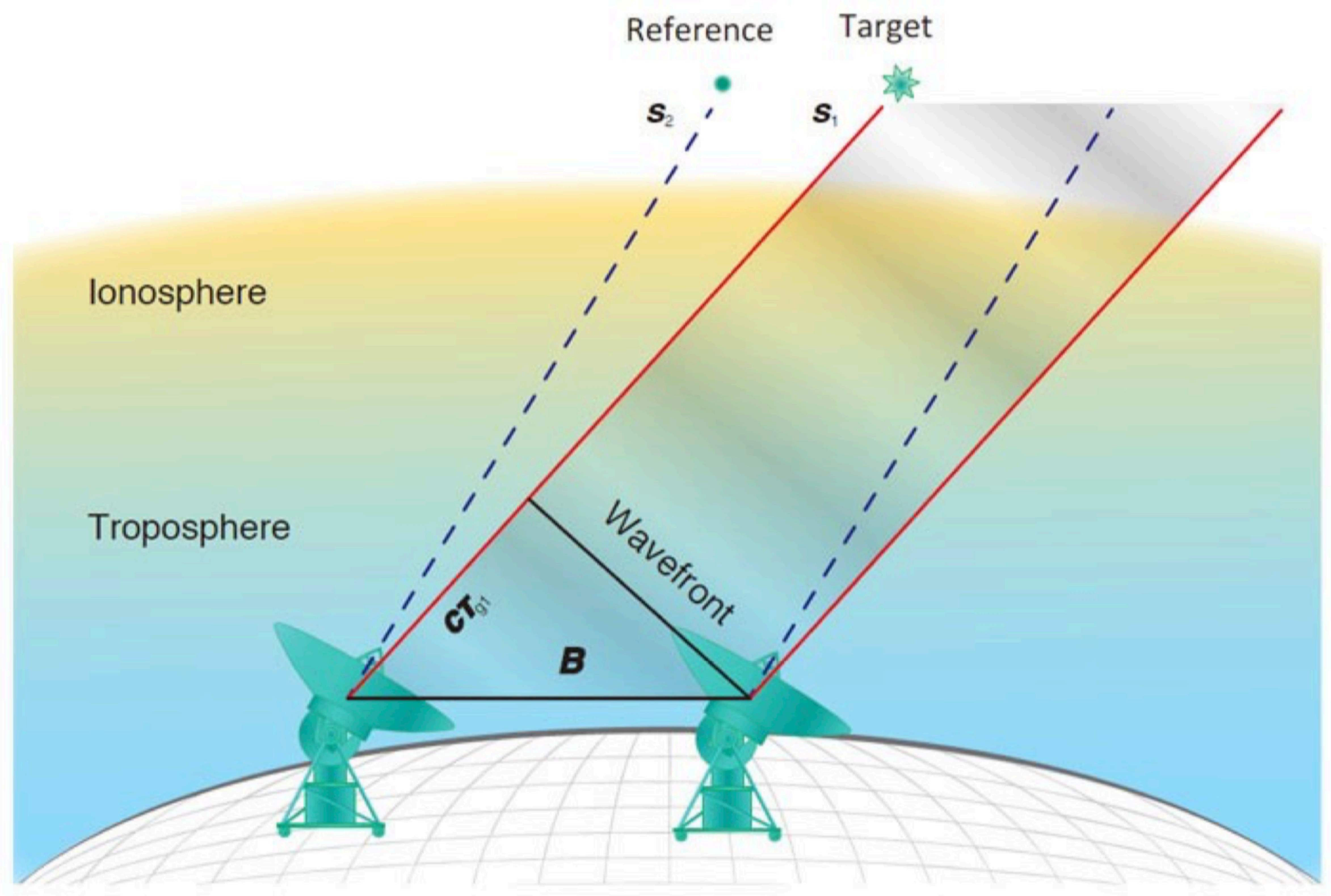
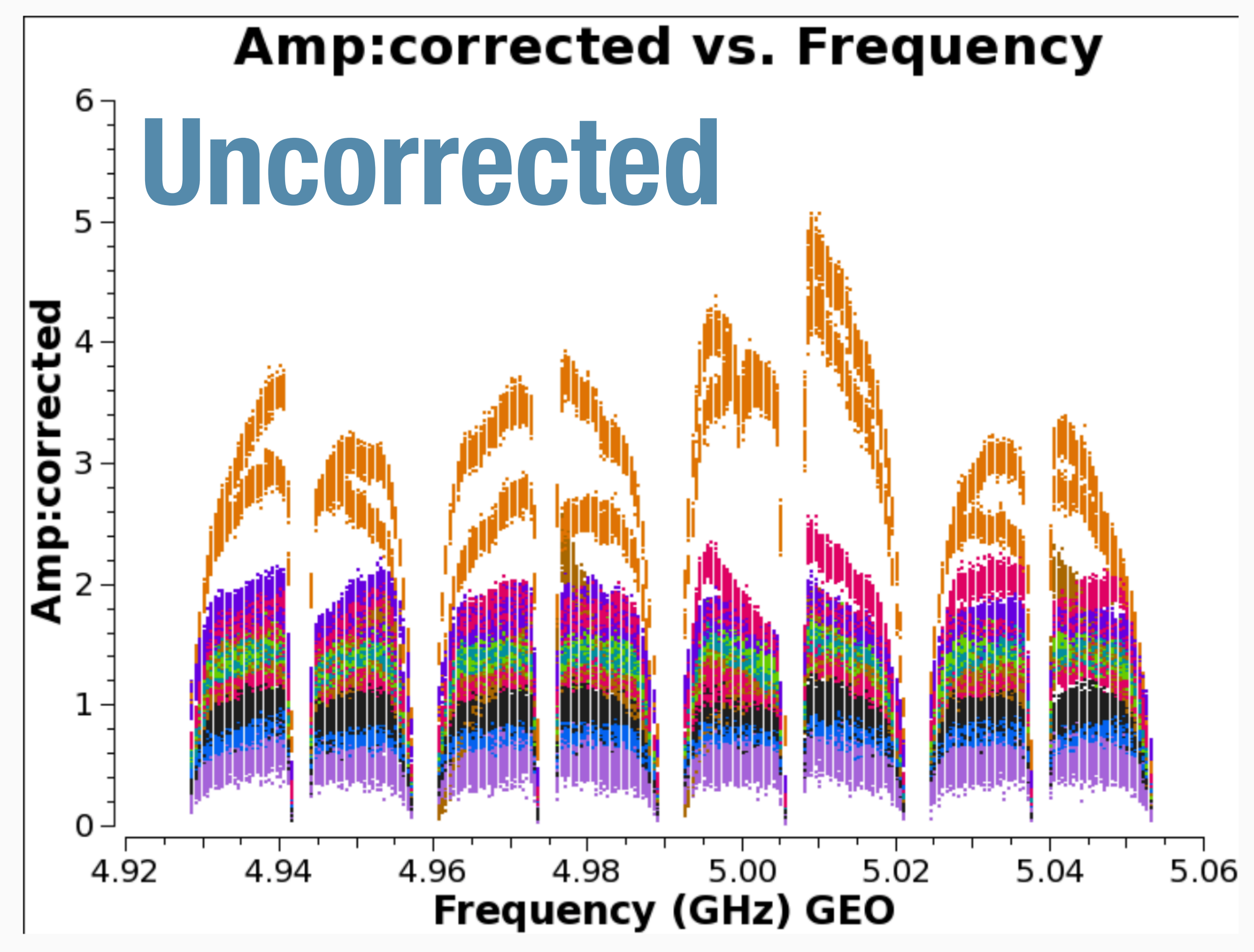
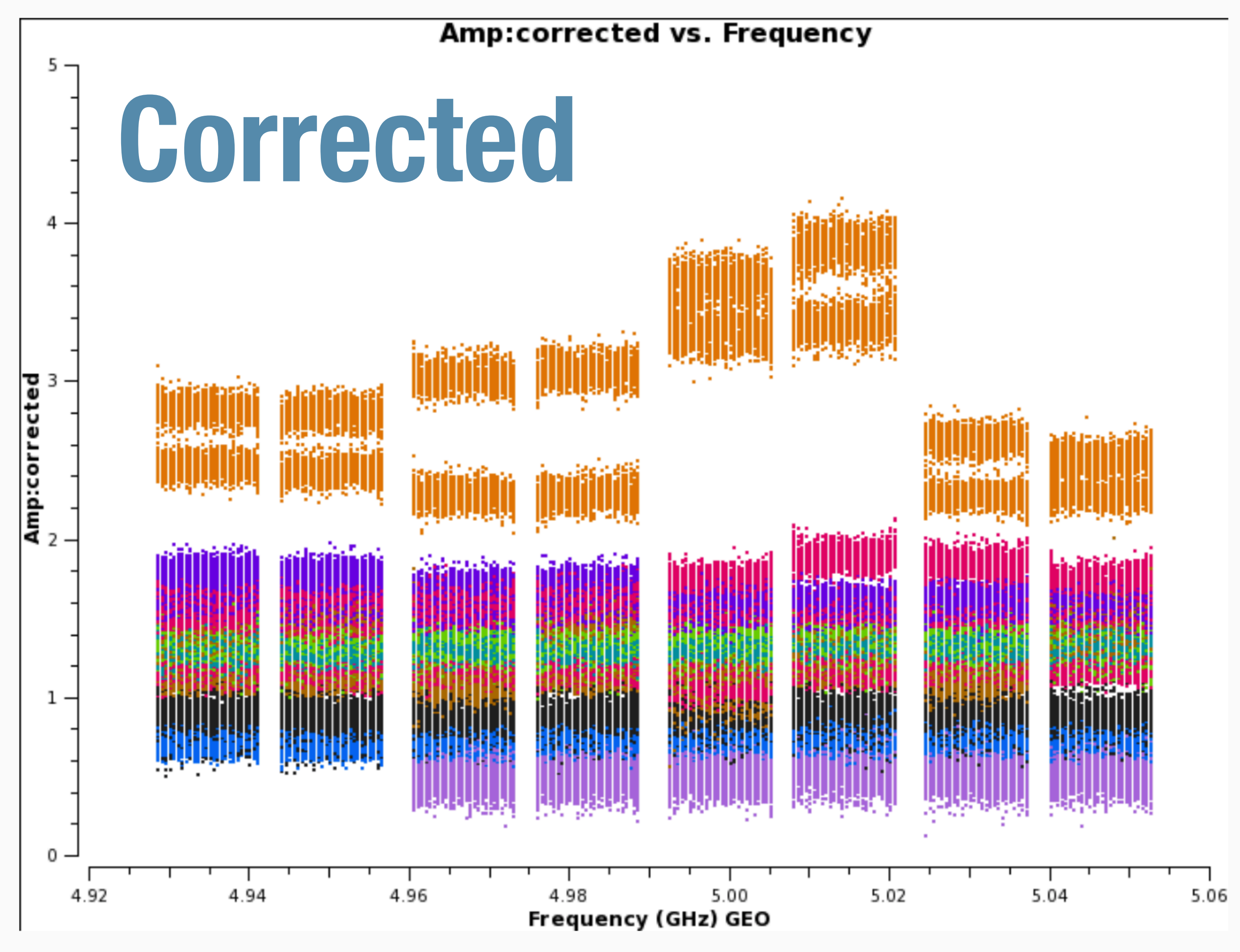


