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Netherlands Institute for Radio Astronomy

Lecture 6
Calibration

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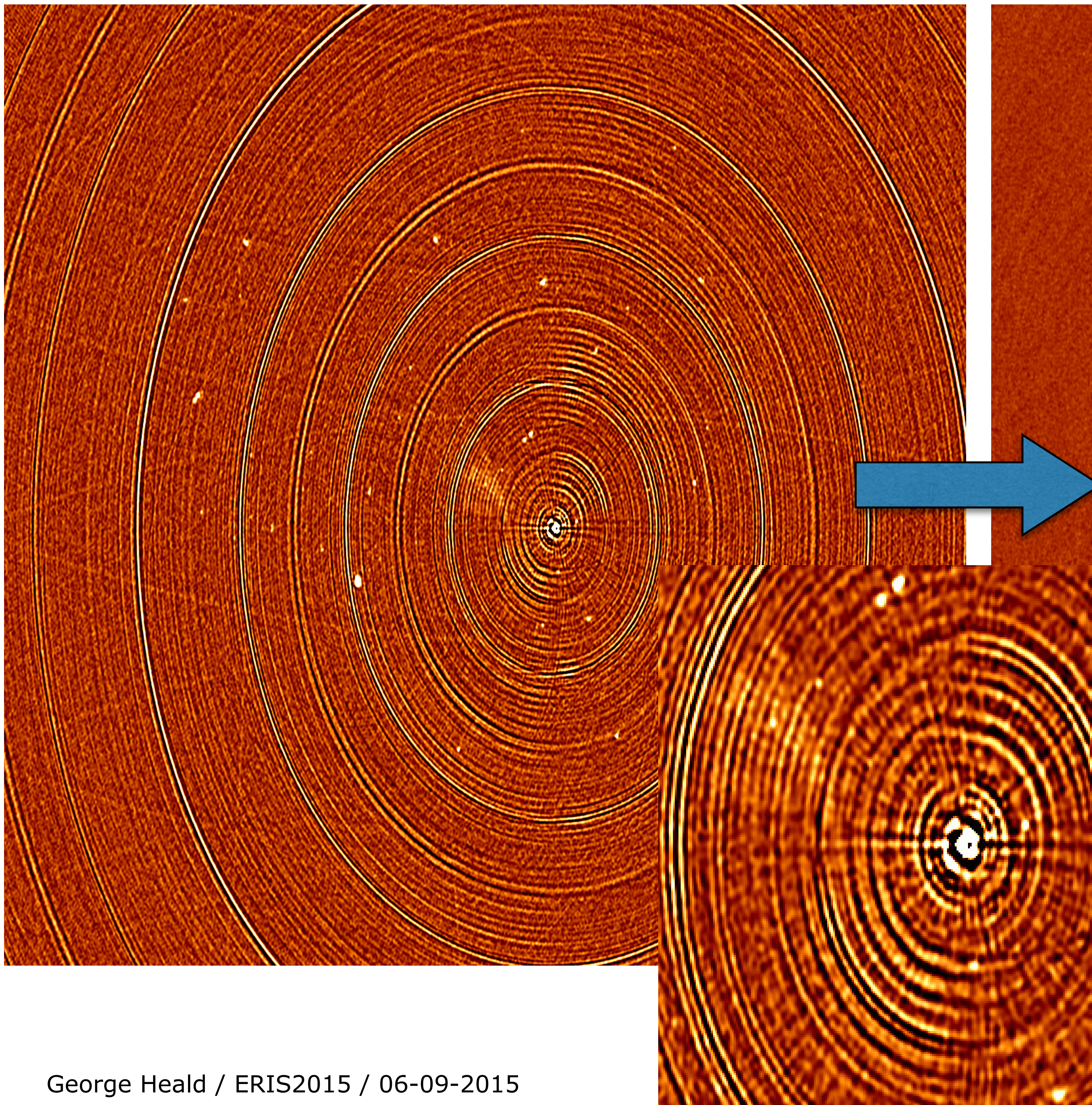
Outline

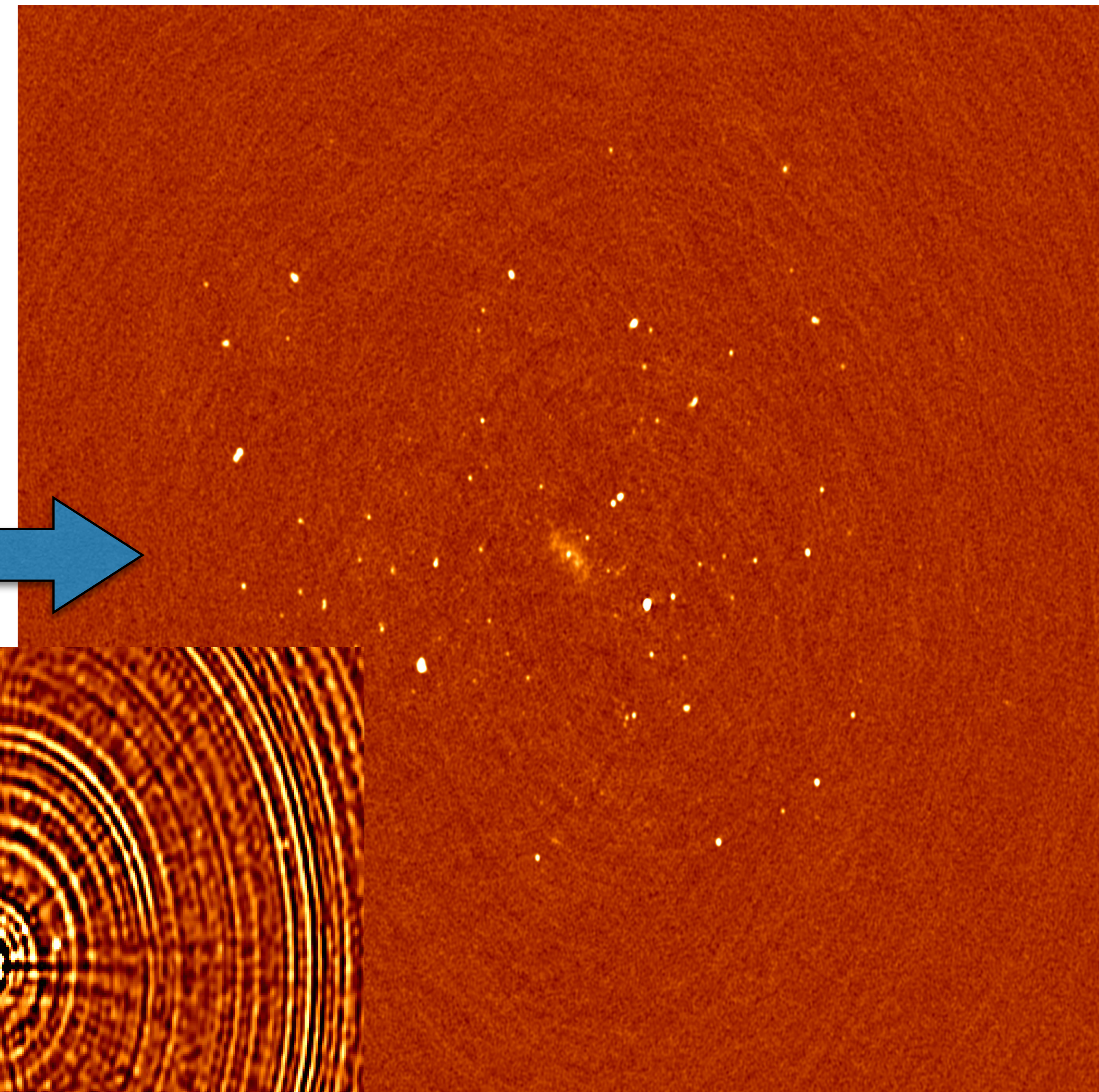
- Why calibration is needed
- The measurement equation
- Rules of thumb
- Basics: Tsys, delays, primary and secondary calibration
- Self-calibration
- Direction dependent calibration

- Source material
  - Synthesis Imaging in Radio Astronomy II:
    Chapter 5 "Calibration and Editing" by Fomalont & Perley
  - Lecture slides by John McKean, Emil Lenc, Mike Garrett, Tom Oosterloo …

Why calibration is needed

- Not the case that the FT of observed visibilities will provide a nice image!
- Example image demonstrating effect of calibration:



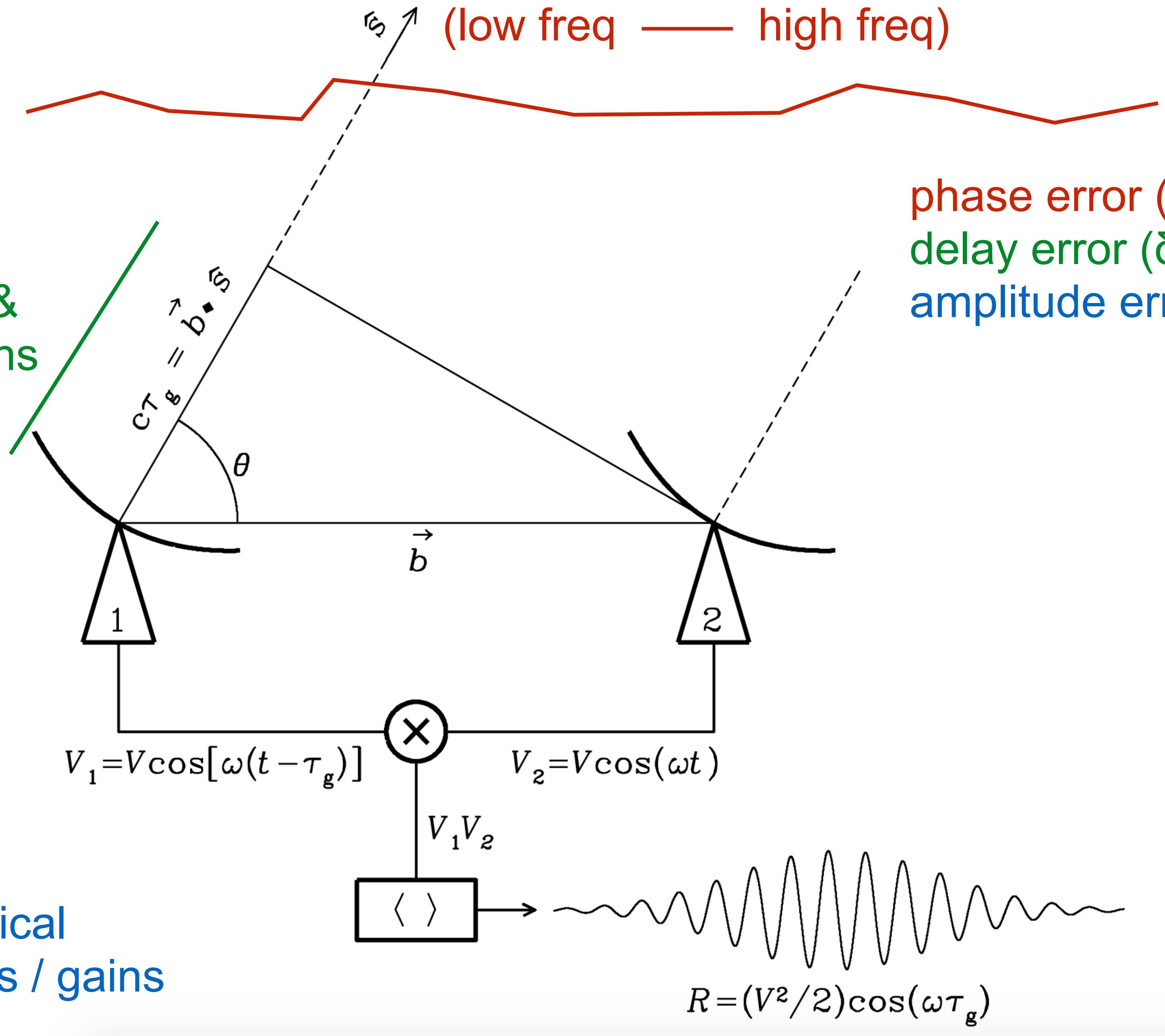


Sketch of an ideal interferometer

Ionosphere+Troposphere
(low freq —— high freq)

Bad positions &
wide bandwidths

phase error ($\delta\omega t$)
delay error ($\delta\tau_g$)
amplitude errors (δV)



Non-identical
electronics / gains

Solve for these issues using calibration

Why calibration is needed

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- Relevant physical effects:

Antenna/feed
- System temperature
- Primary beam
- Pointing
- Position (location)

Atmosphere
- Ionosphere
- Troposphere
- water vapor

Digitiser/Correlator
- Auto-leveling
- Baseline errors

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

- Key factors: corresponding timescales, frequency dependence, polarimetric properties, **order in signal path**, …

Introduction to the RIME

The **radio interferometry measurement equation** (RIME) relates the **observed** (perturbed) visibility to the **ideal** (unperturbed) **visibility.**

$$\vec{V}_{ij} = \begin{pmatrix} XX & XY \\ YX & YY \end{pmatrix}$$

Jones matrix for antenna *i*

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

observed visibility

ideal visibility

Combined Jones matrix

A Jones matrix is a 2 x 2 matrix that describes the *antenna* based calibrations, for each correlation, for a given correction (gain, bandpass, delay, etc.), for example,

