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An Introduction to Calibration and Self-Calibration

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Photo Credit: Wei-Hao Wang

Outline

Introduction

- Why do we need to do calibration ?
- What kinds of calibration are needed ?

Gain Calibration

- What does gain mean ?
- Why do we need to do gain calibration ?
- How to do gain calibration ?
- What kind of sources can be served as gain calibrators ?

Self-Calibration

- The limitation of Standard Gain Calibration Scheme
- Self-Calibration
  - strong source
  - improving dynamic range

Introduction (I)

The direct inversion of the visibilities will provide the information (i.e., position and brightness) of source structure.

- However, in reality, the observed visibilities are usually different from the desired visibility data (i.e., the true source visibilities).

The reasons which cause the difference between observed and true visibilities:

- Weather (atmospheric) conditions
  - Absorption by the troposphere and ionosphere
  - Troposphere becomes increasing opaque with increasing frequency, mostly due to the absorption by H_2O and O_2
  - Variations of water vapor content lead to variations in the measured phases.
- Instrument conditions
  - Pointing of antennas : pointing errors will cause time dependent gain (amplitude) errors.
  - Front-end systems (filter and amplifiers) do not have a flat response to frequency, and so do the back-end filters

Calibrations are needed !!

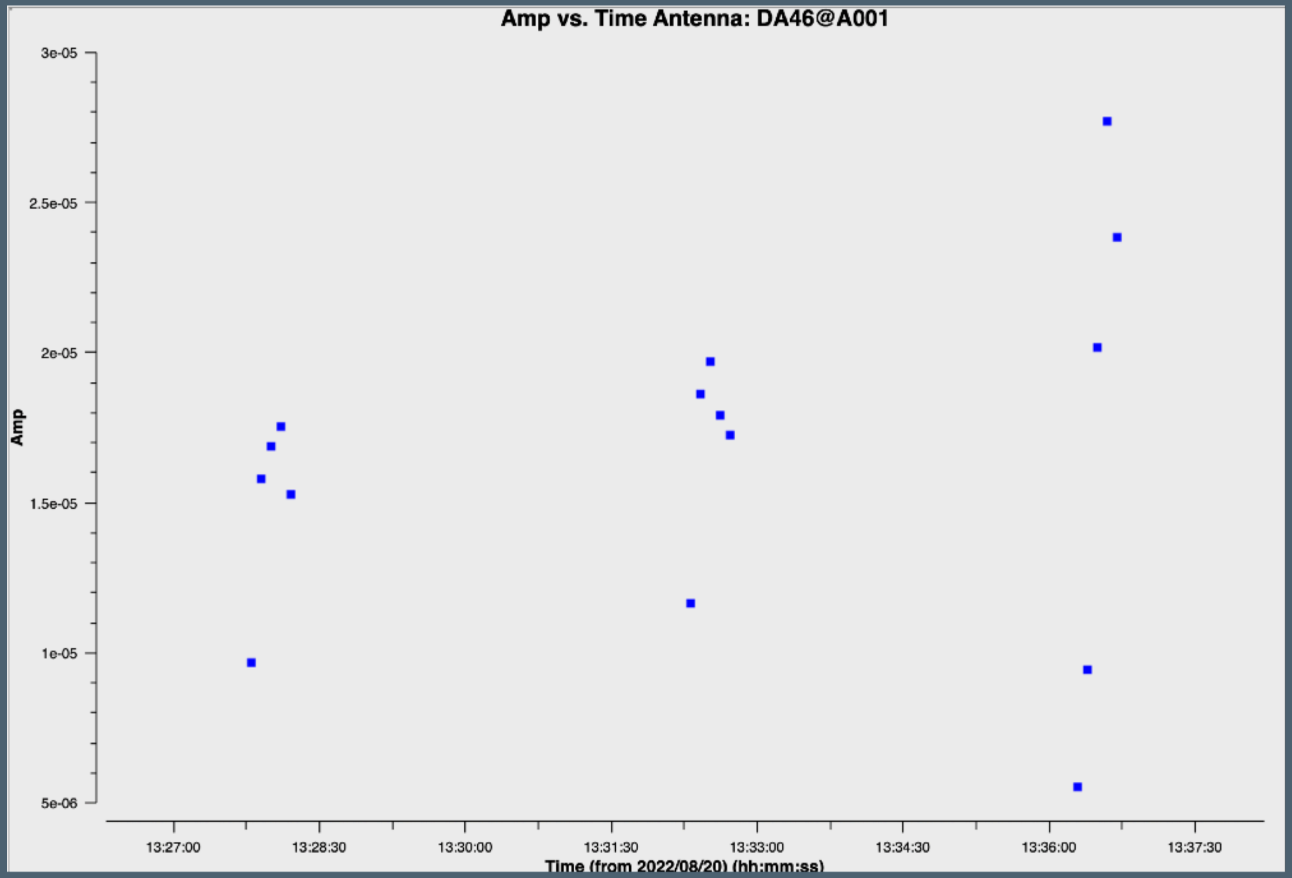
Introduction (II)