Credit: Jack Radcliffe, SARAO

Bandpass correction

- Instrumental effect that should not change very much with time
- Calculates a complex correction to fit to the data
- Will not adjust the net scaling
- Do not need to do bandpass calibration again during self-cal





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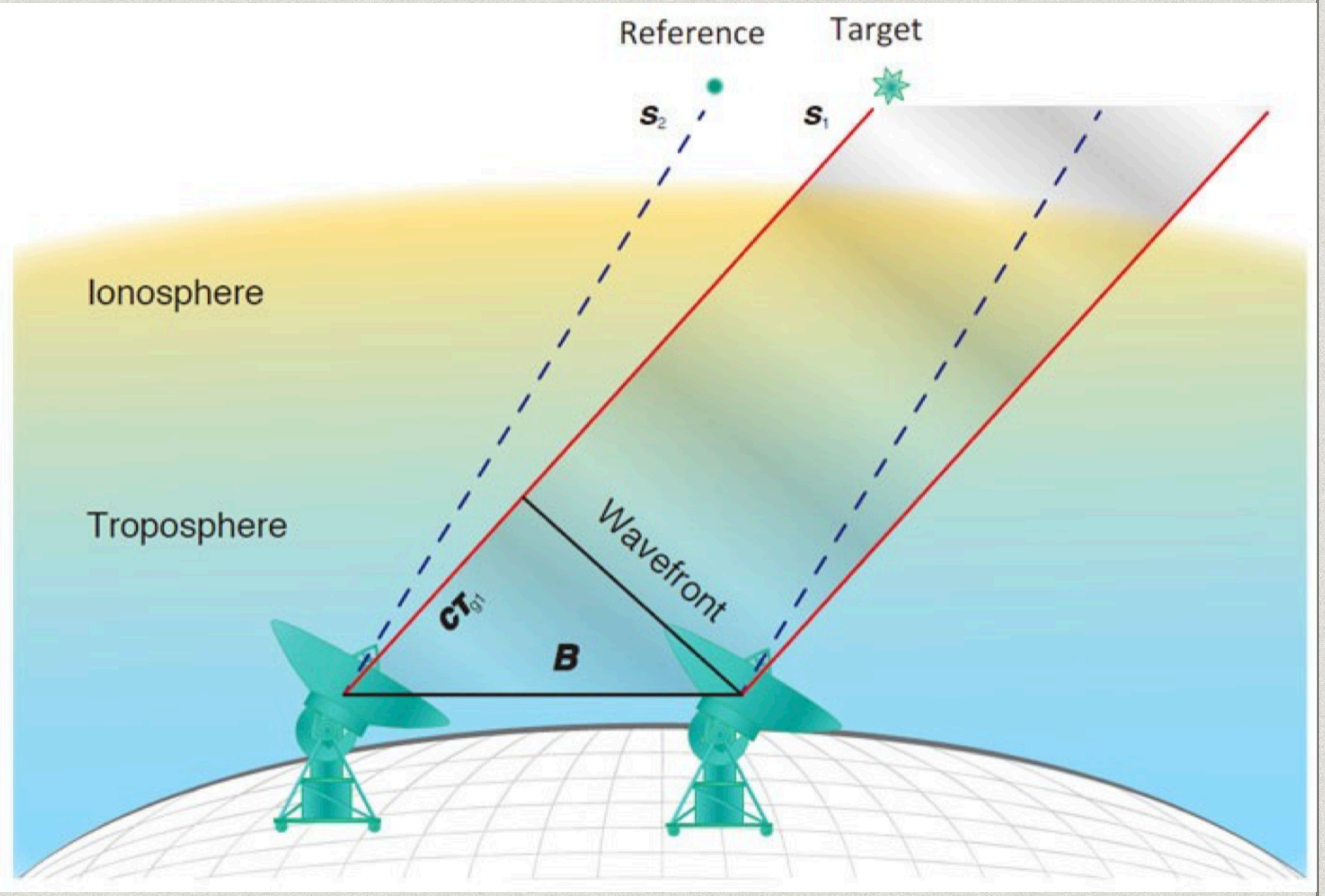