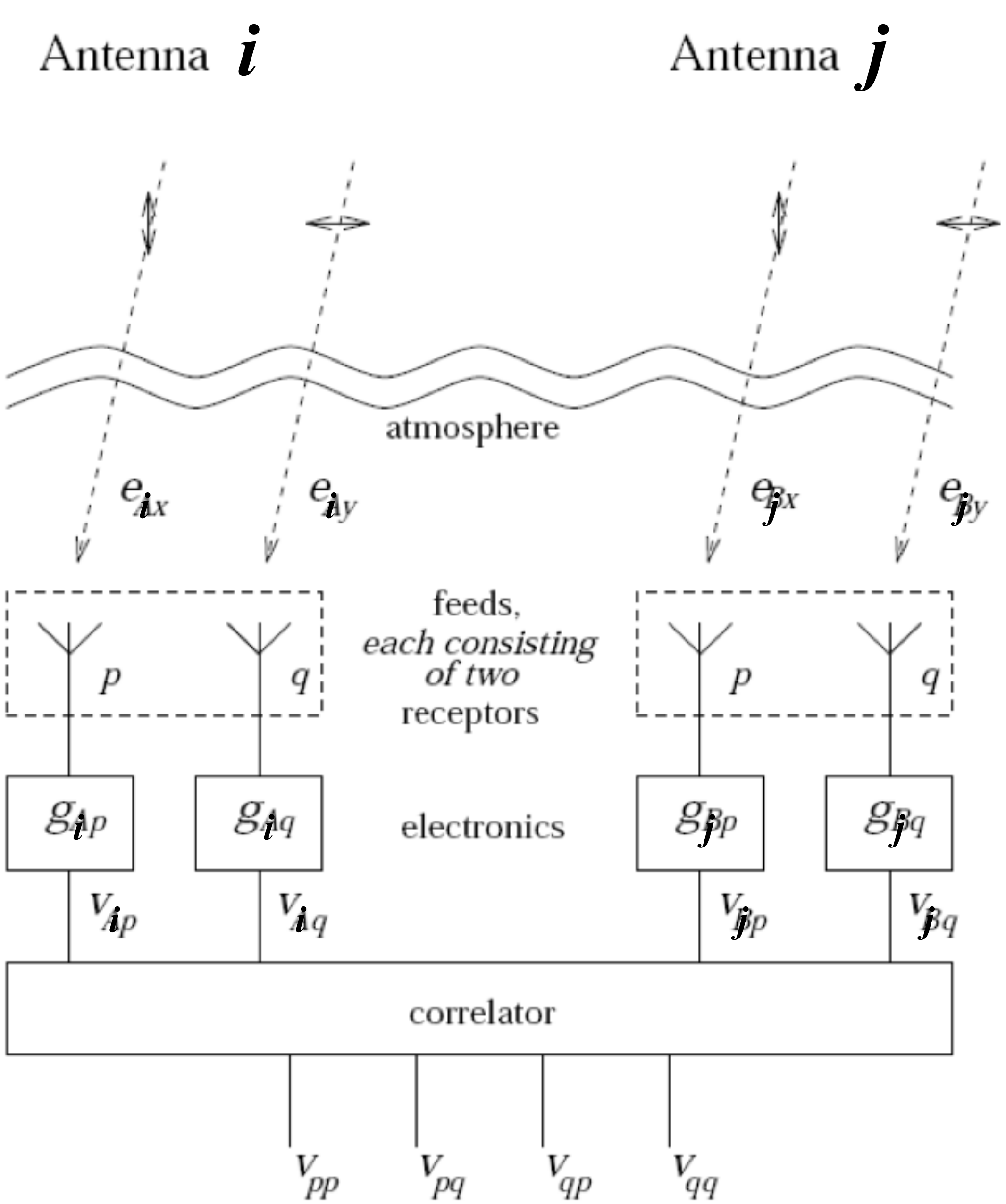
$$J_{\mathrm{gain}} = \begin{pmatrix} g_{\mathrm{R}} & 0 \\ 0 & g_{\mathrm{L}} \end{pmatrix} \qquad J_{\mathrm{leakage}} = \begin{pmatrix} 1 & D_{\mathrm{R}} \\ D_{\mathrm{L}} & 0 \end{pmatrix}$$ such that $$J_{\mathrm{overall}} = J_1 J_2 J_3$$

Gain phases in the RIME & closure

- Phase fluctuations caused by structure in atmosphere, troposphere, ionosphere

$$V_{ij}^{\mathrm{obs}} = G_{ij} V_{ij}^{\mathrm{true}} \qquad G_{ij} = G_i \times G_j^*$$

$$G = \begin{pmatrix} g_{00} e^{-i\theta_{00}} & 0 \\ 0 & g_{11} e^{-i\theta_{11}} \end{pmatrix}$$



- Constant gain offset on ***all*** antennas has no net effect
- Phase closure around triangle:

$$\theta_i(t) = \arg g_i(t).$$

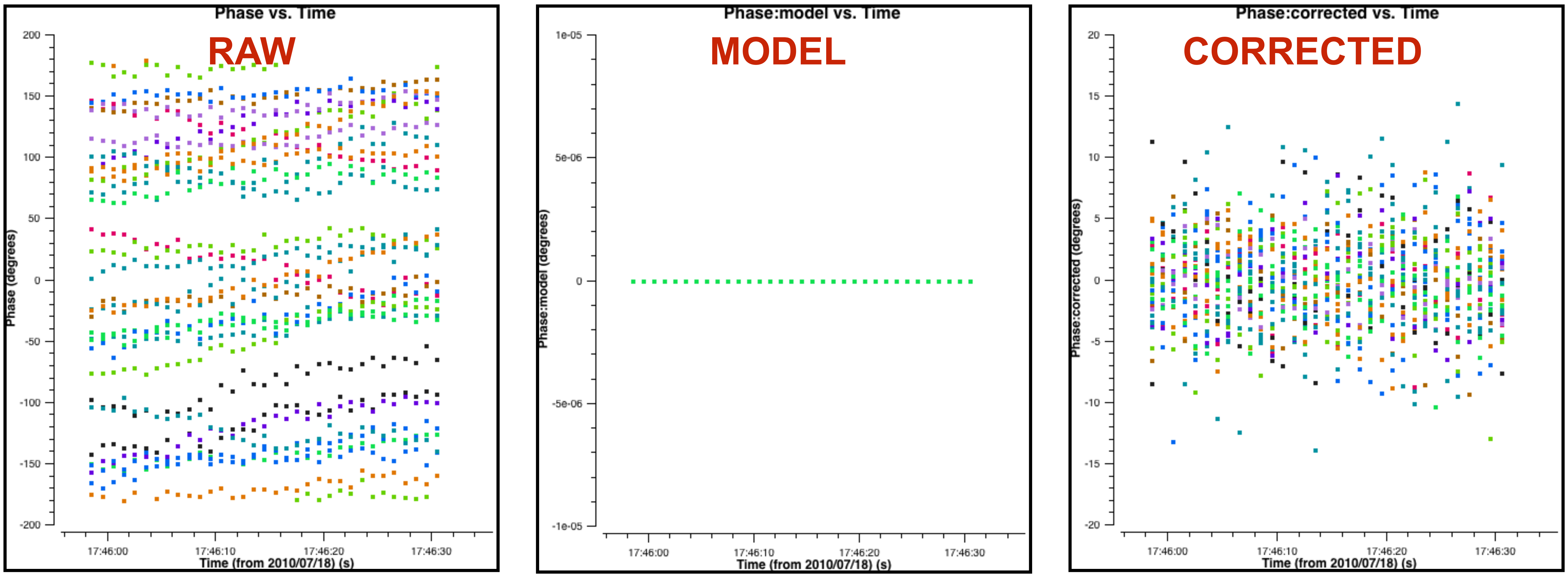
$$\widetilde{\phi}_{ij}(t) = \phi_{ij}(t) + \theta_i(t) - \theta_j(t) + \text{noise term}\,,$$

$$\begin{aligned} \widetilde{C}_{ijk}(t) &= \widetilde{\phi}_{ij}(t) + \widetilde{\phi}_{jk}(t) + \widetilde{\phi}_{ki}(t) \\ &= \phi_{ij}(t) + \phi_{jk}(t) + \phi_{ki}(t) + \text{noise term} \\ &= C_{ijk}(t) + \text{noise term}\,. \end{aligned}$$

Example of phase calibration

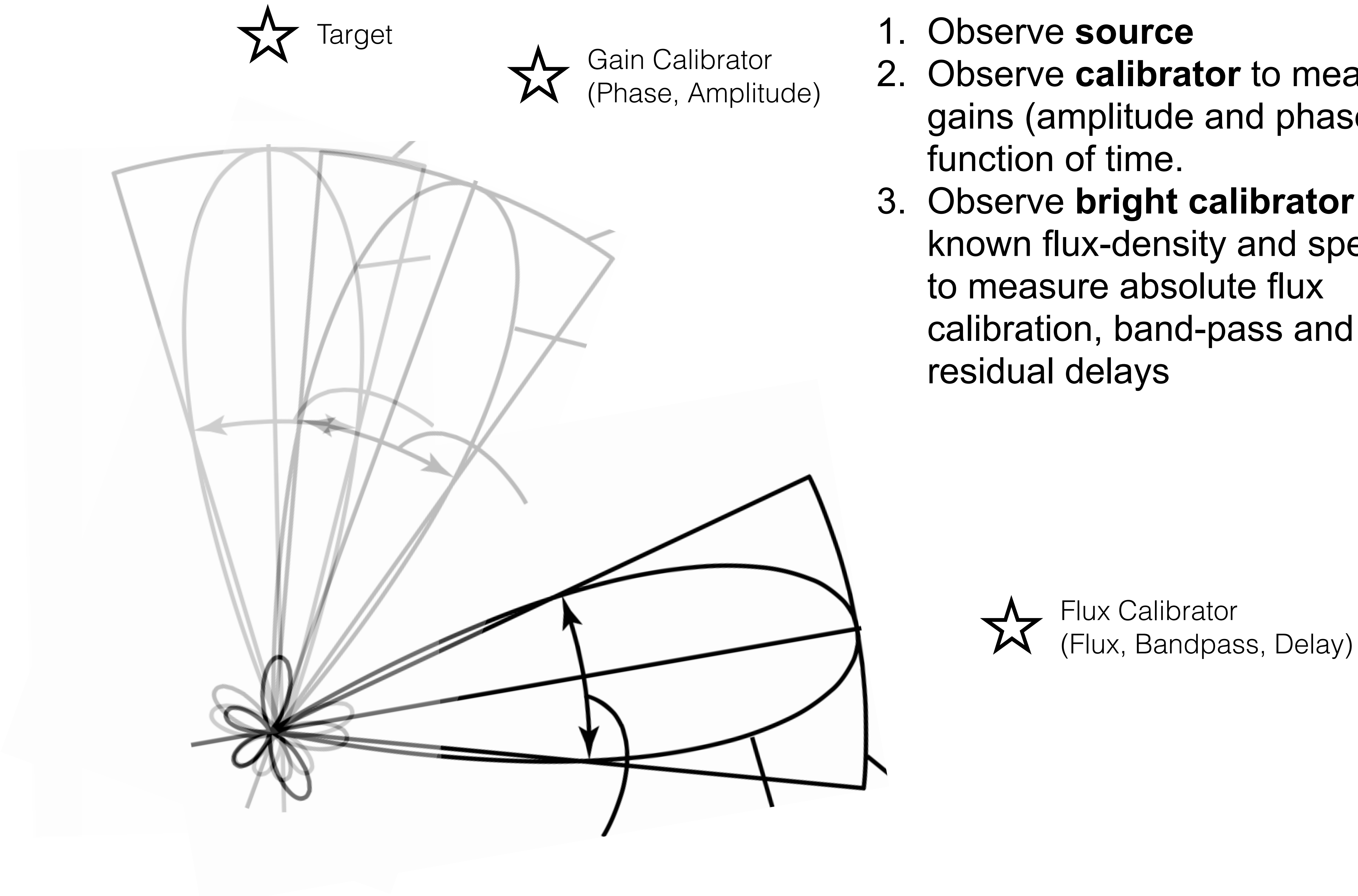
Here is an observed visibility function (phase), the ideal visibility function and the calibrated data (after solving the G_{ij} in the the measurement equation).

Main source of phase error: Variable ionosphere or troposphere + electronics.



More complex delay corrections require ‘fringe fitting’ : see VLBI lecture.

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

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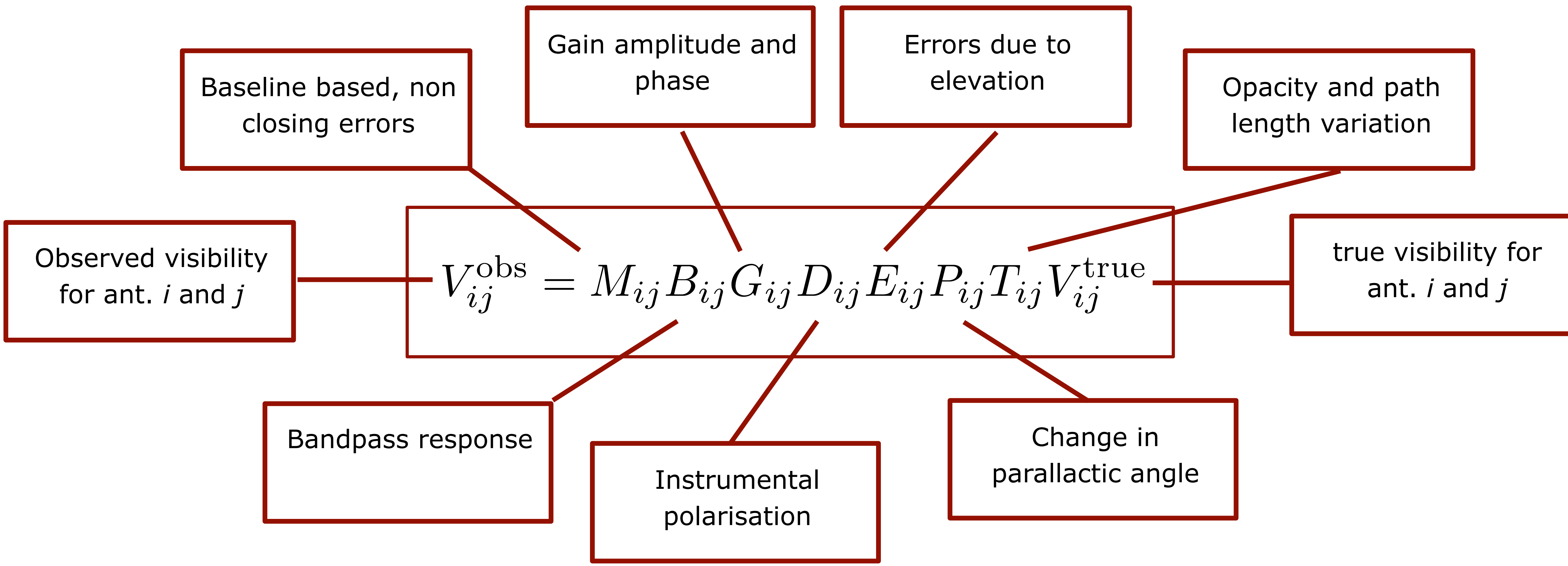
Within, for example **CASA**, the full radio interferometry measurement equation can be written as,



$$V_{ij}^{\mathrm{obs}} = M_{ij} B_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\mathrm{true}}$$

Calibration solves for each Jones matrix (when required) given a **model** for the sky.