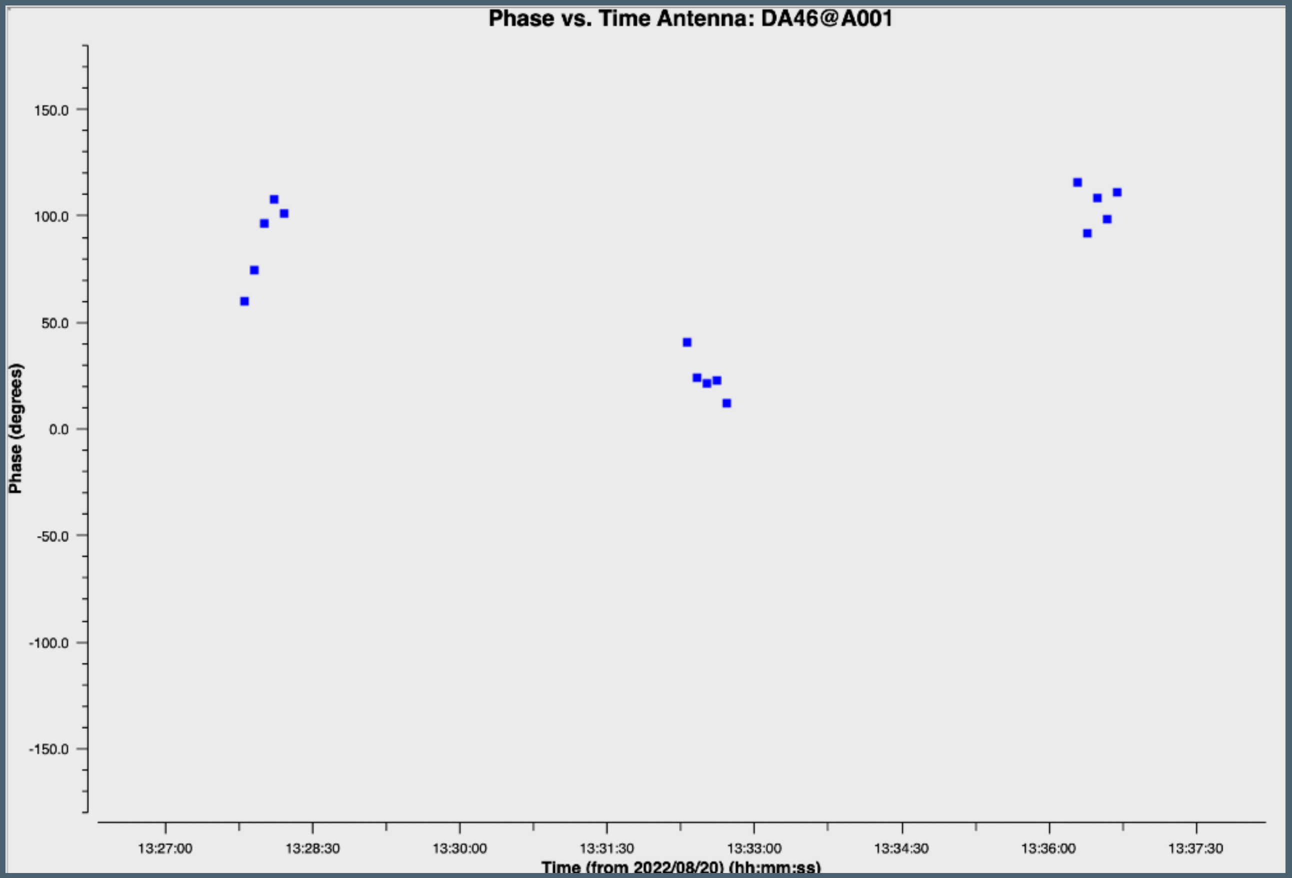
Time-dependent plots

J0730-1141 (a point-like quasar with relatively stable continuum emission)

In ideal case, amplitude and phase should