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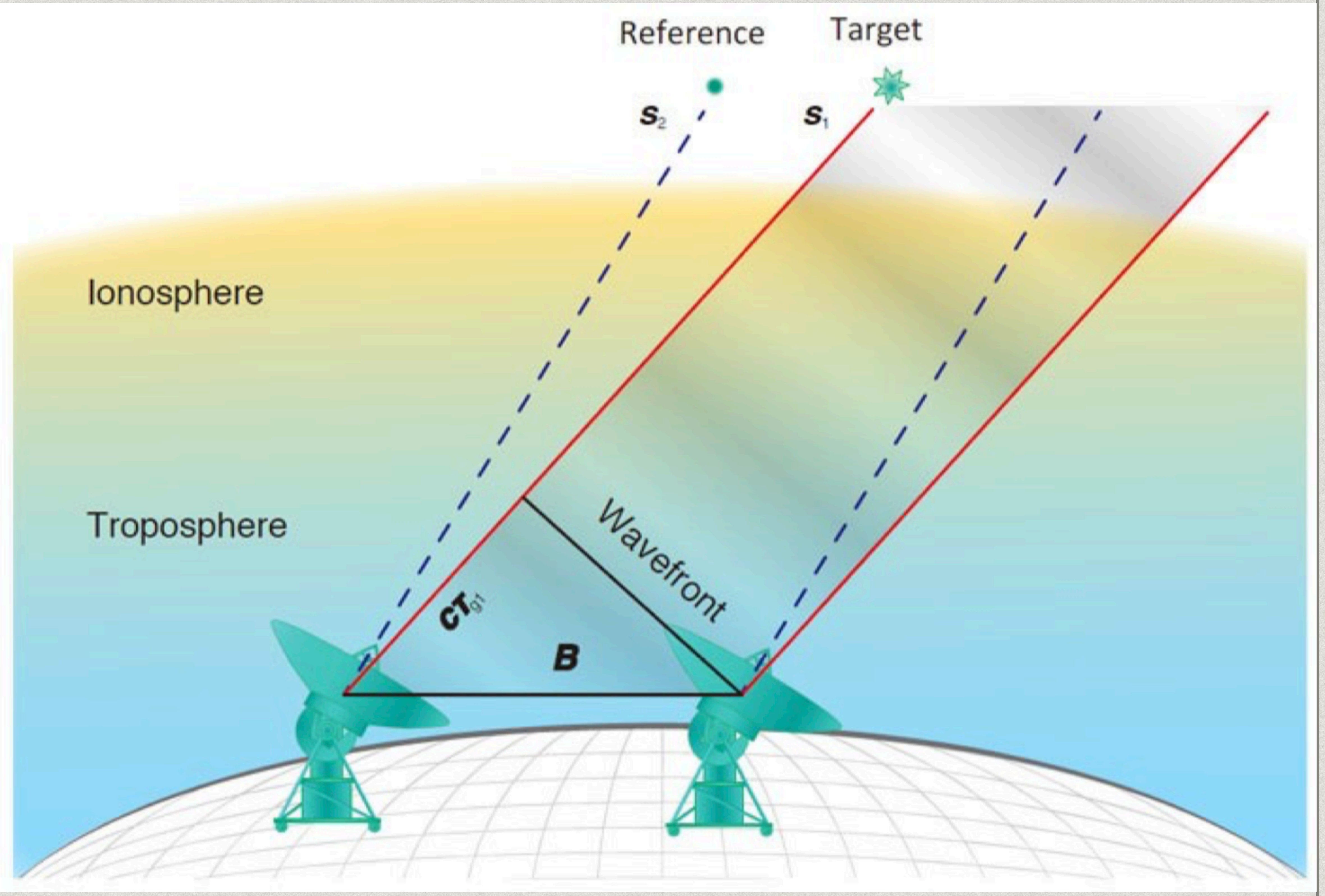
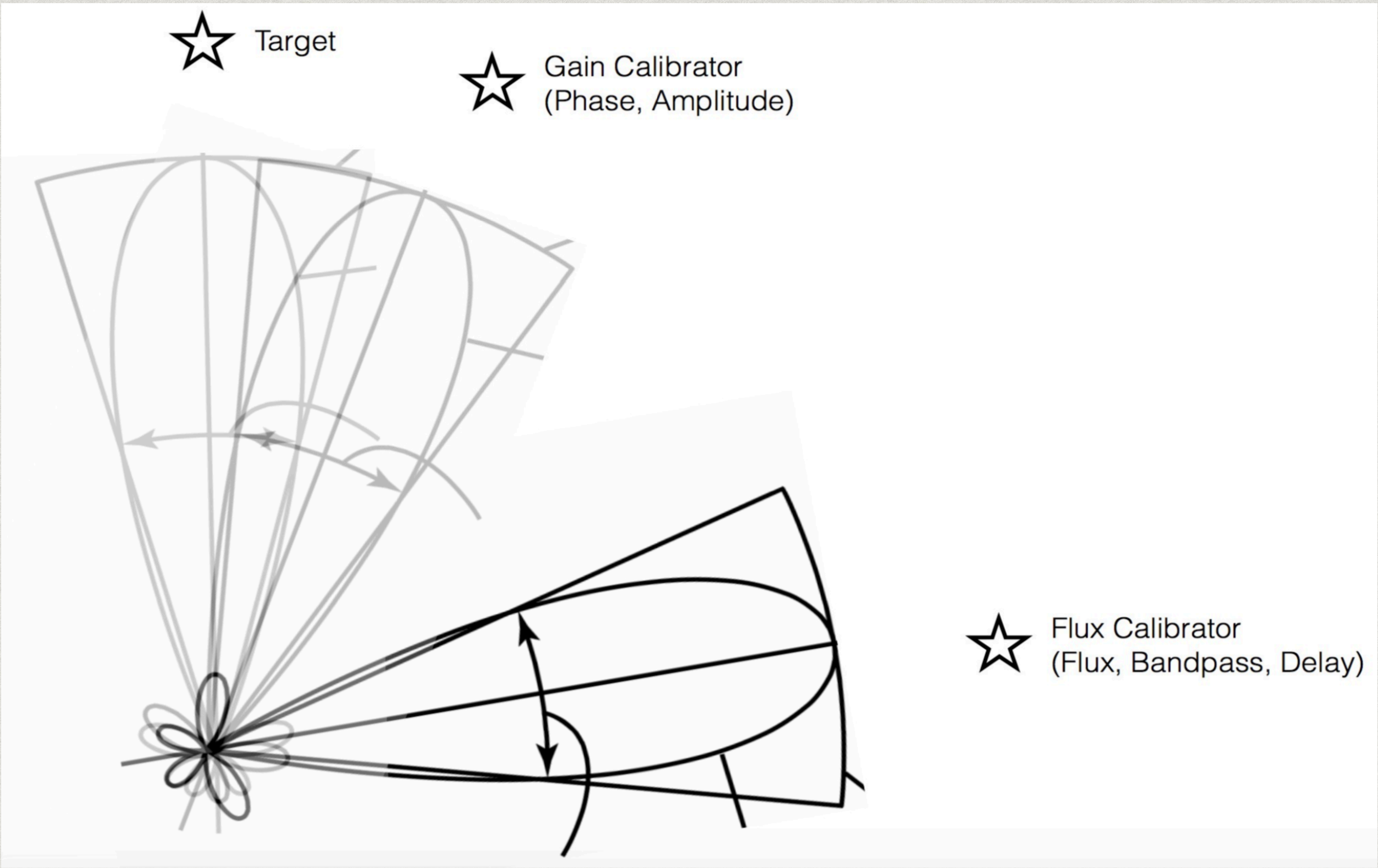