Faraday rotation

- Jones matrix representation of Faraday rotation

$$F(\nu) = \begin{pmatrix} \cos(\phi\frac{c^2}{\nu^2}) & -\sin(\phi\frac{c^2}{\nu^2}) \\ \sin(\phi\frac{c^2}{\nu^2}) & \cos(\phi\frac{c^2}{\nu^2}) \end{pmatrix}$$

- Can be thought of as rotating the linear polarization coordinate frame, in a frequency-dependent manner

- See polarization lecture

Calibration

- Calibration is the process of perfecting the sky and instrument models

$$V_{ij}^{\mathrm{obs}} = \underbrace{M_{ij}B_{ij}G_{ij}D_{ij}E_{ij}P_{ij}T_{ij}}_{\text{instrument}}\underbrace{V_{ij}^{\mathrm{true}}}_{\text{sky}}$$

- Parameters determined through fitting (typically least-squares)

- Note, fundamental assumption:

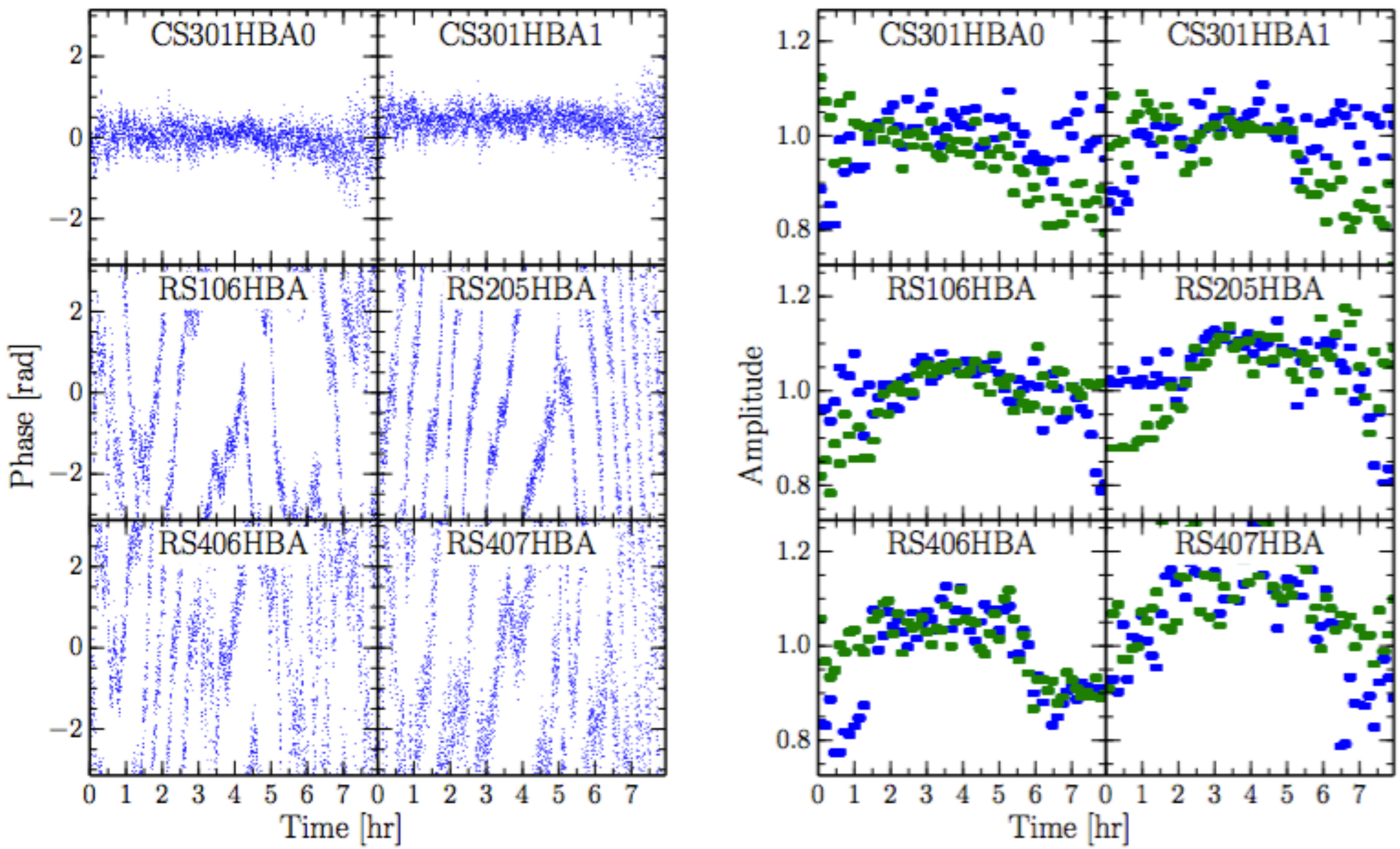
  Calibration parameters are antenna based

- Three levels:

  - (Primary) Calibration: use of a "known" standard source to determine time independent quantities e.g. B_{ij}
  - Secondary Calibration: estimate local conditions with nearby calibrator
  - Self-Calibration: use of the target field to determine time dependent quantities, e.g. G_{ij}

Rules of thumb

- Always inspect your data carefully!
  - Both visibilities and calibration solutions
  - Amplitude and phase



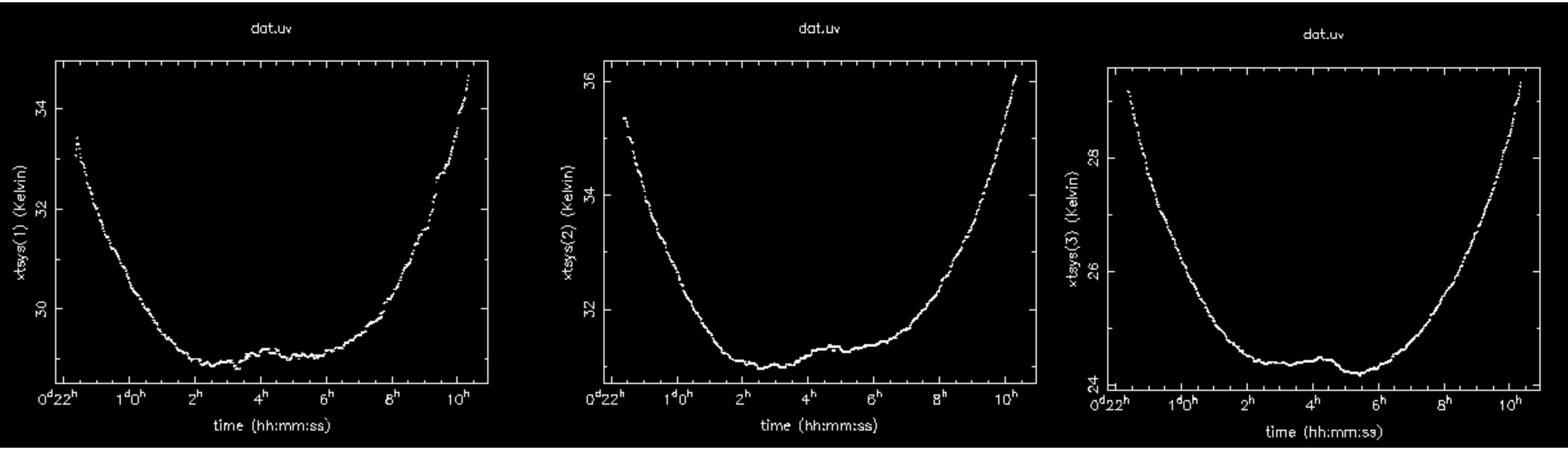
Wendy Williams et al, submitted

Rules of thumb

- Don’t be afraid to flag bad data!
  - Corrupted data can reduce the image quality significantly
  - Effect of missing data (even 25%) is often minor and easily corrected in deconvolution
- Consider physical effects when choosing calibration parameters
  - What are the timescales and frequency dependence?
- Visualize your data!

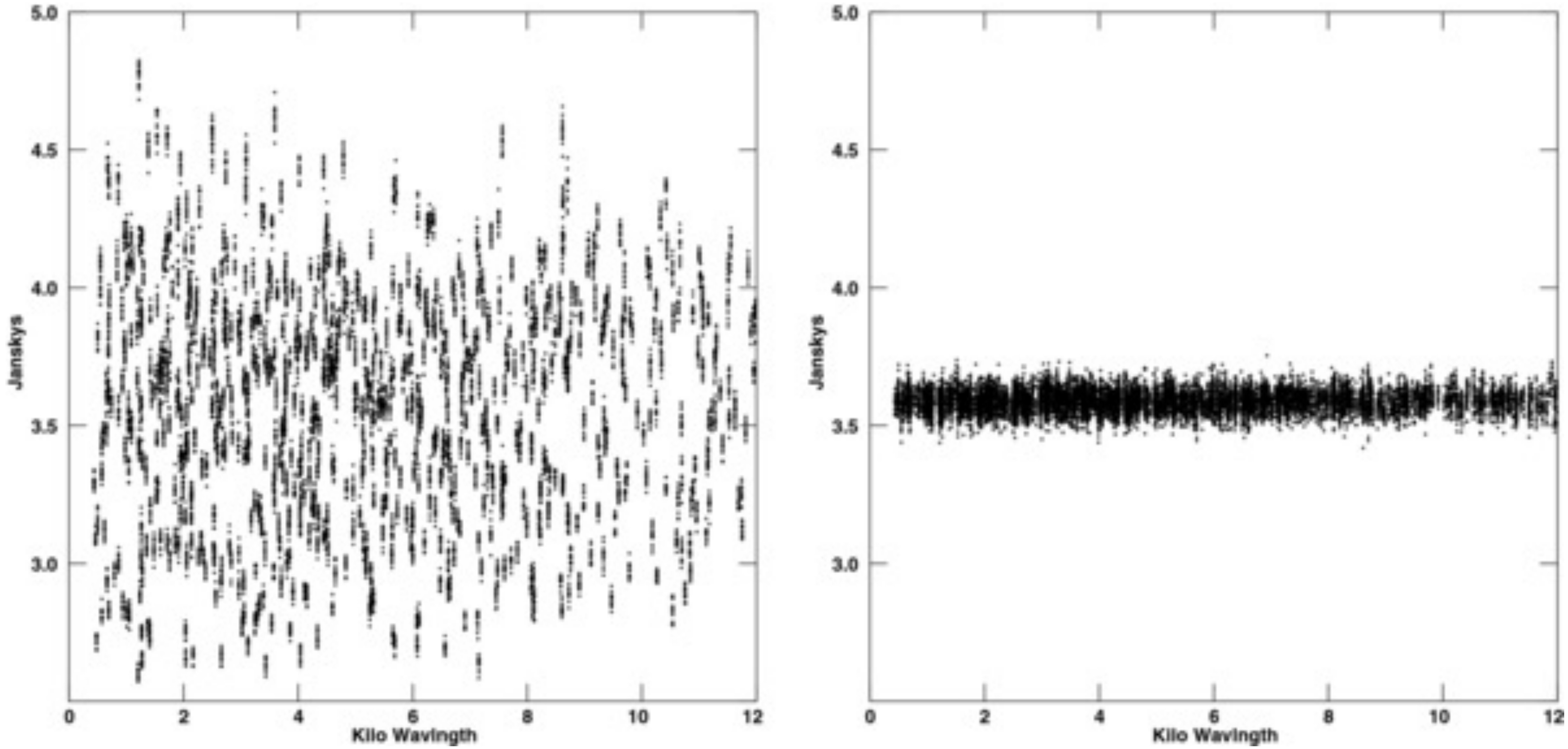
System temperature

- The system temperature (T_{sys}) is a time-dependent measure of the sensitivity of each antenna
  - Often measured directly (using on-dish calibrator source) and included with visibility data
  - When available, apply it first!
  - Example: 3 WSRT antennas (measured T_{sys} values for the X feed):



Online gain correction (JVLA)

- Variable system gain corrected online (via a calibrated signal injected in the receivers and detected in the correlator)



Perley & Butler (2013)