be constant and zero, respectively, over time.

However, this is not the case that we see in the raw data...





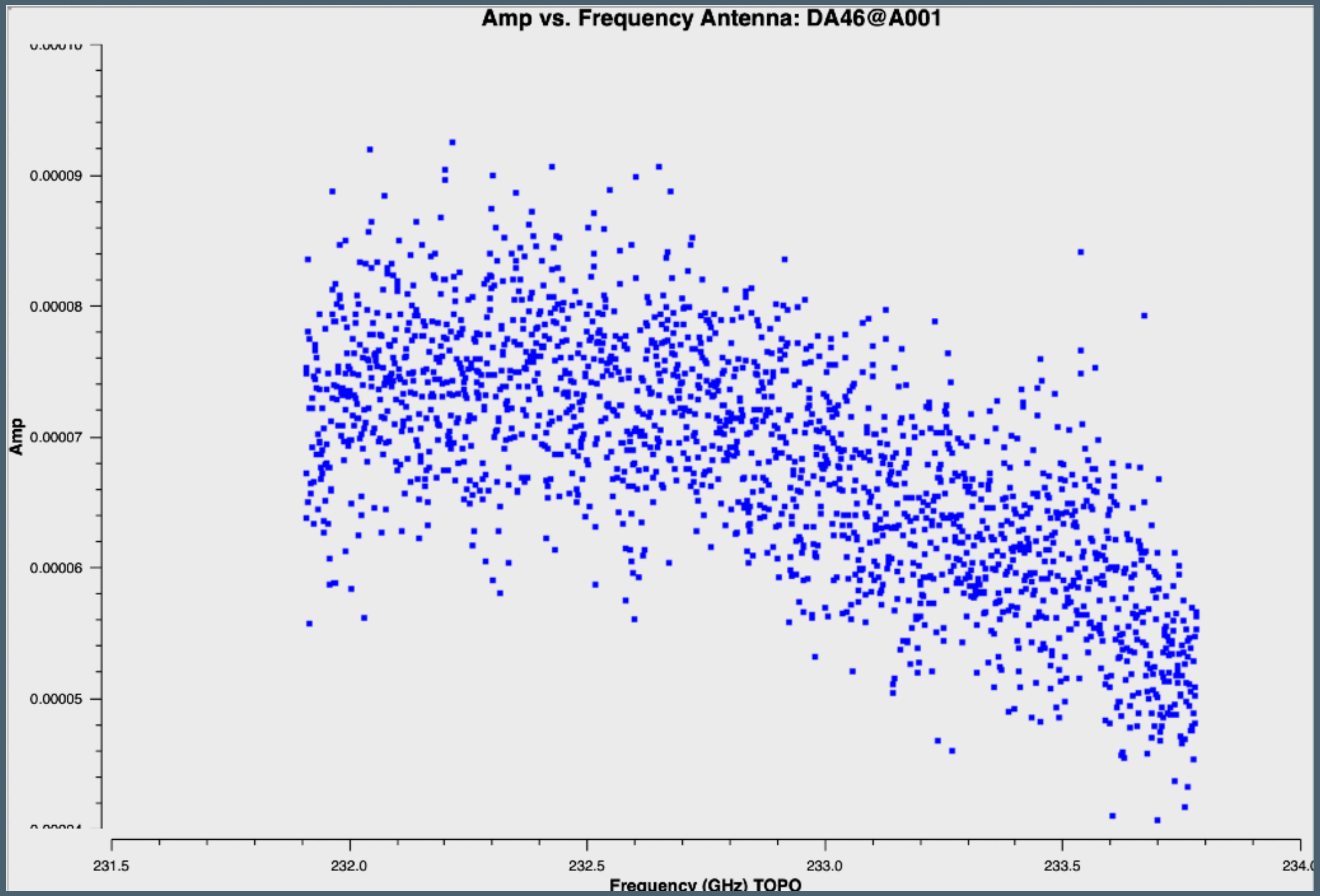
Introduction (III)