Credit: Jack Radcliffe, SARAO

Phase referencing

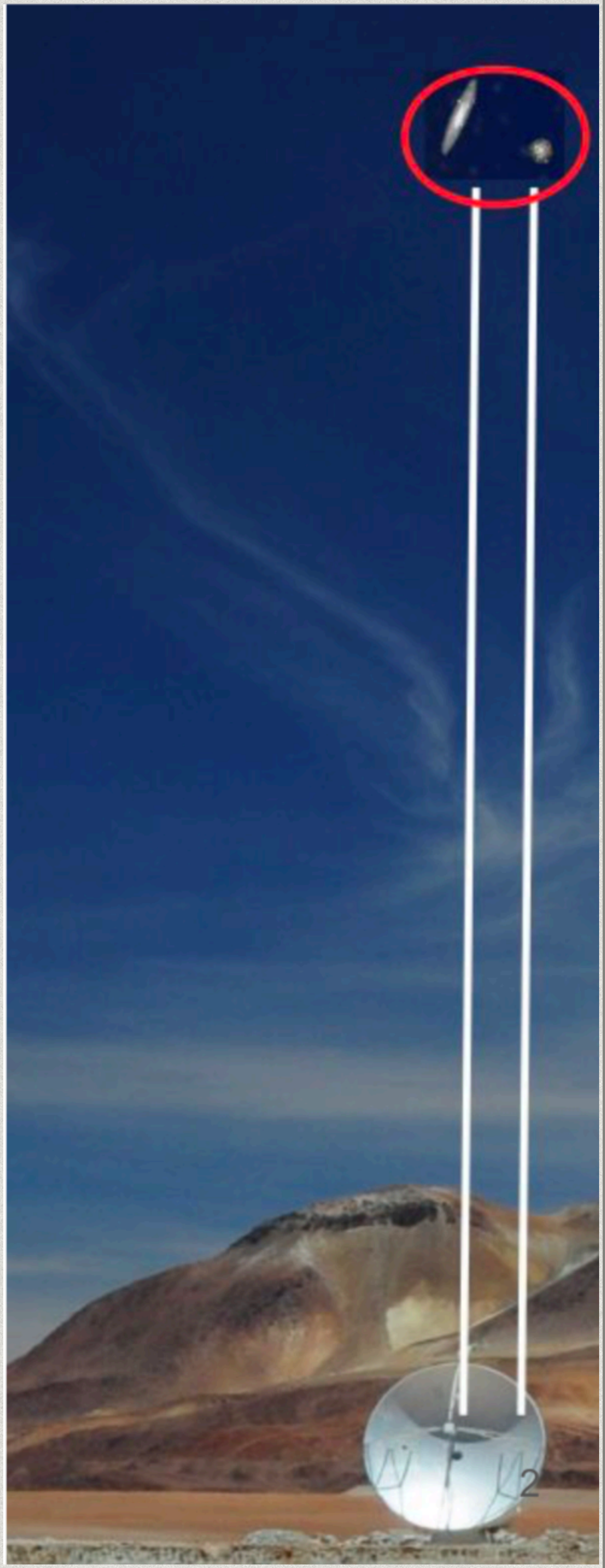


1. Observe a source.
2. Observe a calibrator to measure gains (amplitude and phase) as a function of time.
3. Observe a bright calibrator with a known flux-density and spectrum to measure absolute flux calibration, bandpass, and residual delays.

Phase referencing

Why is phase referencing not enough?

- Atmospheric differences
  - Atmosphere is not exactly the same (although similar) around the target and the phase-reference.
  - Offsets in distance and in time
  - Neutral atmosphere contains water vapor
  - Index of refraction differs from "dry" air
  - Variety of moving spatial structures in the atmosphere
  - Worse for low frequencies (~100s MHz, ionosphere) & high frequencies (~20+ GHz, water vapor)



Credit: Moravec/Perez-Sanchez/Toribo/RIchards

Calibration errors

True visibilities are corrupted by various other effects:

1. Radio “seeing” —“twinkling” of objects
2. Atmospheric attenuation — reduction in intensity in the Earth’s atmosphere due to absorption and scattering or radiation
3. Variable pointing offsets
4. Variable delay offsets
5. Changes in electronic gain, delay, and phase
6. Correlator malfunctions
7. Interference signals
8. Radiometer noise

Antenna based (items 1–5)

Baseline (items 6–8)

Errors in the image

Phase errors:

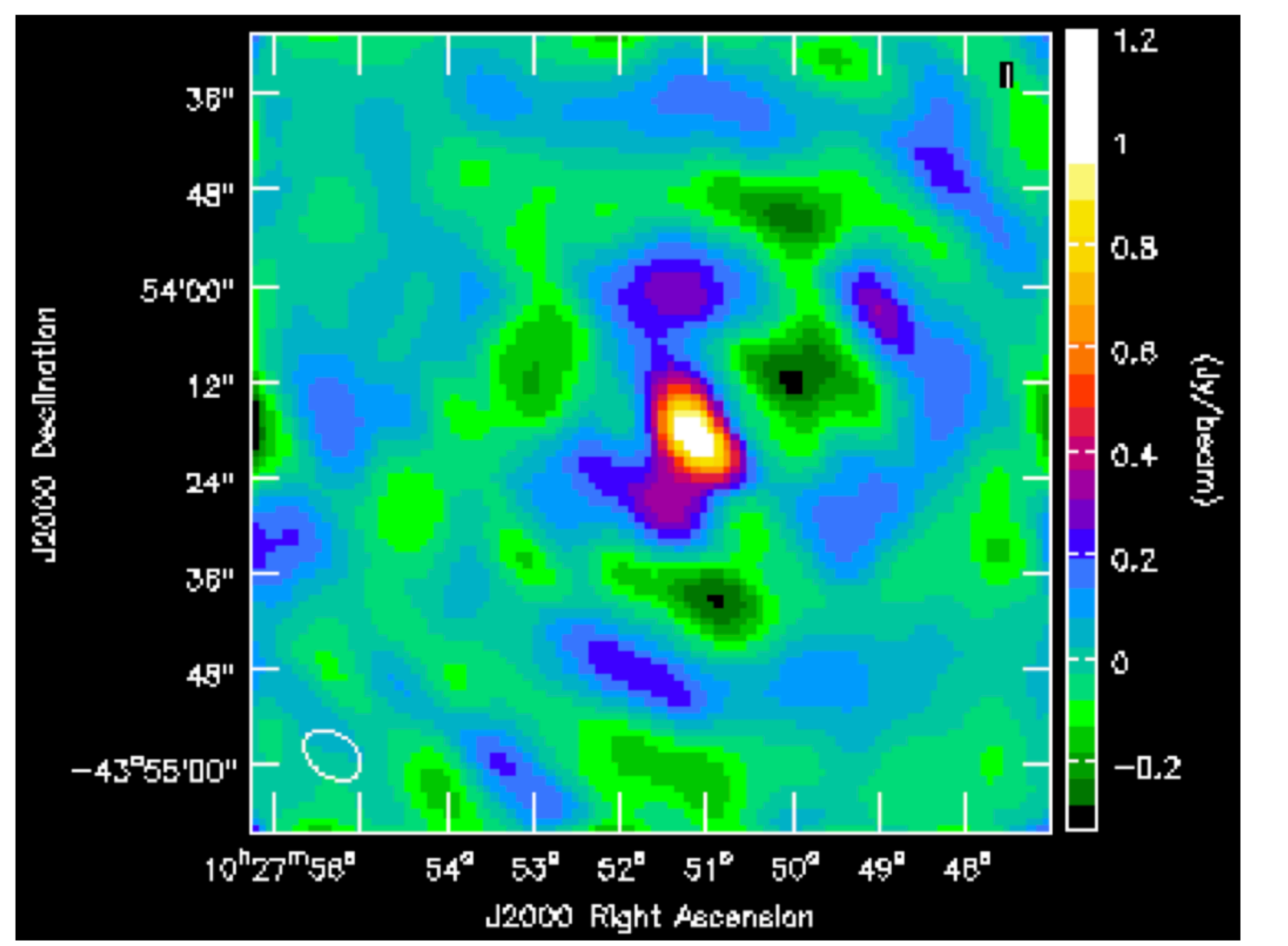
- Amplitudes decorrelated — reduction in flux measurements
- Difficulty detecting weaker emission
- High noise
- Anti-symmetric artifacts
- Smeared emission