Calibrator models

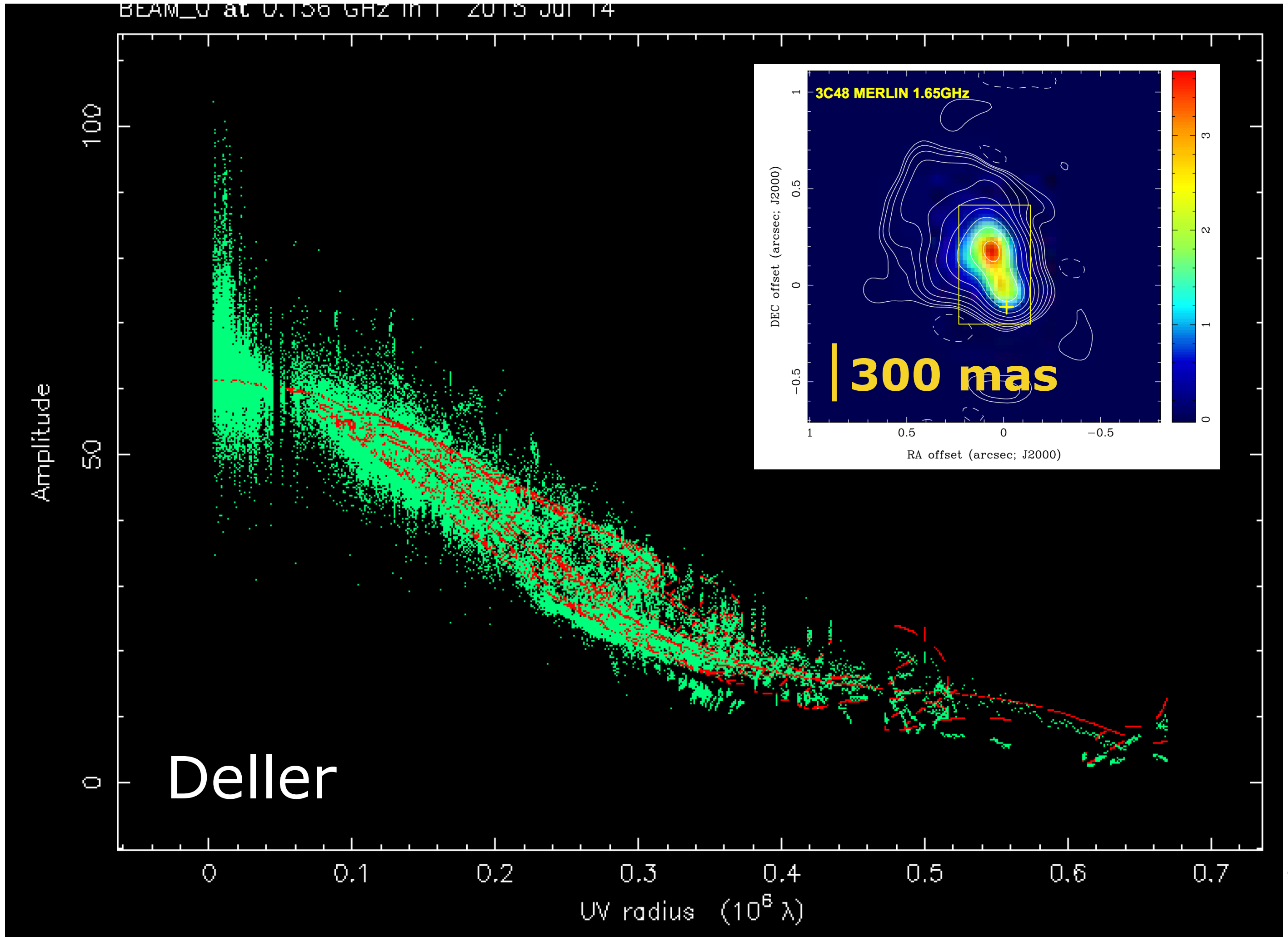
- Recall that the antenna voltage:

$$V \propto E \propto \sqrt{I}$$

- Therefore the visibility amplitudes are proportional to the source intensity
- Flux (and bandpass) calibration is the process of empirically determining the proportionality constant

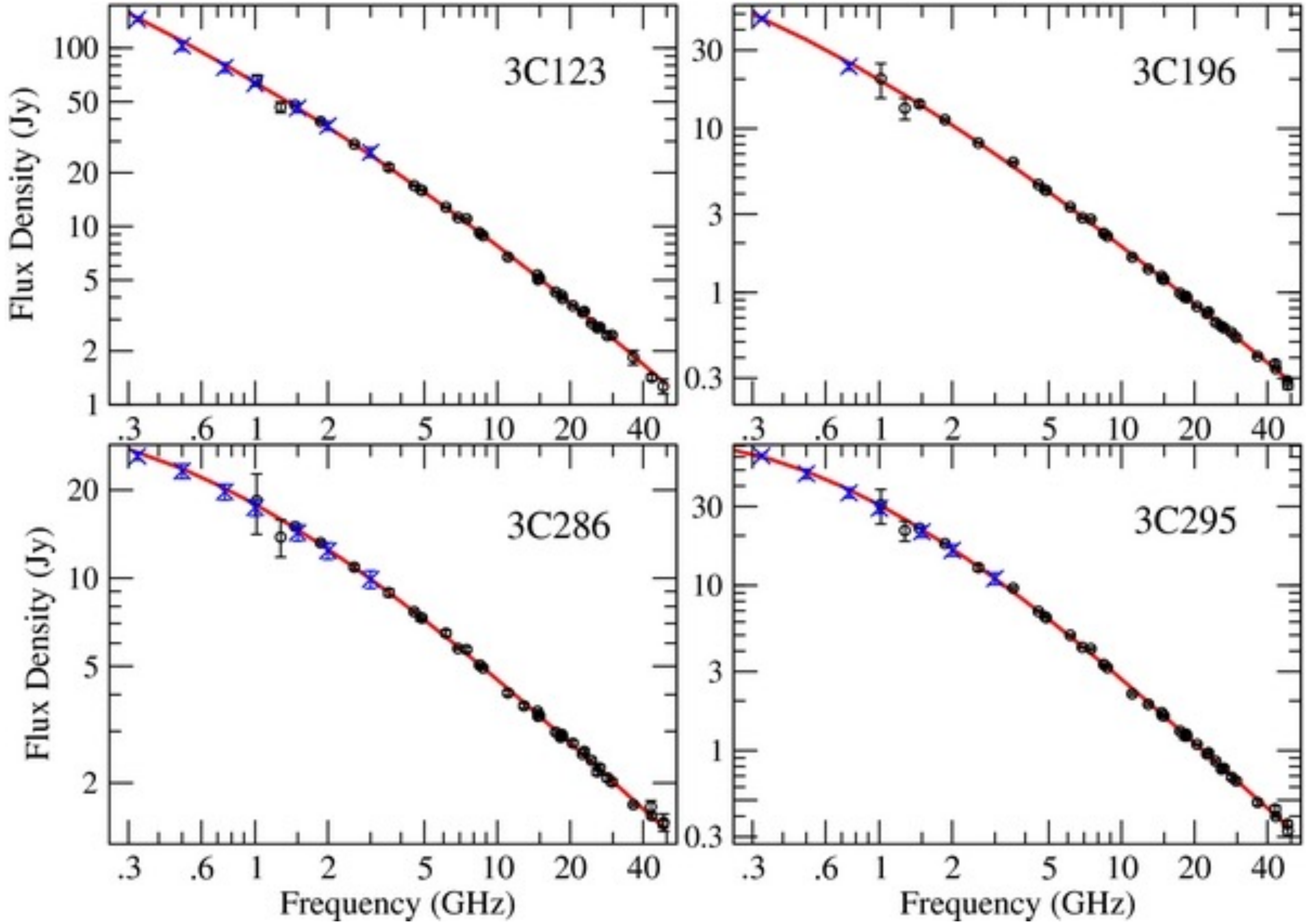
- Since calibration parameters are antenna based, there are N unknowns and N(N-1)/2 equations
  - For N>3, this is an overdetermined problem

- Caution: for high-resolution applications, ensure that the source is compact!



Calibrator models

- Primary calibration derived from dedicated short observations of standard sources, e.g.:



Perley & Butler (2013)

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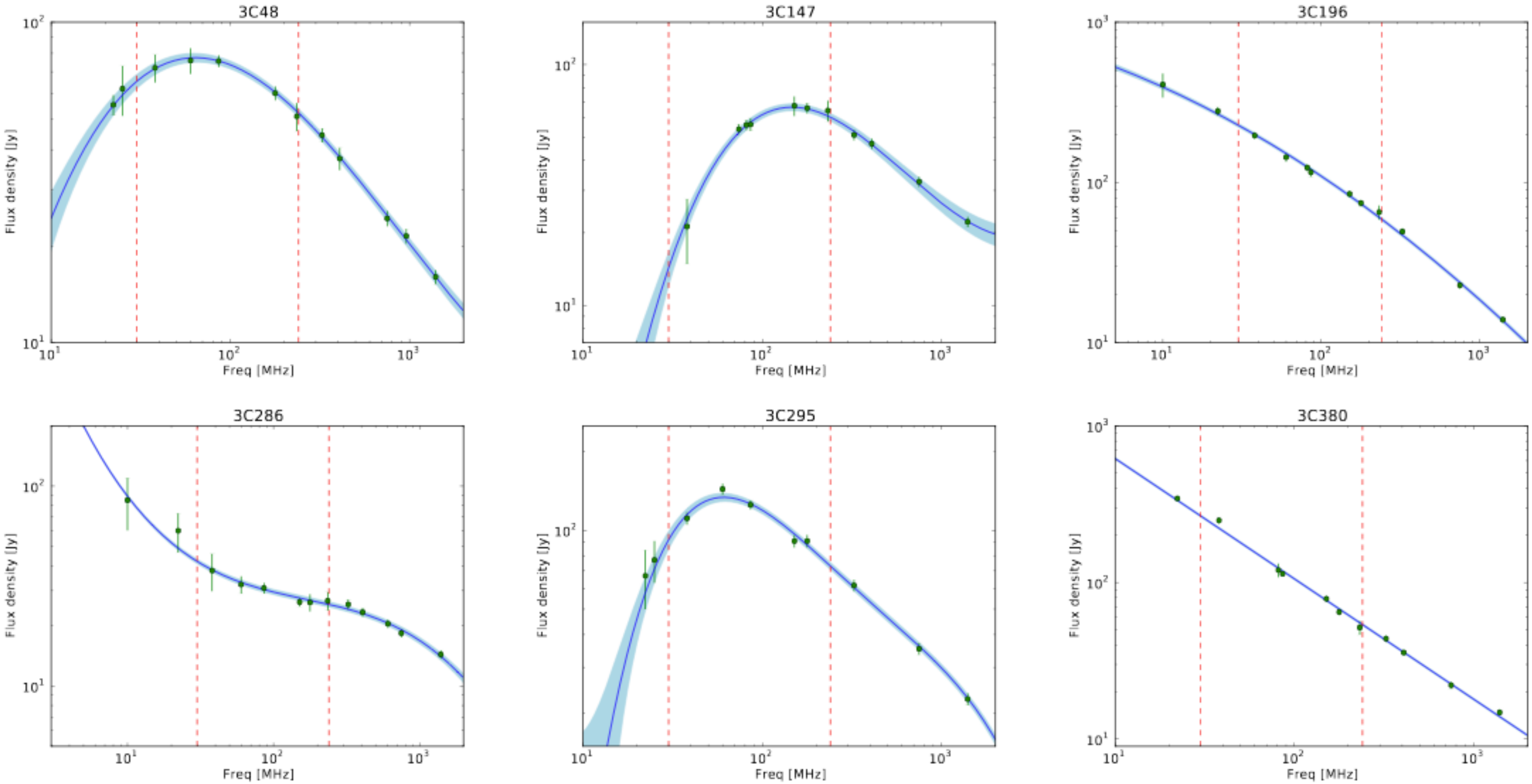
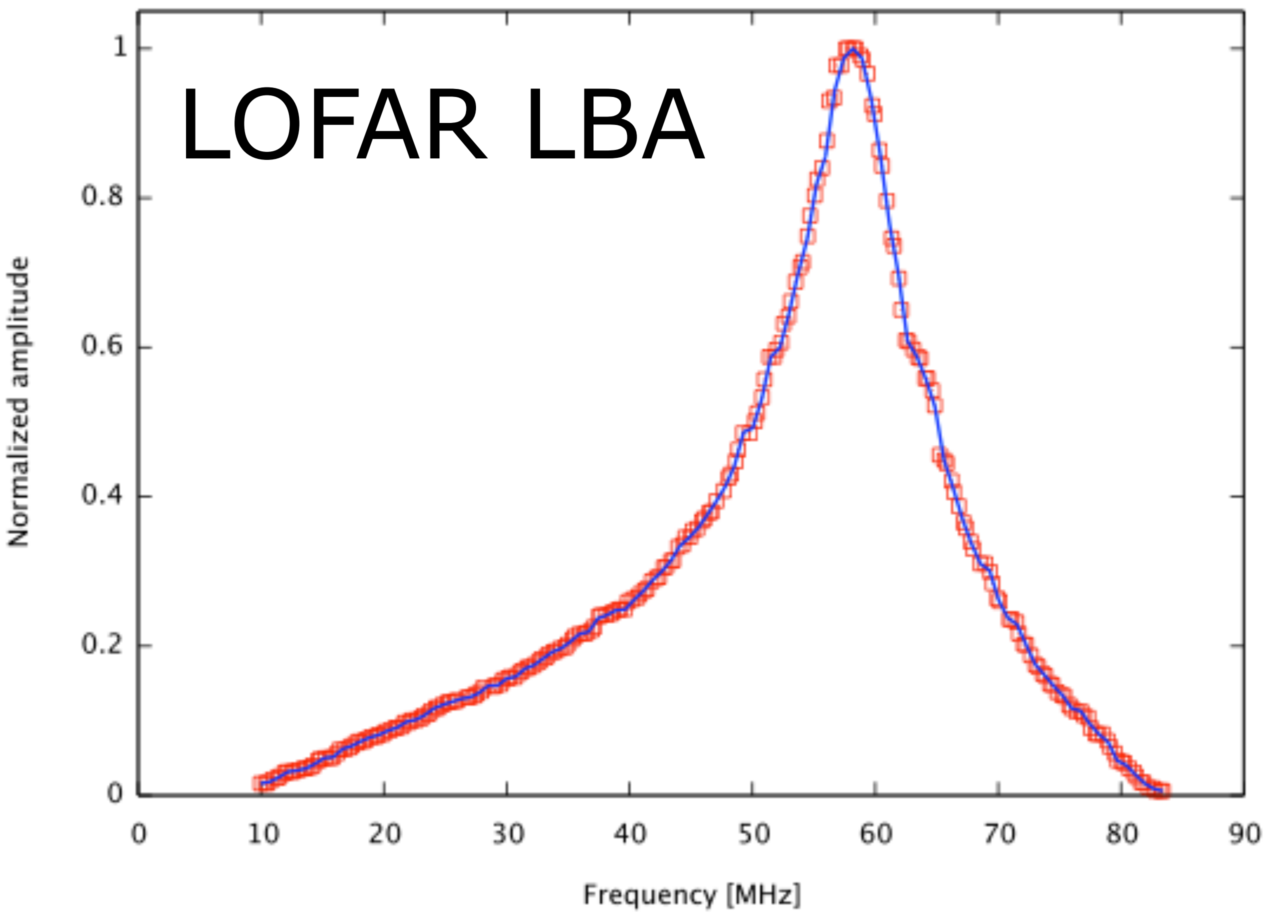
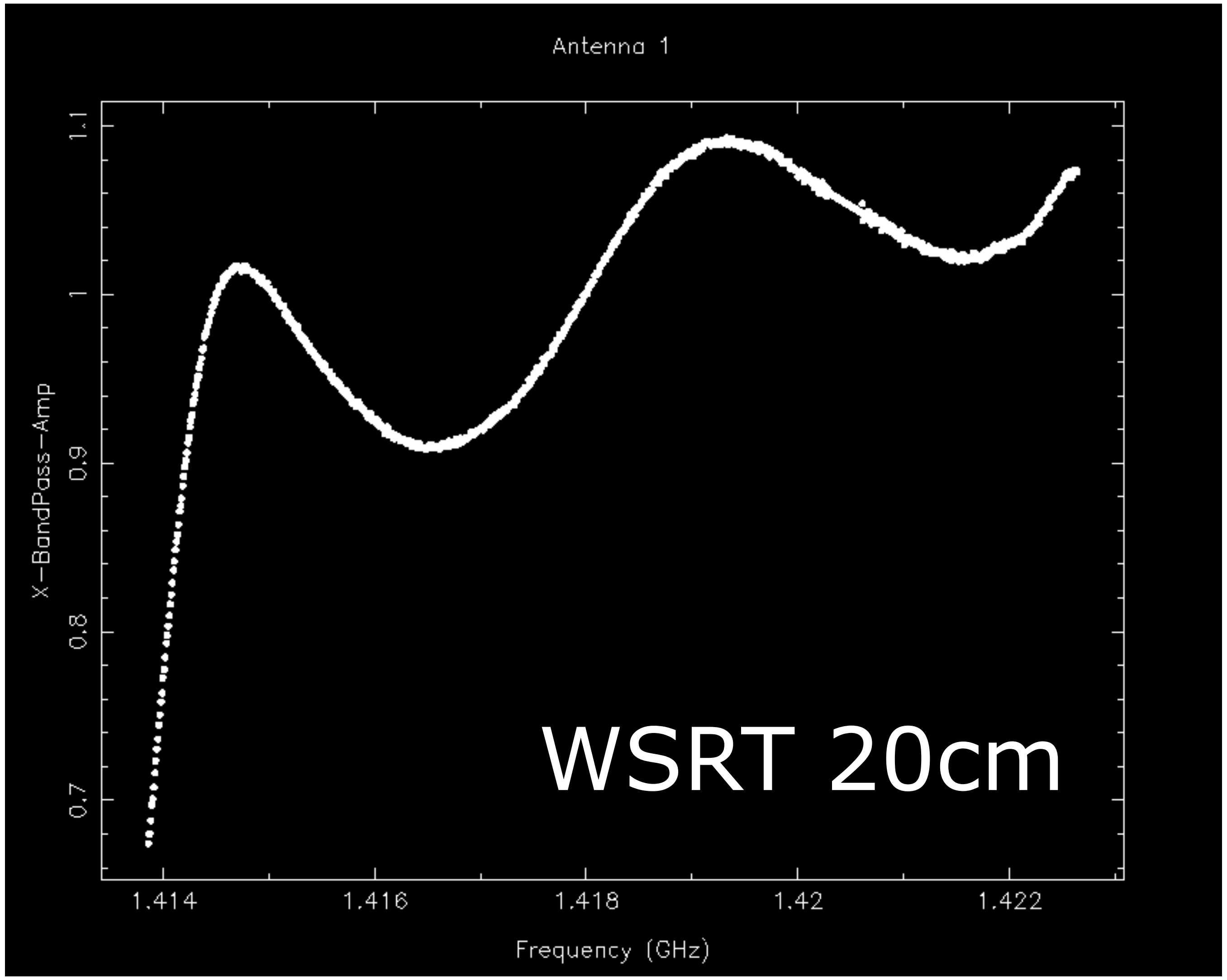