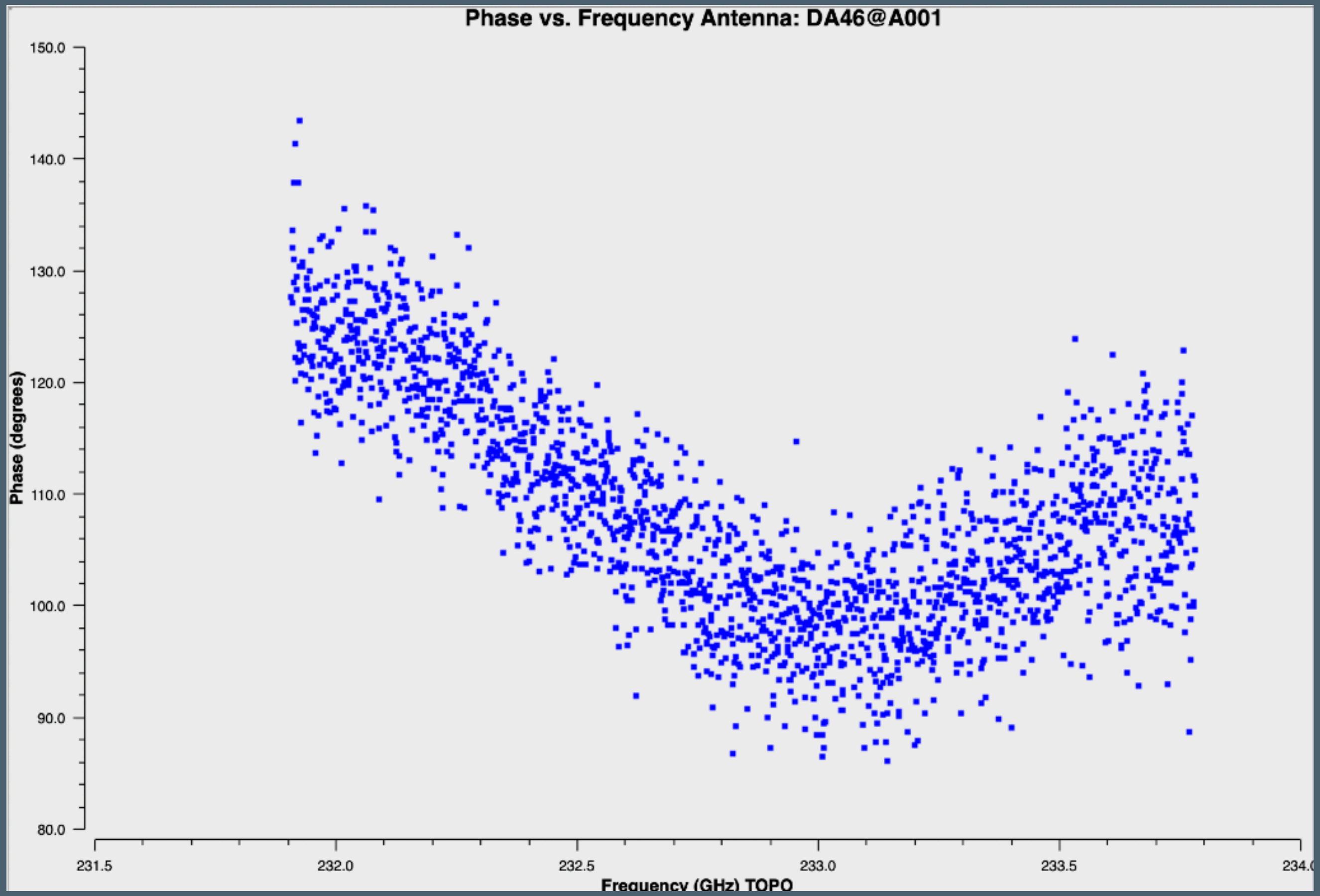
Frequency-dependent plots:

Quasar J0705+1231 (a point, continuum-emitting source)

In ideal case, amplitude and phase should be constant over frequency.