Amplitude errors:

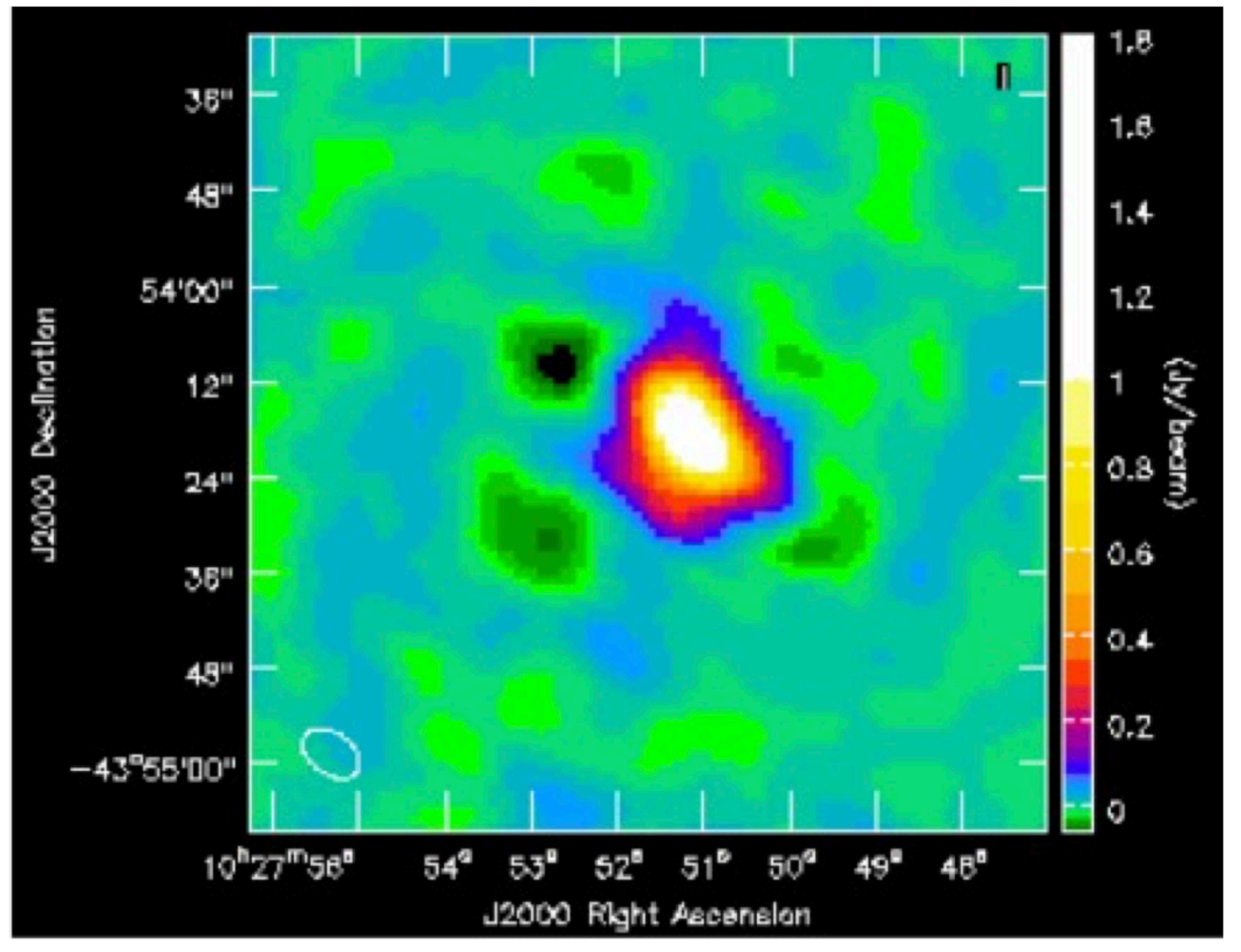
- Symmetric artifacts
- Noise increased
- Flux reduced
- Spotty or stripy emission (could also require additional flagging to remove bad data)

Credit: Moravec/Perez-Sanchez/Toribo/RIchards

Phase errors



Phase referencing solutions only



Phase self-cal only (i.e. removal of phase errors)

Credit: Jack Radcliffe

Self-calibration

- Self-calibration is just calibration but the target is used to calibrate itself!
- Still solving for the gains:

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

$V_{ij}(t)$ - visibility measured between antenna

$G_{ij}(t)$ - complex gain of baseline

$$V^{true}(t) = \int\int T(l,m) e^{-2\pi i(ul+vm)} dl dm$$

← True visibility

When is self-cal appropriate?

- Target image has rms noise > predicted

$$\text{Noise} = \frac{\sqrt{2}k_B T_{\rm sys}}{\sqrt{n_b t \Delta\nu} A\eta}$$

(see Imaging lecture for more details)

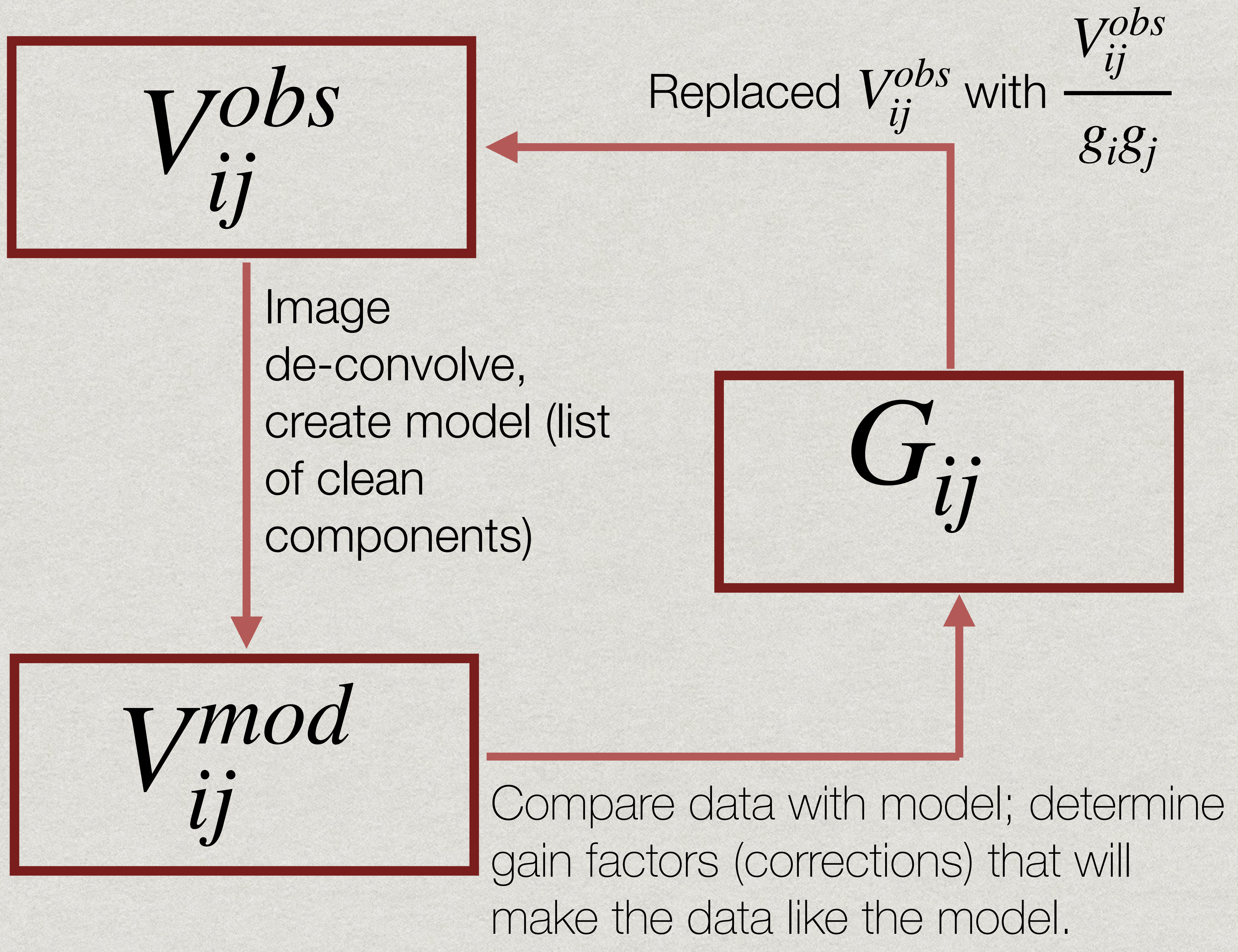
- Target image has a bright peak
  - How bright? Depends! The more antennas the higher the S/N needed
  - Does not need to be a point source - weaker emission okay!