Scaife & Heald (2012)

LOFAR bandpass calibration

- This results in a bandpass and gain amplitude determination:



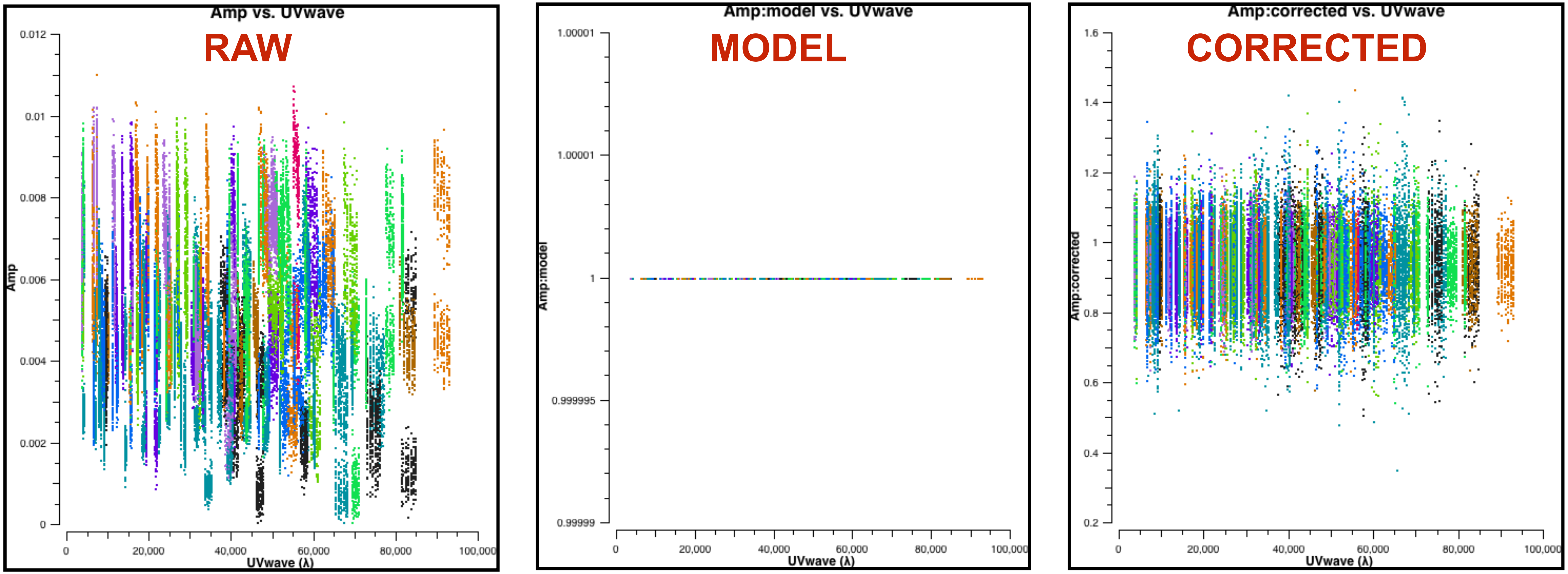


$$V_{ij}^{\rm obs} = M_{ij} \boxed{B_{ij} G_{ij}} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\rm true}$$

Example of amplitude calibration

Here is an observed visibility function (amplitude), the ideal visibility function and the calibrated data (after solving the G_{ij} in the the measurement equation).

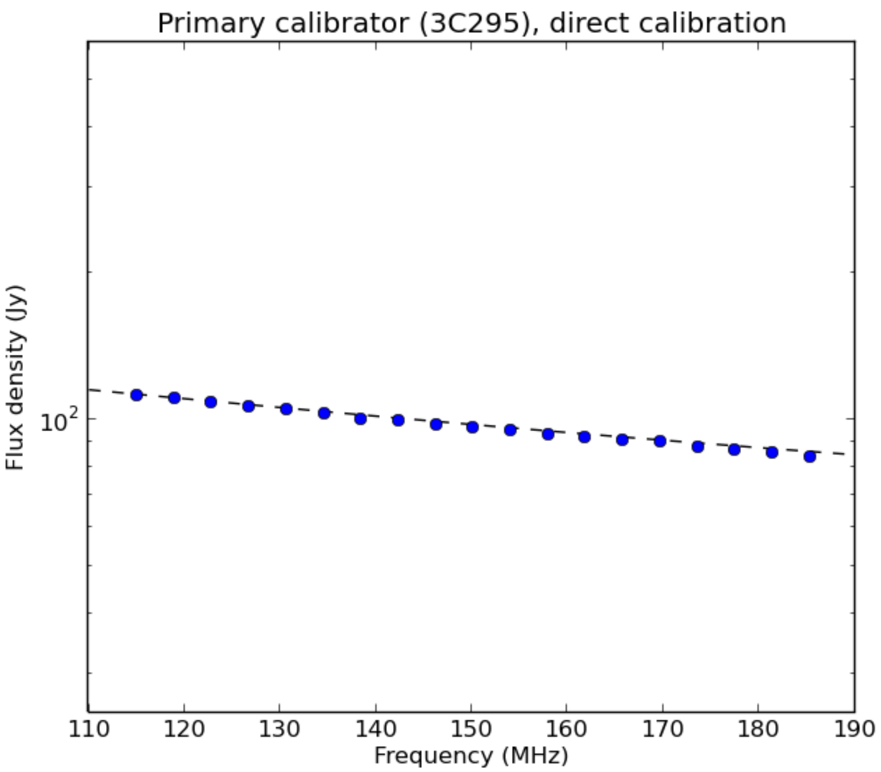
Main source of amplitude error: Variable gain in the amplifiers of the system.

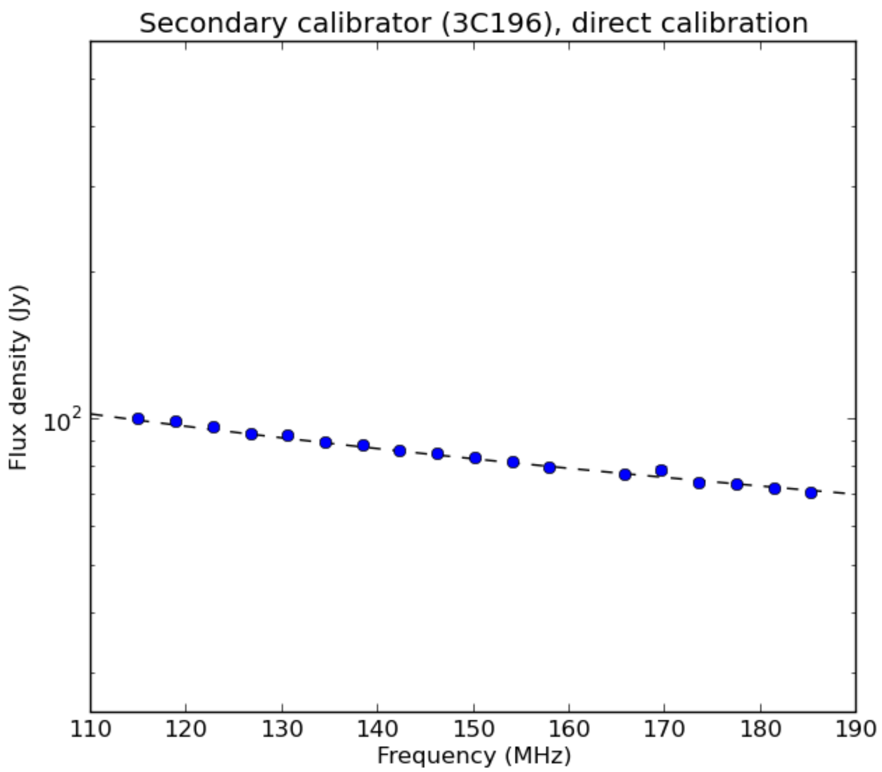


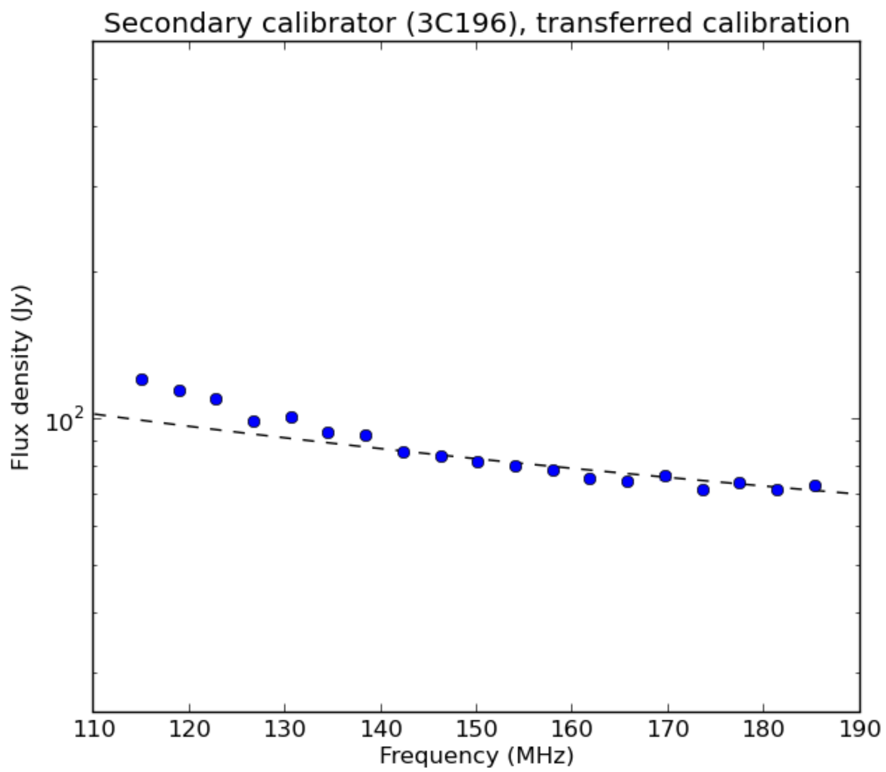
Each colour represents visibilities with a common antenna.