However, those are not constant...





Introduction (IV)

Ideal Case:

$$V_{obs} = V_{source}$$

V_{obs} : observed visibility
V_{source} : true source visibility

In reality:

$$V_{obs} \neq V_{source} \quad \longrightarrow \quad V_{obs} = G \cdot V_{source}$$

- Need another term (i.e., the complex gain term) to compensate the atmospheric/instrumental effects.
- The intent of calibration is to recover the true visibilities

Introduction (V)

Two necessary calibrations:

- Frequency-dependent calibration
    - Bandpass calibration

$$V_{obs}(\nu) = G(\nu) \cdot V_{source}(\nu)$$

- Time-dependent calibration
    - Gain calibration

$$V_{obs}(t) = G(t) \cdot V_{source}(t)$$

Gain Calibration (I)

What does gain mean ?

Why do we need to do gain calibration ?

How to do gain calibration ?

What kind of sources can be served as gain calibrators ?

Gain Calibration (II)

Interferometric observations measure

- Phase (source position)
- Amplitude (source intensity)
- phase and amplitude are referred to as gain

However, the true and measured visibilities of target source are different due to telescope electronics and earth atmosphere (both are time-dependent)

$$
\begin{aligned}
V_{obs}(t) &= G(t) \cdot V_{source}(t) \\
&= a_{gain}(t) \cdot A_{source}(t) \cdot \exp\left[i\{\varphi_{gain}(t) + \varphi_{source}(t)\}\right]
\end{aligned}
$$

To determine source position and intensity accurately, we have to calibrate both phase and amplitude information along time !!

Gain Calibration (III)

How to determine the time-varied gain (amp & pha)

- Observing a source in the sky to monitor the gain variation.
  - Such sources are called gain calibrators.
- If we know how the phase and amplitude of the "true"source visibility vary over time, we can derive the gain.

If we know how the phase and amplitude of the "true"source visibility vary over time, we can derive the gain.

$$G(t) = V_{obs}(t) / V_{source}(t)$$

$$g(t) = A_{obs}(t) / A_{source}(t)$$

$$\varphi_{gain}(t) = \varphi_{obs}(t) - \varphi_{source}(t)$$

Gain Calibration (IV)

What are good sources to serve as gain calibrators

- The ideal gain calibrators are
  - Compact (point-like) source with known position
    - Simple phase structure

$$\varphi_{gain}(t) = \varphi_{obs}(t) - \varphi_{source}(t)$$

  - Emission should be stable enough (at lease within an observation run)
    - Source amplitude ~ constant
  - Close to the target source (better to be within 10 degrees or so)
    - Atmospheric effect is very localized in the sky
  - Moderately strong intensity
    - Moderately strong to calibrate with reasonable integration time (at most several minutes or so)

Self-calibration (I)

Limitations of normal gain calibration scheme

- Interpolation of gain solution to science target is required
  - Fast gain variation may not be well calibrated by the normal calibration scheme
  - Example:
- The solutions are not inferred exactly along the direction of science targets
  - Atmospheric effect is very localized in the sky

The phase errors will limit the image dynamic range

- the noise level can not be reduced by increasing the observation time
- the faint structure associated with strong component can not be well discerned

Self-calibration (II)

Self-calibration

- Using science target itself to derive gain solutions
  - science target needs to be strong enough, otherwise no solutions can be inferred
  - usually several steps are needed
    - model 1-> solution 1-> image 1 -> model 2 -> solution 2 -> image 2 -> mode 3 ->solution 3 -> image 3 -> ....
    - Model:
      - first try with models of strongest components
      - then go down to relative fainter components
    - Solution:
      - first try with longer time intervals
      - then gradually reduce time intervals