Credit: Moravec/Perez-Sanchez/Toribo/RIchards

The self-calibration method

$$\vec{V}_{ij}^{obs} = G_{ij}\vec{V}_{ij}^{true}$$

1. Create an initial source model
   - Typically done when you make an initial image (or can use a point source)
2. Find corrections for antenna gains
   - Uses “least squares” fit to visibility data
3. Apply gains to correct V_{ij}^{obs}
4. Create new image and model from corrected visibilities
   - Check quality (noise, artifacts, amplitudes…)
5. Repeat from step 2 until image is satisfactory
   - start with only phase corrections and shorter solution intervals
   - start amplitude and phase self-cal when only amplitude errors are present

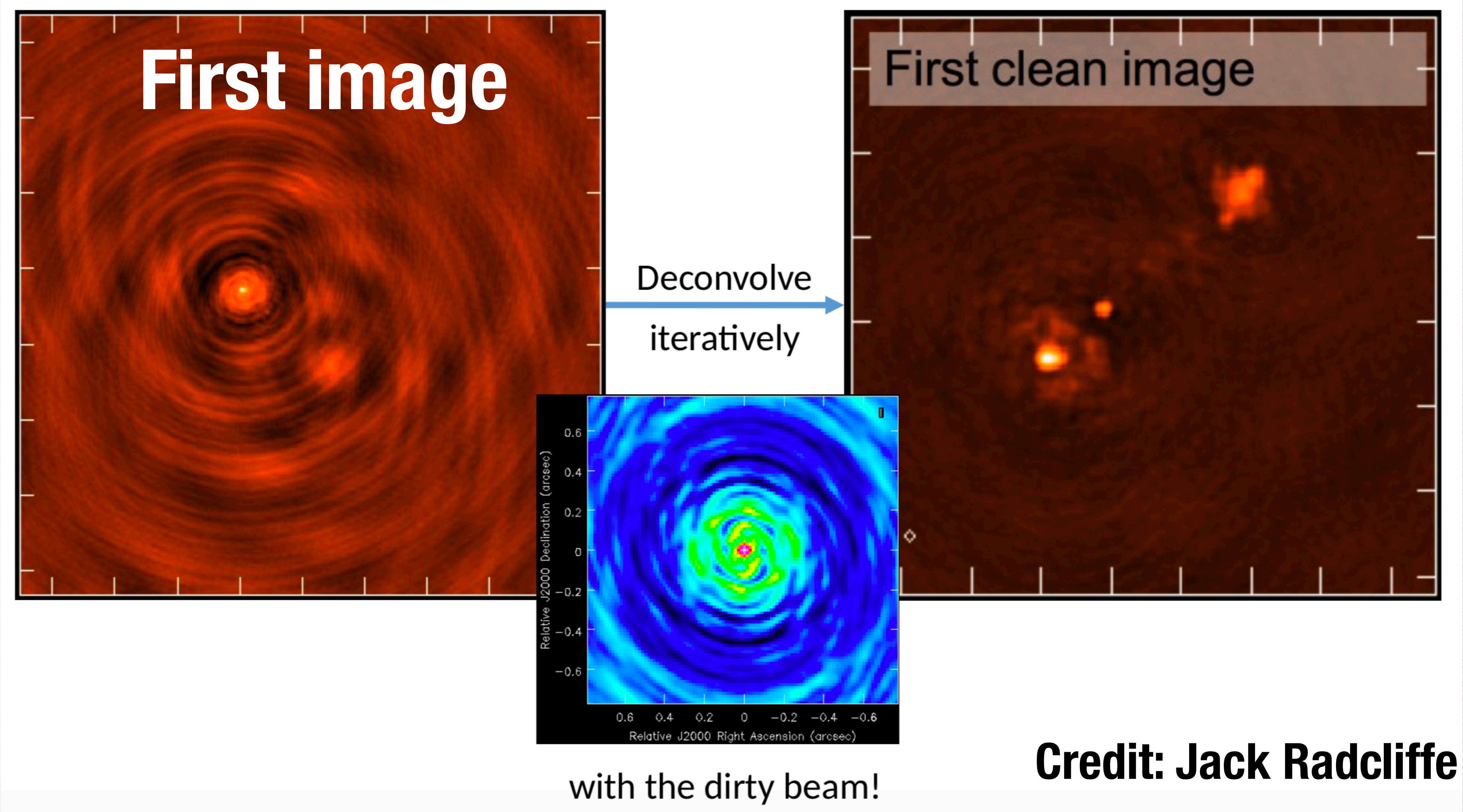


Credit: Jack Radcliffe

Self-calibration in CASA

1. **Image target — CASA task "*tclean*" or "*clean*"**
   - Make a box around the brightest emission
   - Don't clean too deeply (~ >3xnoise)
   - set usescratch=True, or task "FT" if the clean components have not been added to the model column properly
   - check model against visibilities using the task *plotms*
2. Estimate antenna gain corrections with task *gaincal*
   - set calmode='p'