LOFAR primary flux calibration

- Enables calibrating the flux density of sources in one direction using reference calibrator in another (entirely different) direction

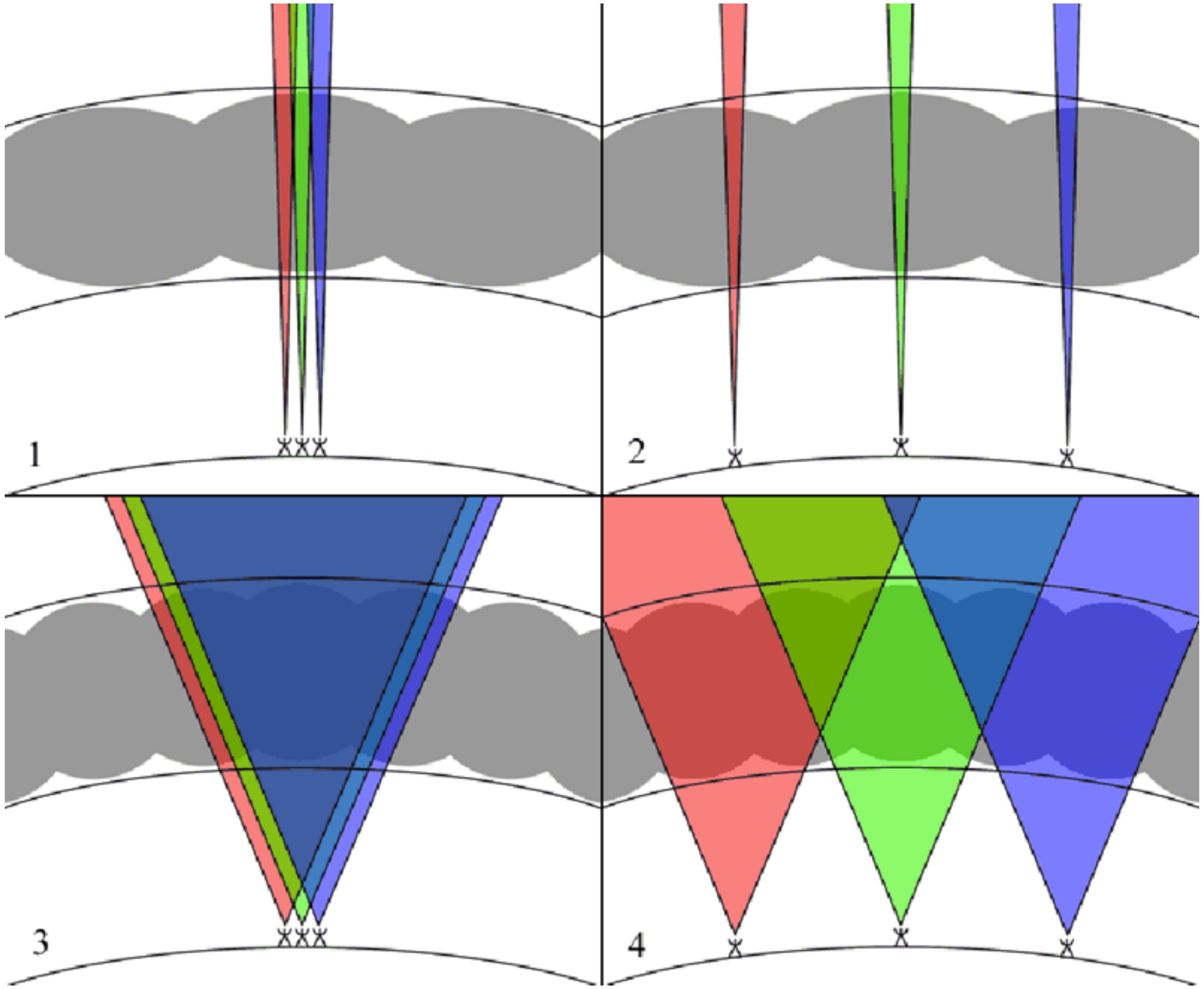






Gain phases

- Phase fluctuations caused by structure in atmosphere, troposphere, ionosphere

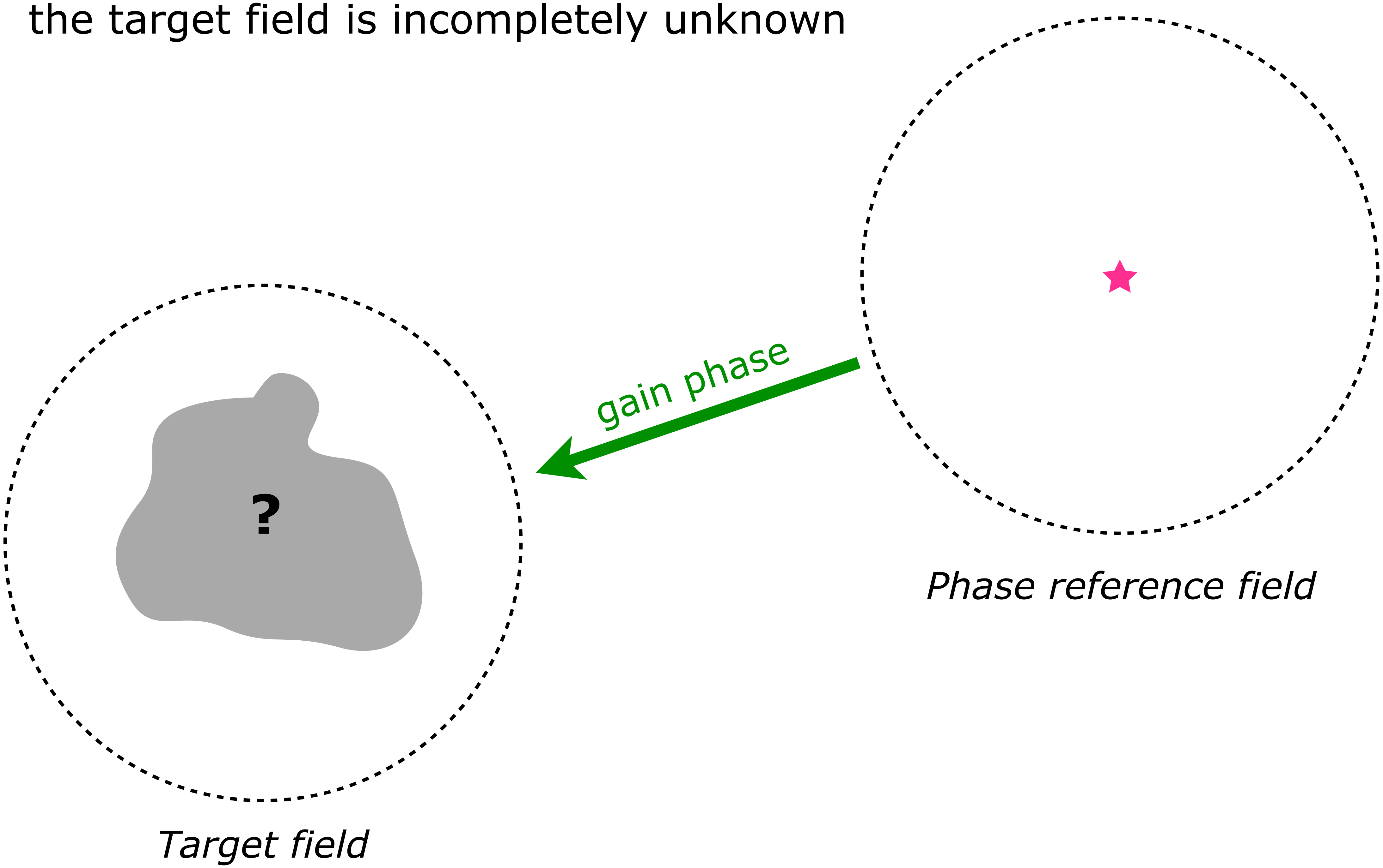


Intema et al. (2009)

- Determined from nearby phase calibrator, or field itself if good model available

Secondary calibration

- Phase calibrator used in cases where either
  - number of antennas is small (so that the number of constraints is insufficient to give a robust solution), or
  - the target field is incompletely unknown



Self-calibration philosophy

After **transferring the solutions** from a calibrator we may find that there are **residual errors** in our data.

Why?

Our calibrators are observed at a **different time** (except for simultaneous observations; in beam-calibration) and **position** on the sky than our target.

Use the process of self-calibration:

1) Make an image of your target (after applying calibrator solutions).
2) Use this model to calibrate the data over some solution interval.
3) Make an image of your target (after applying self-calibration solutions).
4) Use this model to calibrate the data over some solution interval.
5) Iterate this process until no major improvement on image quality.

Advantages:

1) Can correct for residual amplitude and phase errors.
2) Can correct for direction dependent effects (see later).

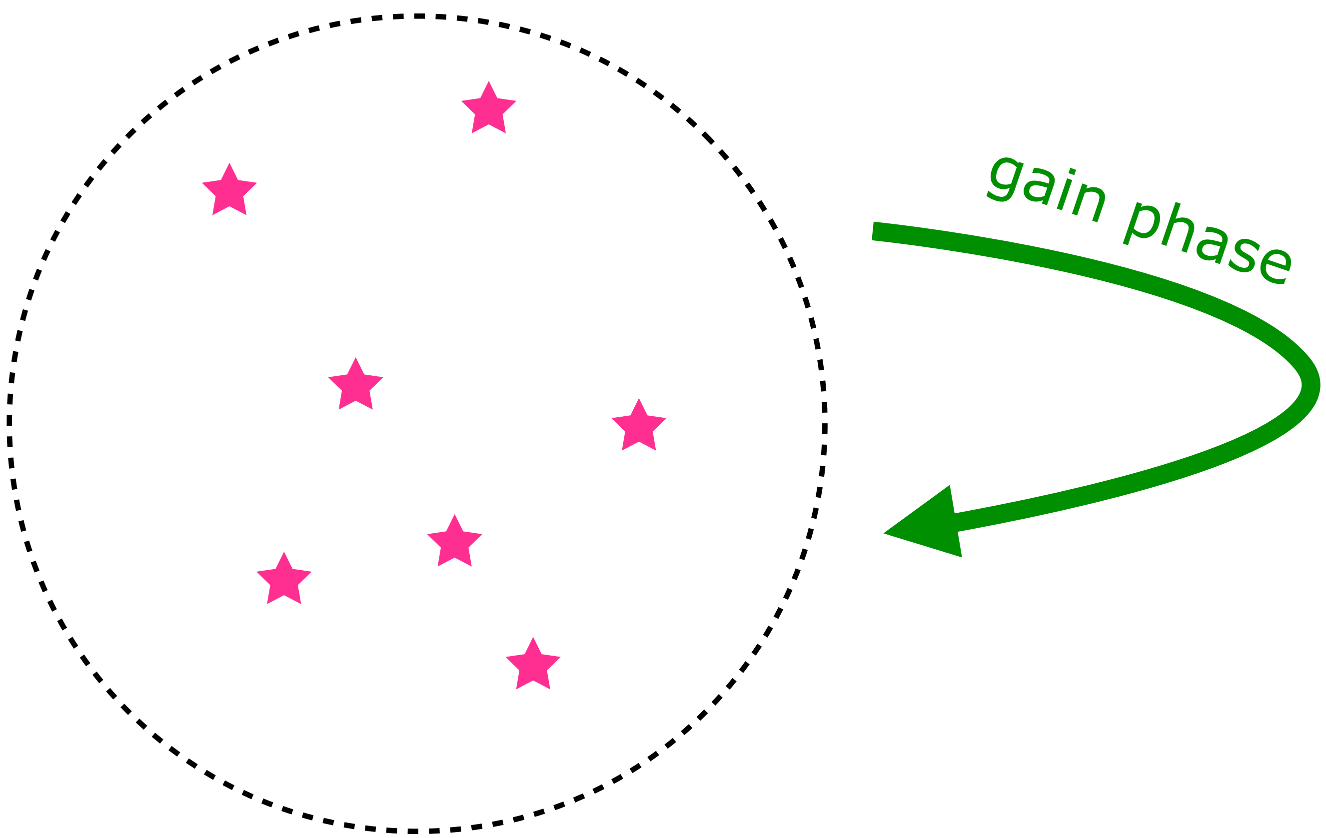
Disadvantages:

1) Errors in the model or low SNR can propagate into your self-calibration solutions, and you can diverge from the correct model.

Self calibration

- Develop model of target field, use to estimate gain term

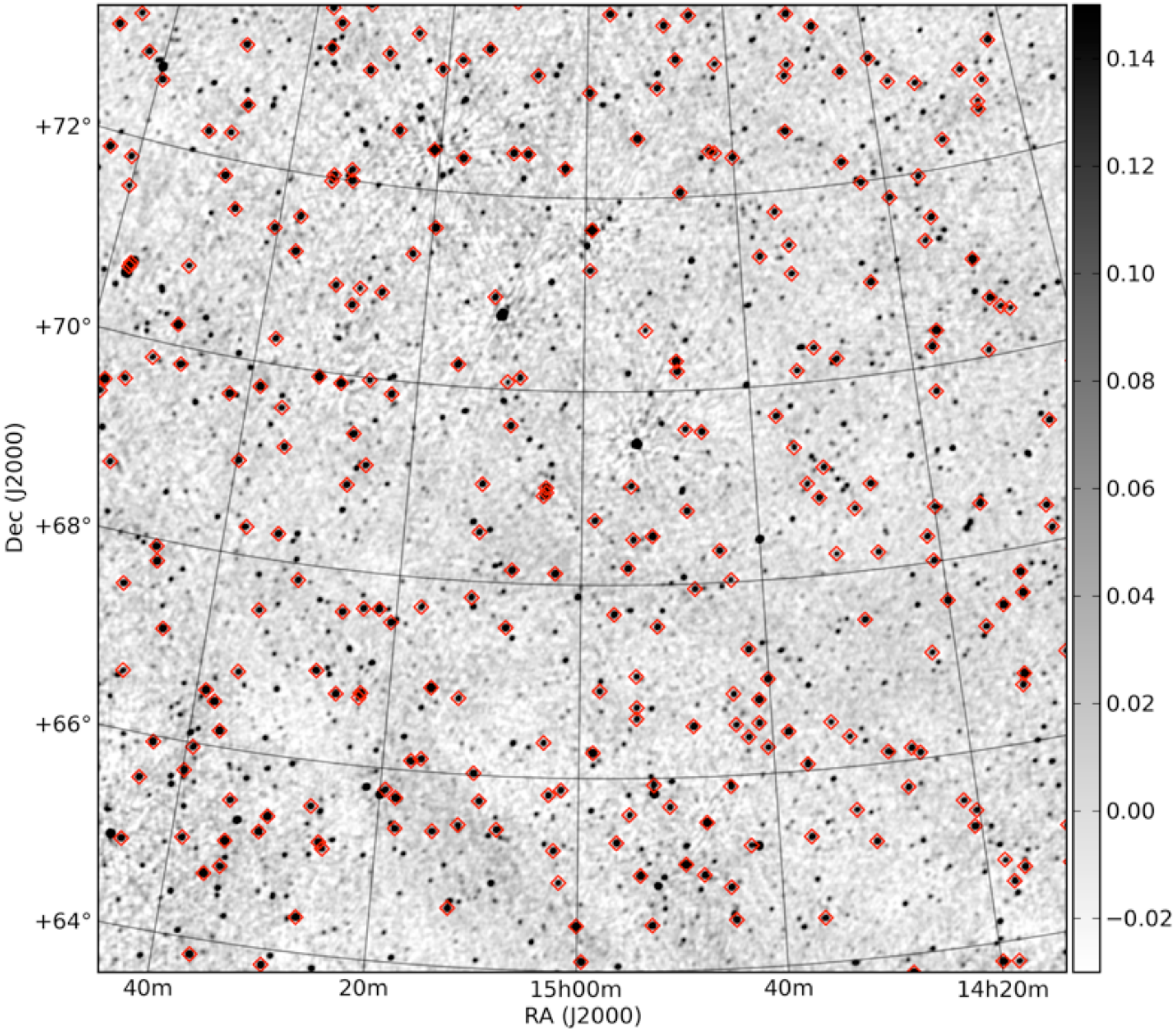
$$V_{ij}^{\text{obs}} = M_{ij} B_{ij} G_{ij} D_{ij} E_{ij} P_{ij} T_{ij} V_{ij}^{\text{true}}$$

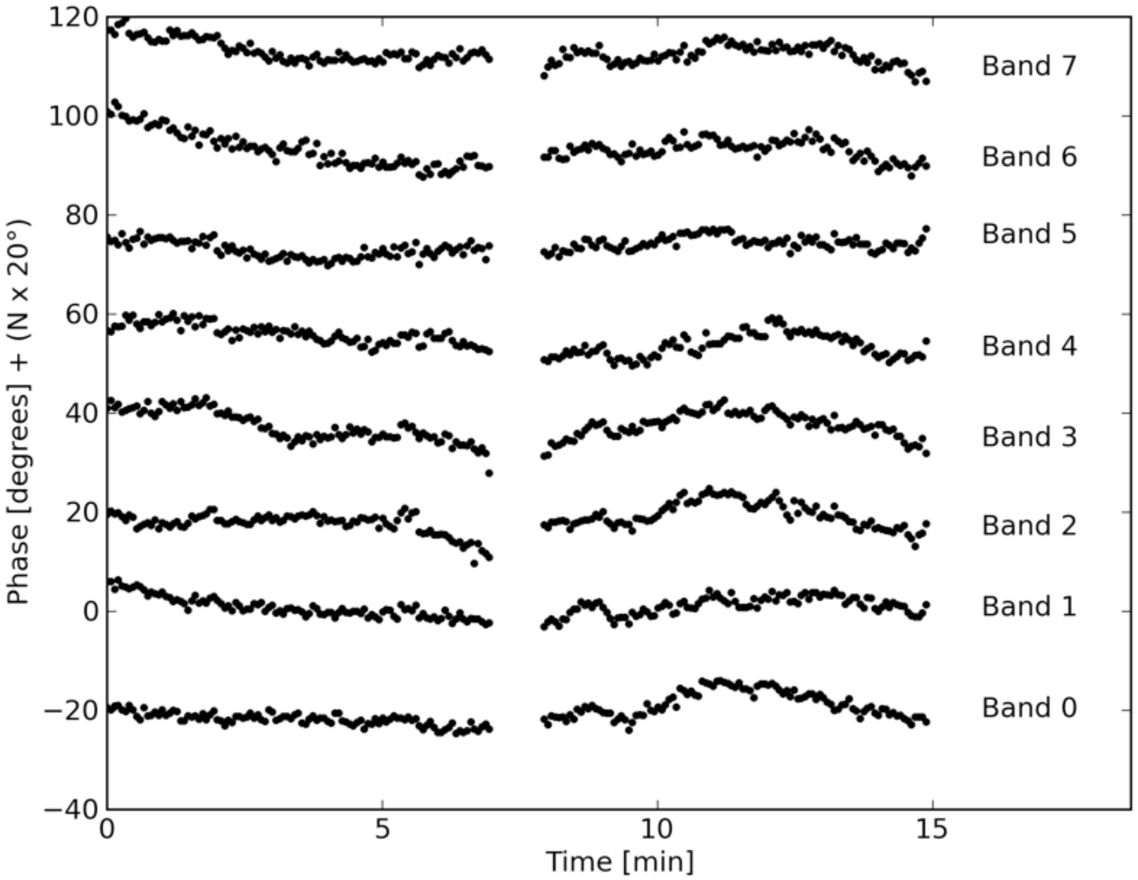


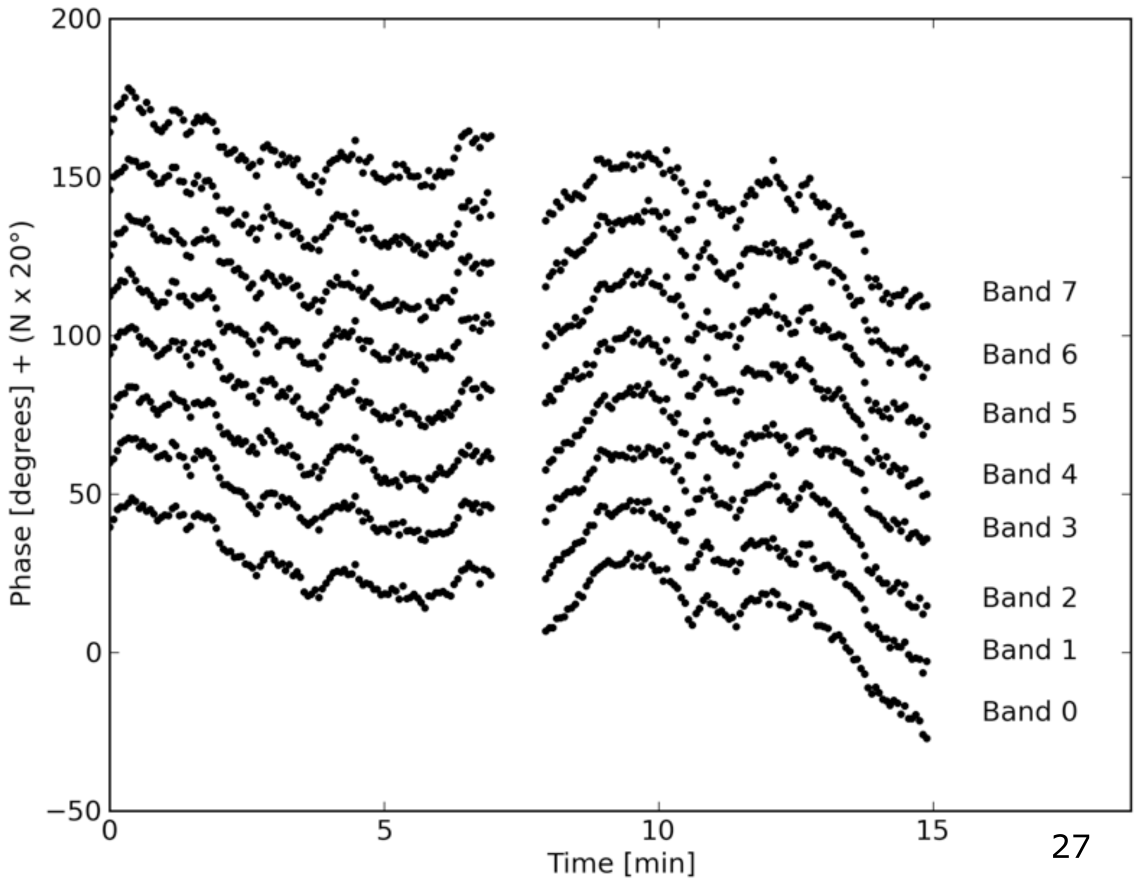
Target field

Example: LOFAR phase solutions

- From MSSS, at HBA frequencies



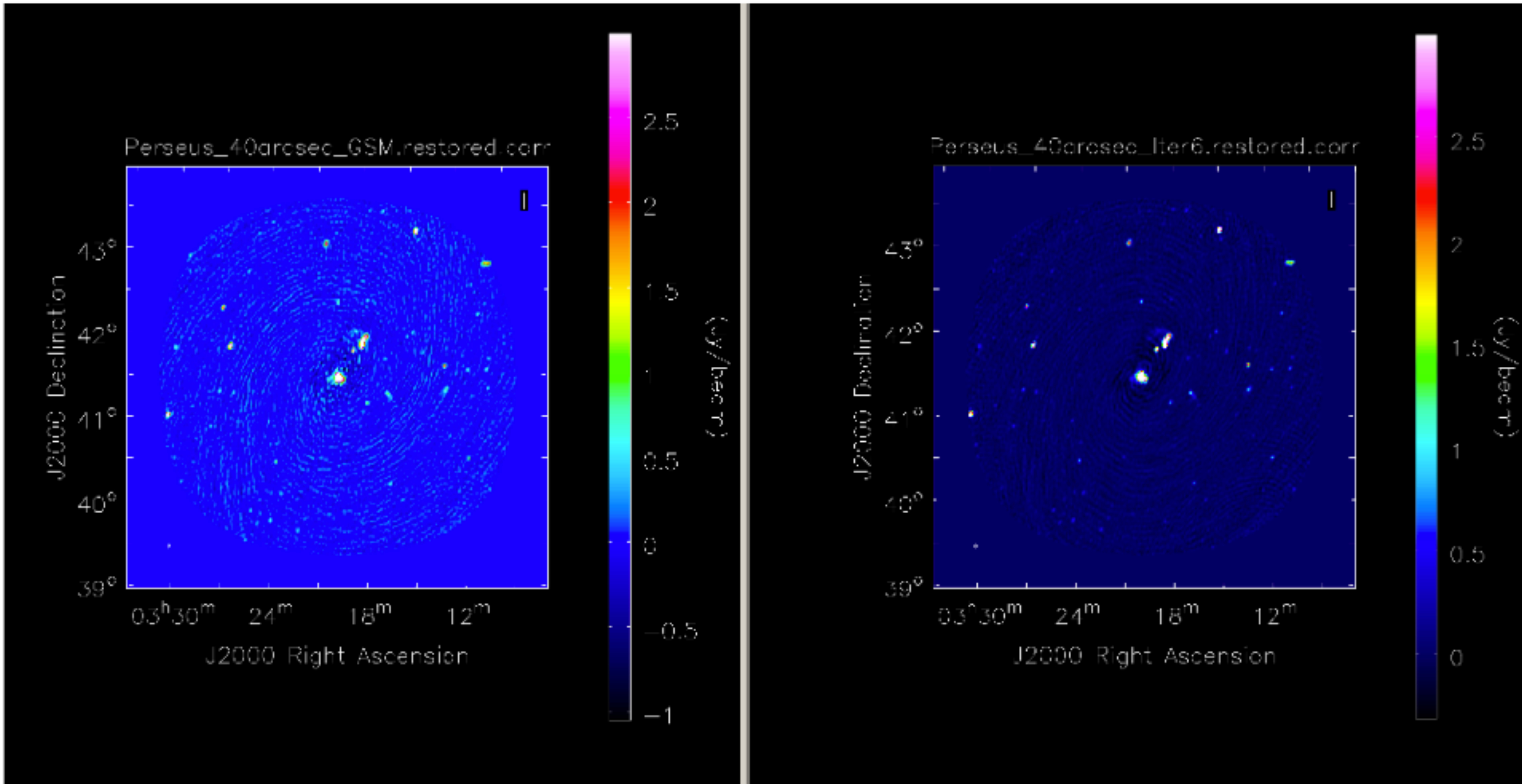




Heald et al (2015)