Target 3C 277.1



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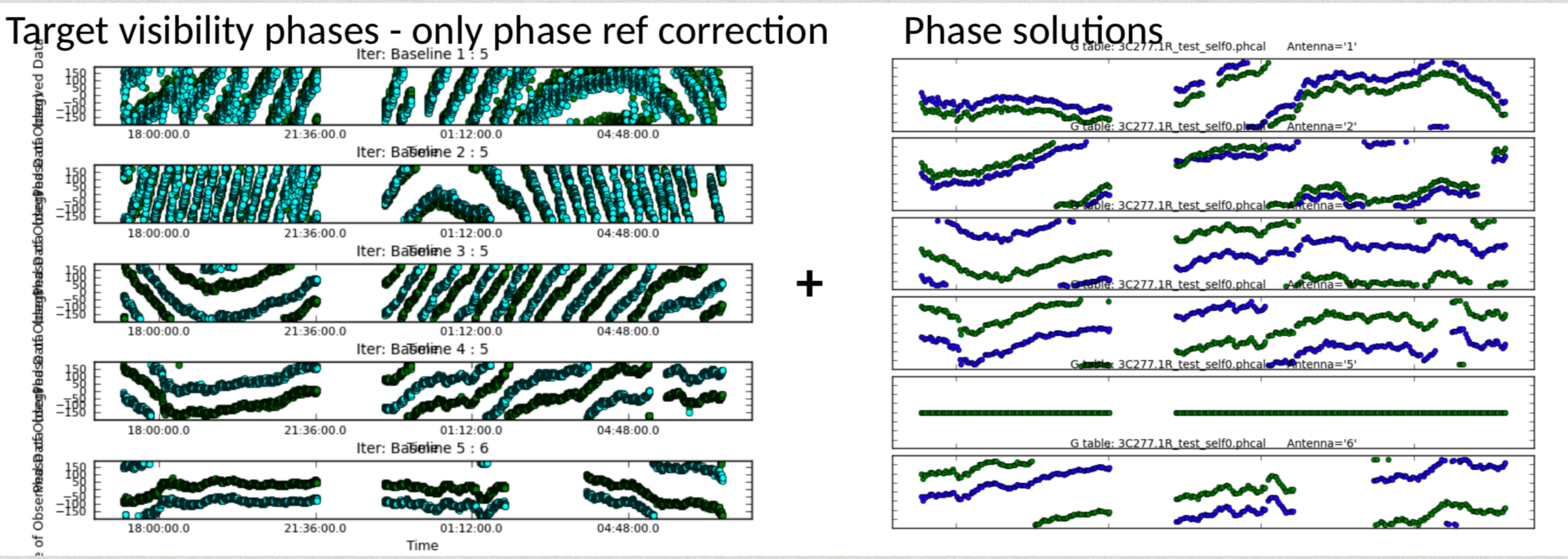
   - set calmode=‘p’

Gainful produces a calibration file where the model is compared to the target visibilities.



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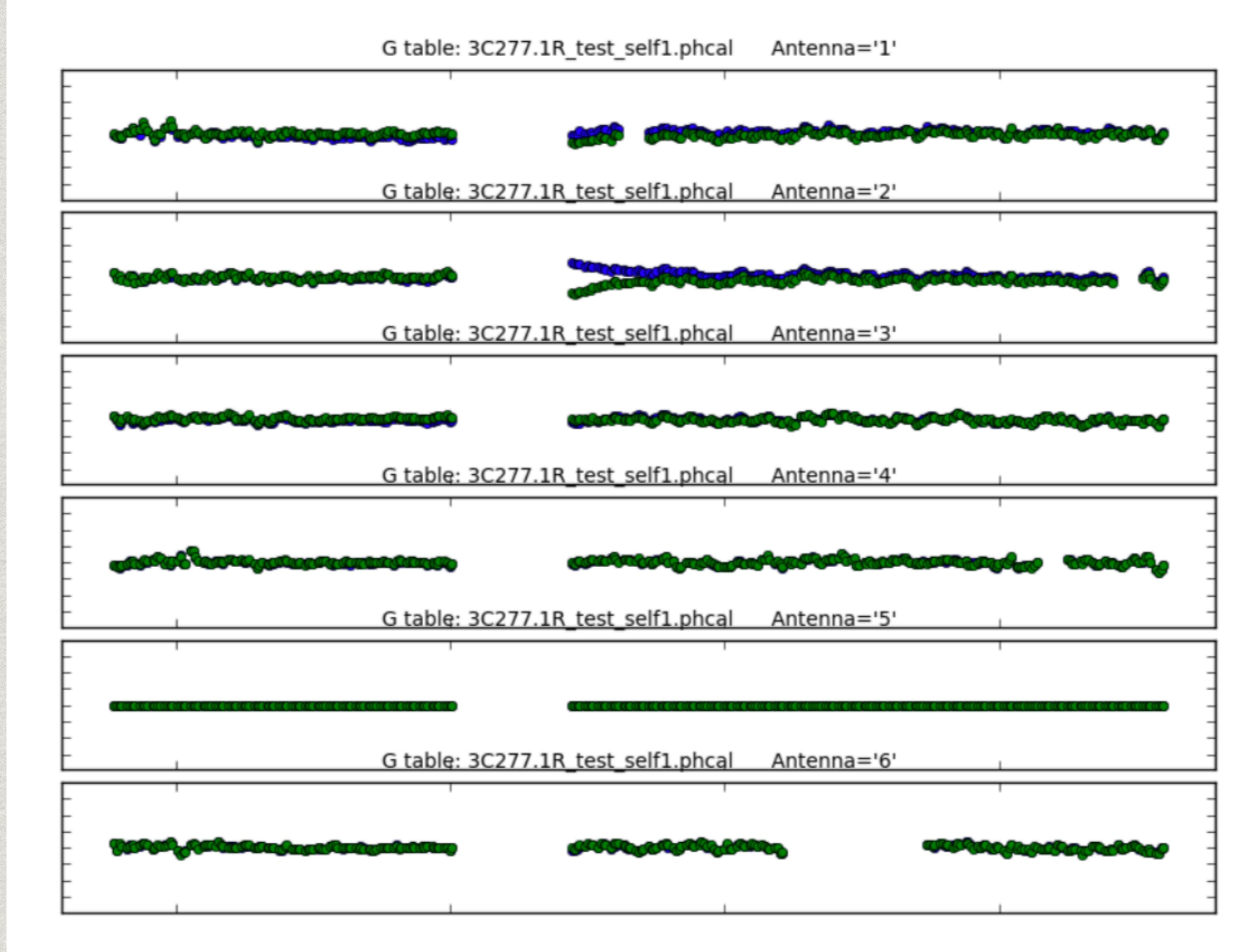


3. Apply the corrections using the task ‘applycal’
4. Make a new image and model
5. Repeat until phase corrections converge (image on left) then continue with phase and amplitude self-calibration
   * When running the amplitude and phase calibration use calmode=‘ap’
   * amplitude solutions should be close to 1

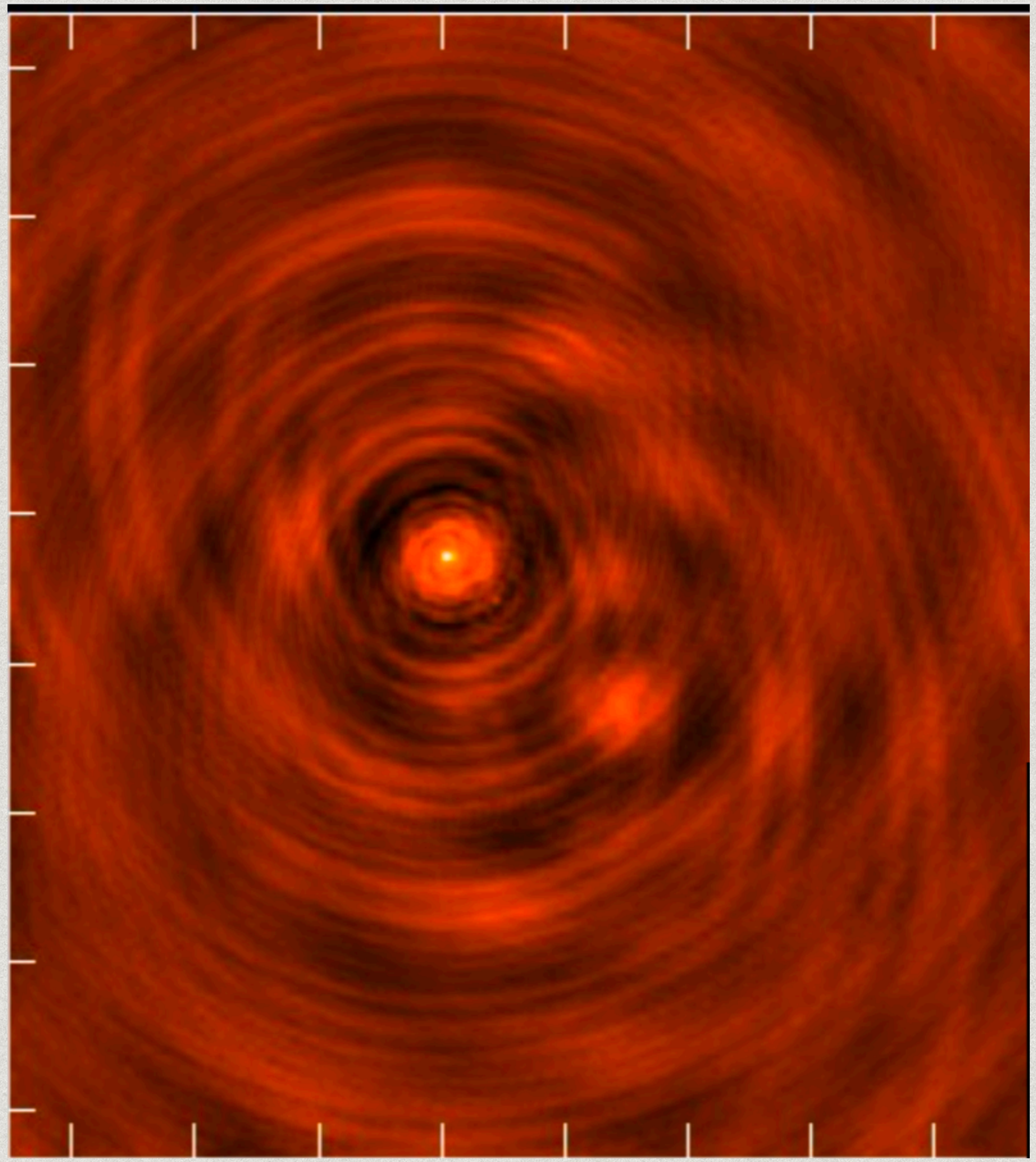
Self-calibration in CASA

* Summary of the self-calibration process

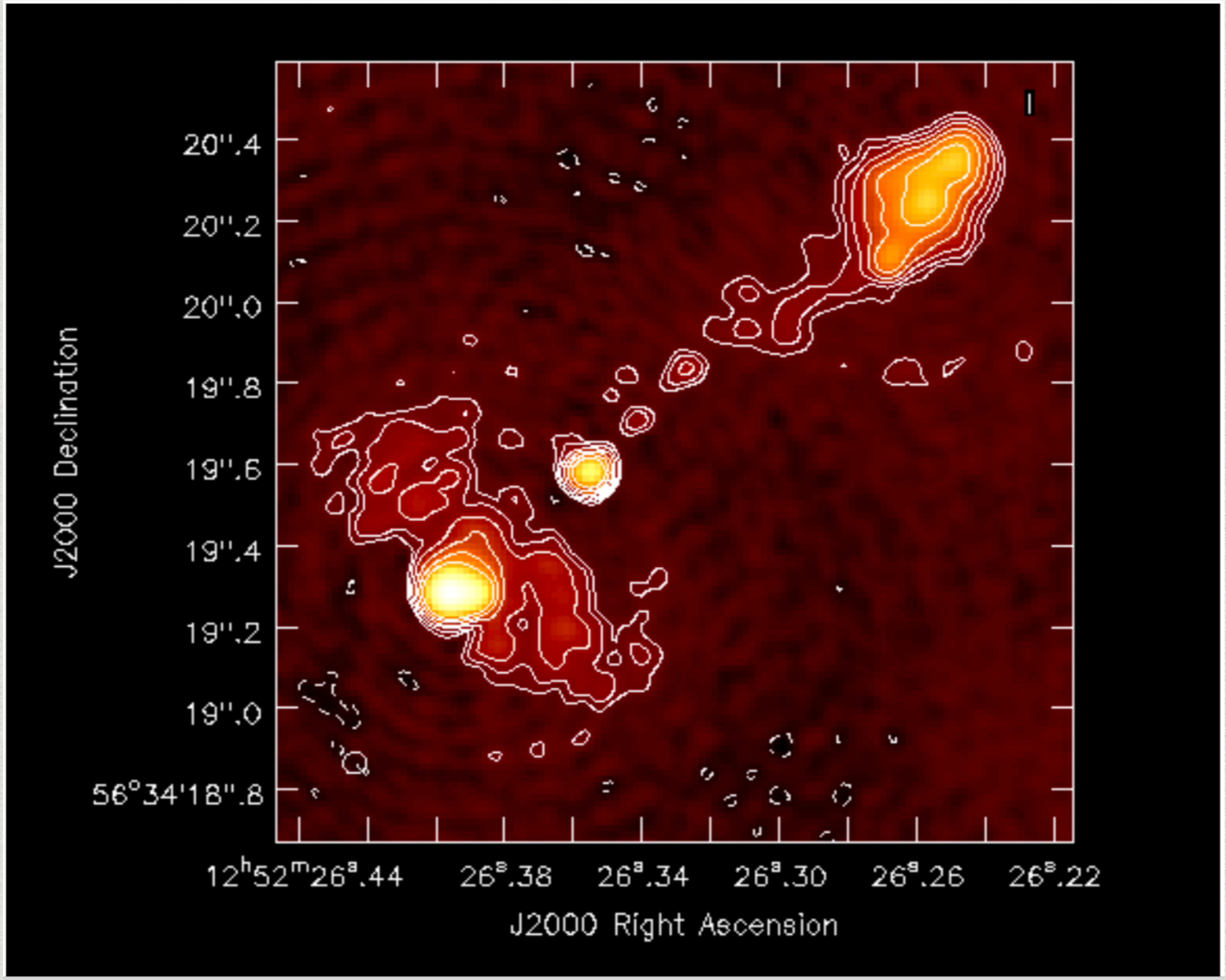
Initial image
↓
Phase self-calibration
↓
Shallow CLEAN image
↓
Phase self-calibration
↓
Deep CLEAN
↓
Amplitude and phase self-calibration
↓
Deep CLEAN

Self-calibration in CASA

First image



Final image!



Self-calibration limitations

What can't be cured by self-calibration?

- Bad data — spikes or low points in amplitude
- Missing short spacings — negative bowl as a result of missing flux on short baselines (may need compact array data and to use advanced imaging techniques)
- baseline-dependent errors (non antenna effects) may need task *blcal* because gainful solves per antenna
- antenna position, variability in source, etc.

Credit: Moravec/Perez-Sanchez/Toribo/RIchards

Self-calibration options

What options do I choose?

1. Initial model
    - CLEAN components from image
    - point source works well
    - barely resolved sources can be fit (e.g. Gaussian)
    - Model-fitting in the uv plane
2. Which baselines?
    - all baselines can be used when the source is simple
    - complex sources may require a model with the most compact components (maybe use longer baselines)
3. What solution interval should be used?
    - shortest interval that gives sufficient S/N
    - short enough to sample phase errors
    - maybe start with solint='inf' (scan length) then move to shorter times when you get a perfect model

Additional resources

- VLA https://casaguides.nrao.edu/index.php?title=VLA_Self-calibration_Tutorial-CASA5.7.0
- ALMA https://casaguides.nrao.edu/index.php?title=First_Look_at_Self_Calibration
- Advanced gain calibration techniques https://arxiv.org/abs/1805.05266
- INAF http://www.alma.inaf.it/images/Selfcalibration.pdf
- ERIS https://www.astron.nl/eris2017/lectures.php
- DARA
- Synthesis Imaging https://link.springer.com/book/10.1007/978-3-319-44431-4