- Before & after Perseus cluster field (development LOFAR selfcal pipeline by Nicolas Vilchez)

GSM calibration **Self-calibration**

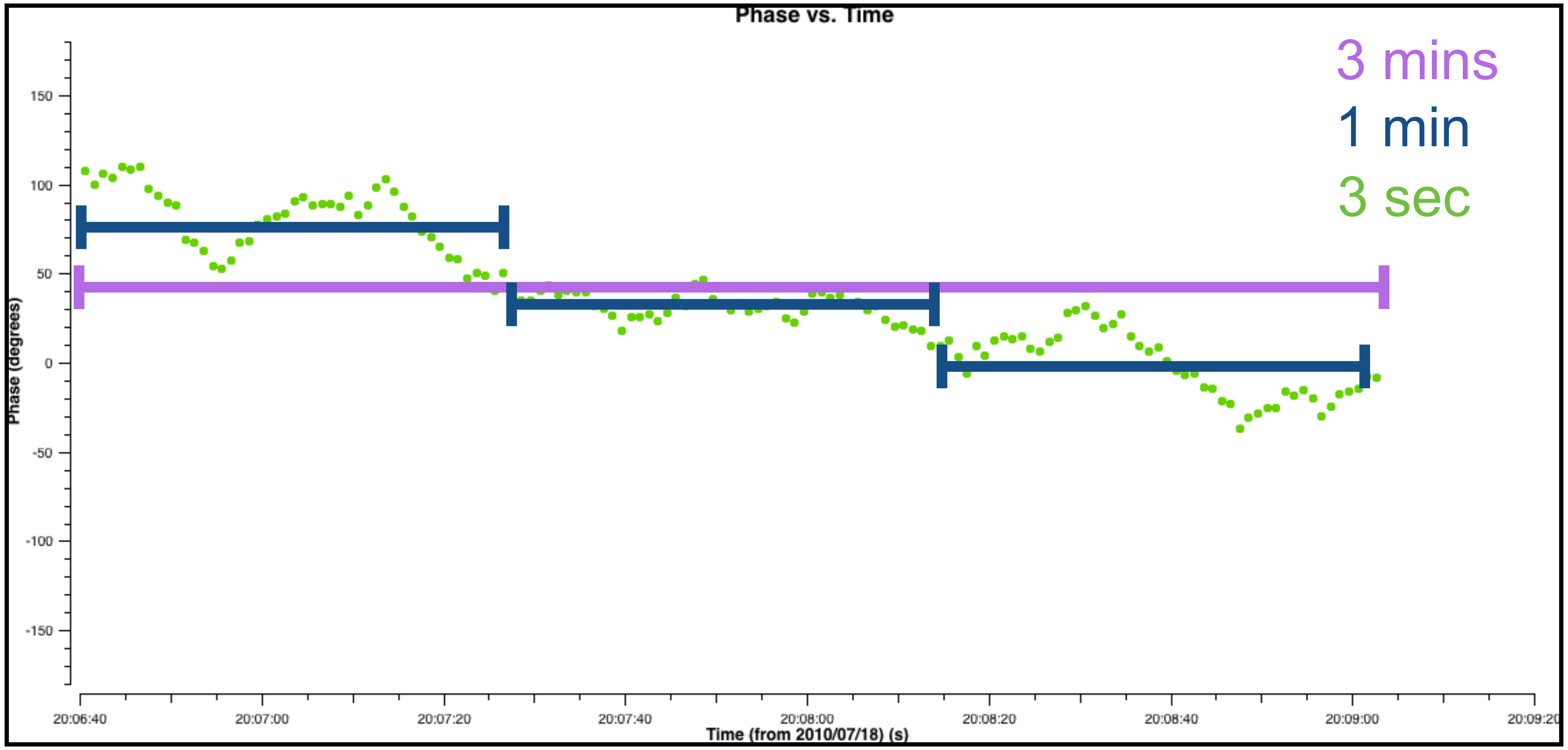


Selfcal rules of thumb

- Sky model used in each stage is fundamentally important!

$$V_{ij}^{\rm obs} = G_{ij} V_{ij}^{\rm true}$$

  - Balancing act: include as many real sources as possible, but do not include any fake sources!
- Choose solution intervals well (smallest possible timescale given S/N)

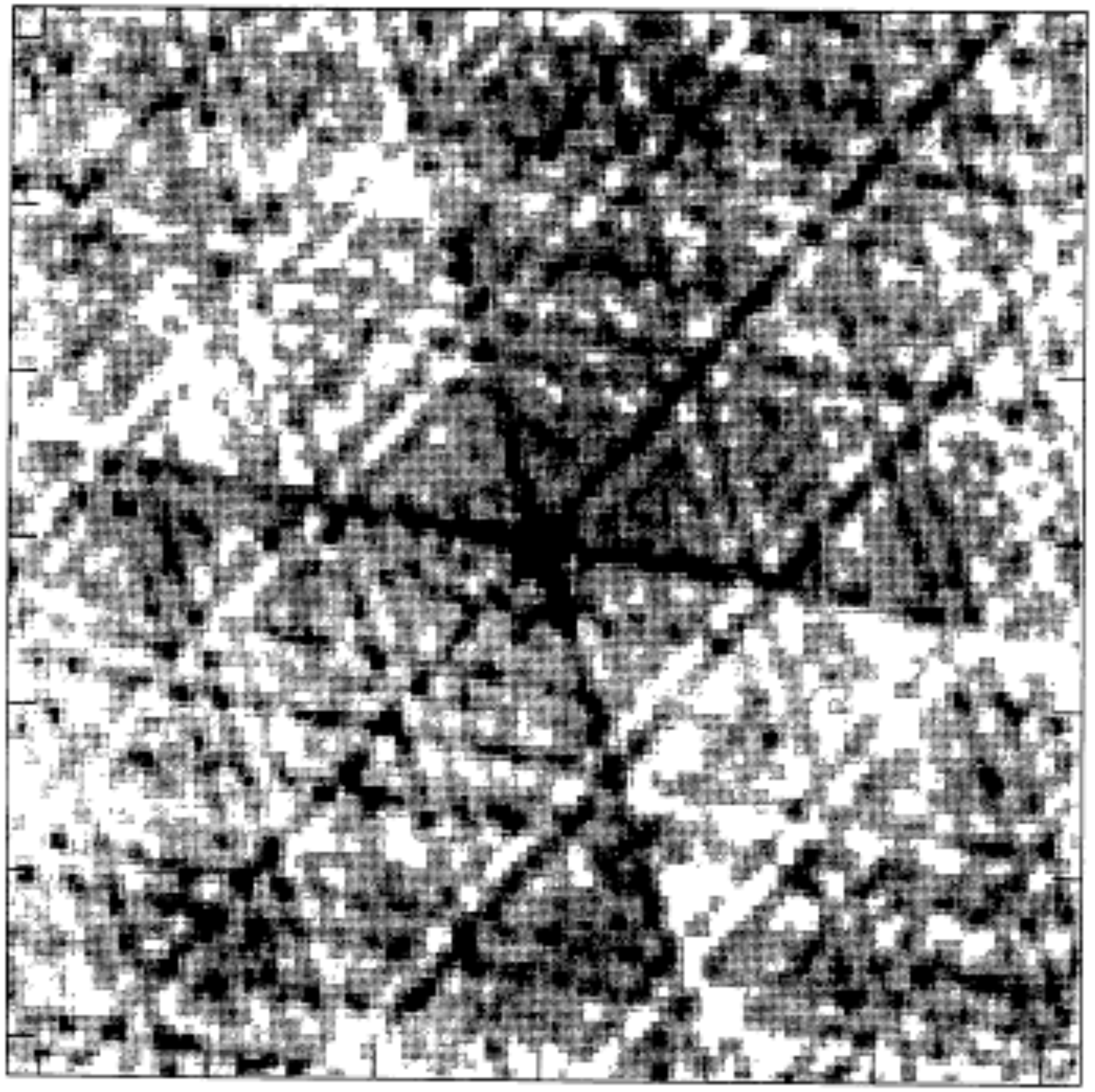


- As always: visualize your data (at every step!)

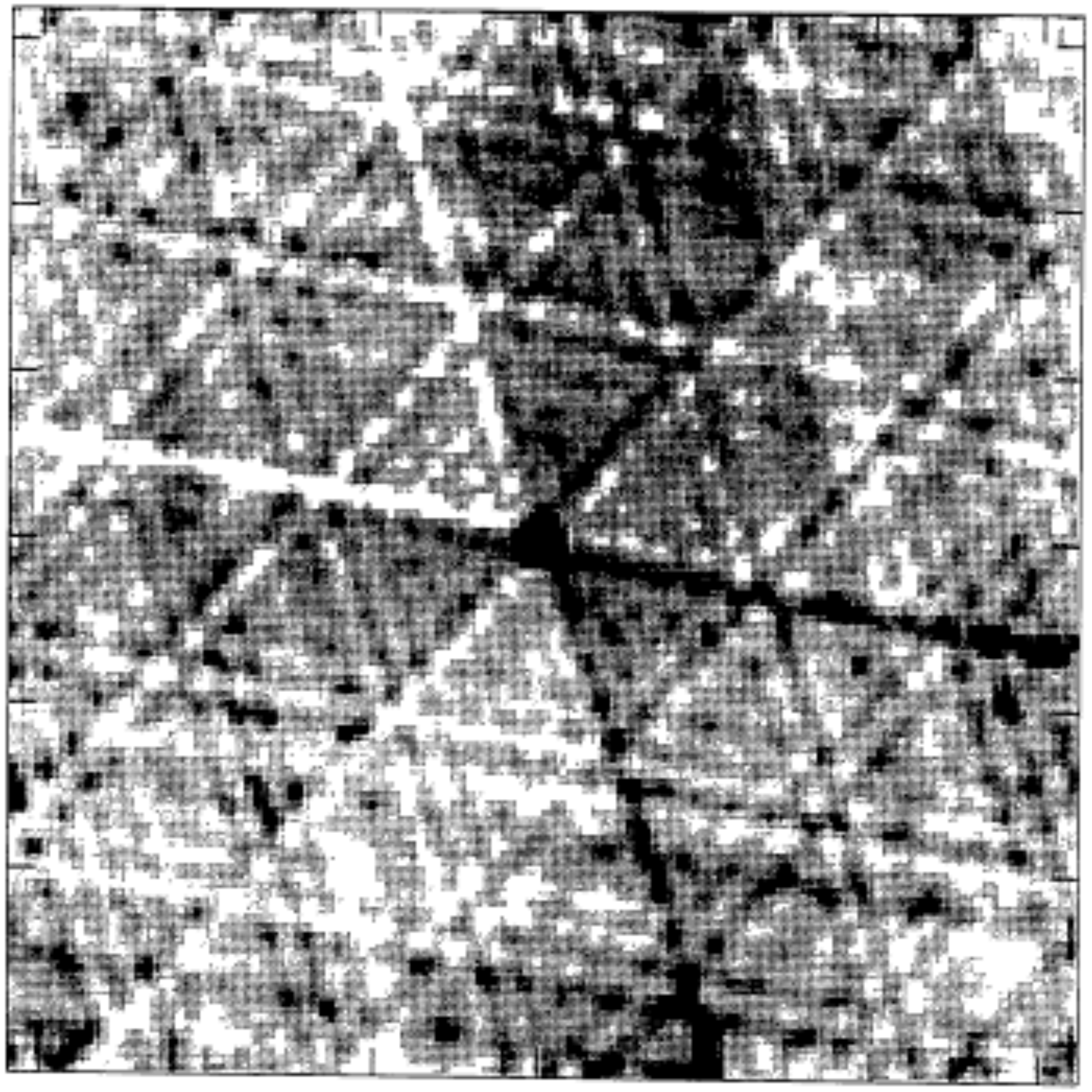
Common error patterns

- Amplitude error gives symmetric pattern; phase error gives asymmetric pattern

(a)



(b)



A 10° phase error is as bad as a 20% amplitude error.

Summary

- Many effects including the atmosphere, delay errors and the electronics of the receiver systems will corrupt the signal from your target of interest.
- Standard calibration transfer techniques, using bright and simple sources can eliminate most of these effects.
- The Measurement Equation is a useful framework for understanding errors, and for determining calibration parameters.
- Residual errors can be removed using self-calibration providing you have sufficient signal-to-noise ratio, enough baselines, and an accurate model for your source.

Your calibration is only as good as your model since model errors will be absorbed into your calibration solutions.

- Direction dependent effects will limit the quality of wide-field imaging due to time variable beam patterns, time- and direction-dependent ionosphere and our limited knowledge of the sky model.

Don't underestimate the value of continually viewing your data and calibration solutions!