Basics of Calibration

George Bendo
UK ALMA Regional Centre Node
Jodrell Bank Centre for Astrophysics
The University of Manchester

As a reminder, an interferometer does not record the signal from individual antennas but from pairs of antennas. The resulting output signals are called complex visibilities. The visibilities can be written as

$$\mathcal{V}(u,v) = Aei^{\varphi}$$

The amplitudes (A) from the correlator output describe the total amount of emission measured by the antenna pair (which corresponds to a specific spatial scale).

The phases (φ) from the correlator output describe the position of the emission offset from the centre of the beam of the telescope.

In radio astronomy, calibration refers to making corrections to the amplitudes and phases and rescaling the amplitudes in the visibility data before images are made.

In practice, the measured visibilities for a baseline between antennas i and j as a function of frequency ν and time t is given by

$$\mathcal{V}_{ij\ \mathrm{obs}}(\nu,t) = G_{ij}(\nu,t)\,\mathcal{V}_{ij\ \mathrm{true}}(\nu,t)$$

where $G_{ij}(\nu,t)$ is a general operator that encompasses multiple effects, including effects related to the atmosphere, antennas, receivers, and correlator, that could alter the phases and amplitudes.

It is difficult to derive corrections for every baseline, so corrections are derived for each individual antenna. These corrections could be written as

$$G_{ij}(\nu,t) = G_i(\nu,t)\, G*_j(\nu,t)$$

(where $G*_j(\nu,t)$ is the complex conjugate of $G_j(\nu,t)$) or

$$A_{ij\ \mathrm{obs}}\, e^{i\varphi_{ij\ \mathrm{obs}}} = A_{ij\ \mathrm{true}}\, a_i\, a_j\, e^{i(\varphi_{ij\ \mathrm{true}} + \theta_i + \theta_j)}$$

Note that the correction (or gain) $G_i(\nu,t)$ for an individual antenna can be written as separate functions of frequency and of time.

$$G_i(\nu,t) = G_i(\nu)\, G_i(t)$$

The visibility calibration process involves calibrating the following (in the following order) for each antenna:

- Amplitude as a function of frequency (A vs ν)
- Phase as a function of frequency (φ vs ν)
- Phase as a function of time (φ vs t)
- Amplitude as a function of time (A vs t)

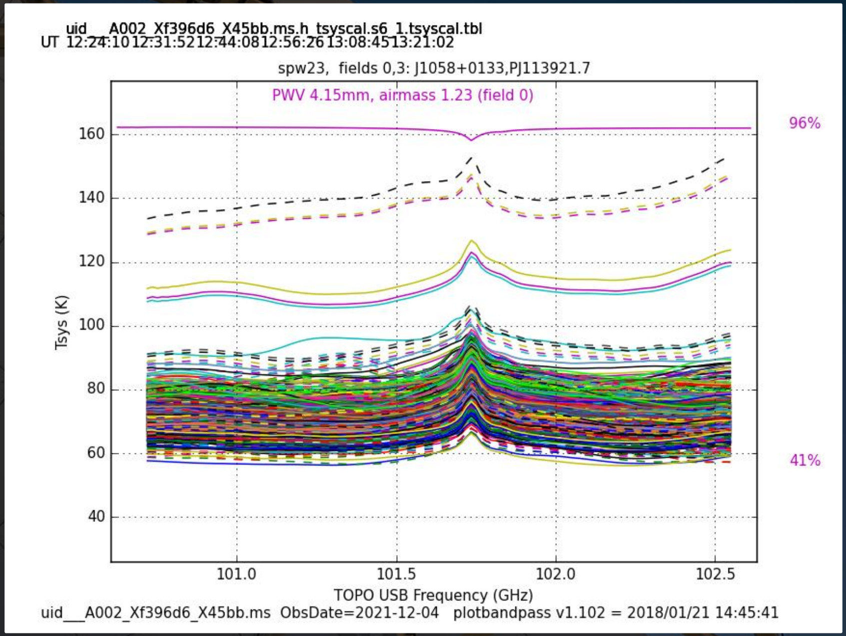
The amplitudes are largely derived independently for each antenna. However, the phases for each antenna need to be derived relative to a reference antenna, which should be selected from near the center of the array.

ALMA and the JVLA also perform some additional calibration steps before performing the above steps.

For ALMA, the following data processing steps are applied to the data:

1. Corrections to the amplitudes are applied based on measurements of the system temperature.

2. Corrections to the phases are applied based on measurements of water vapour along the line of sight.



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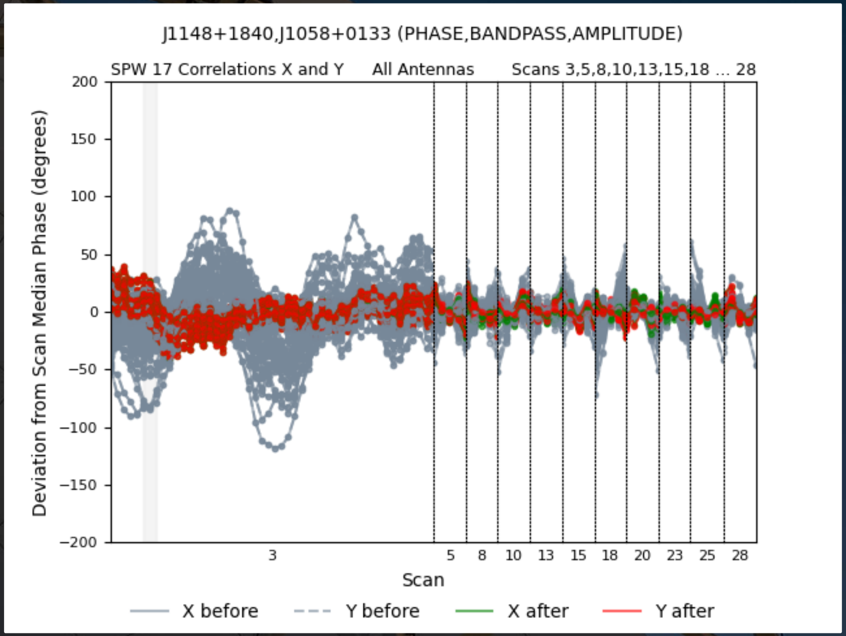
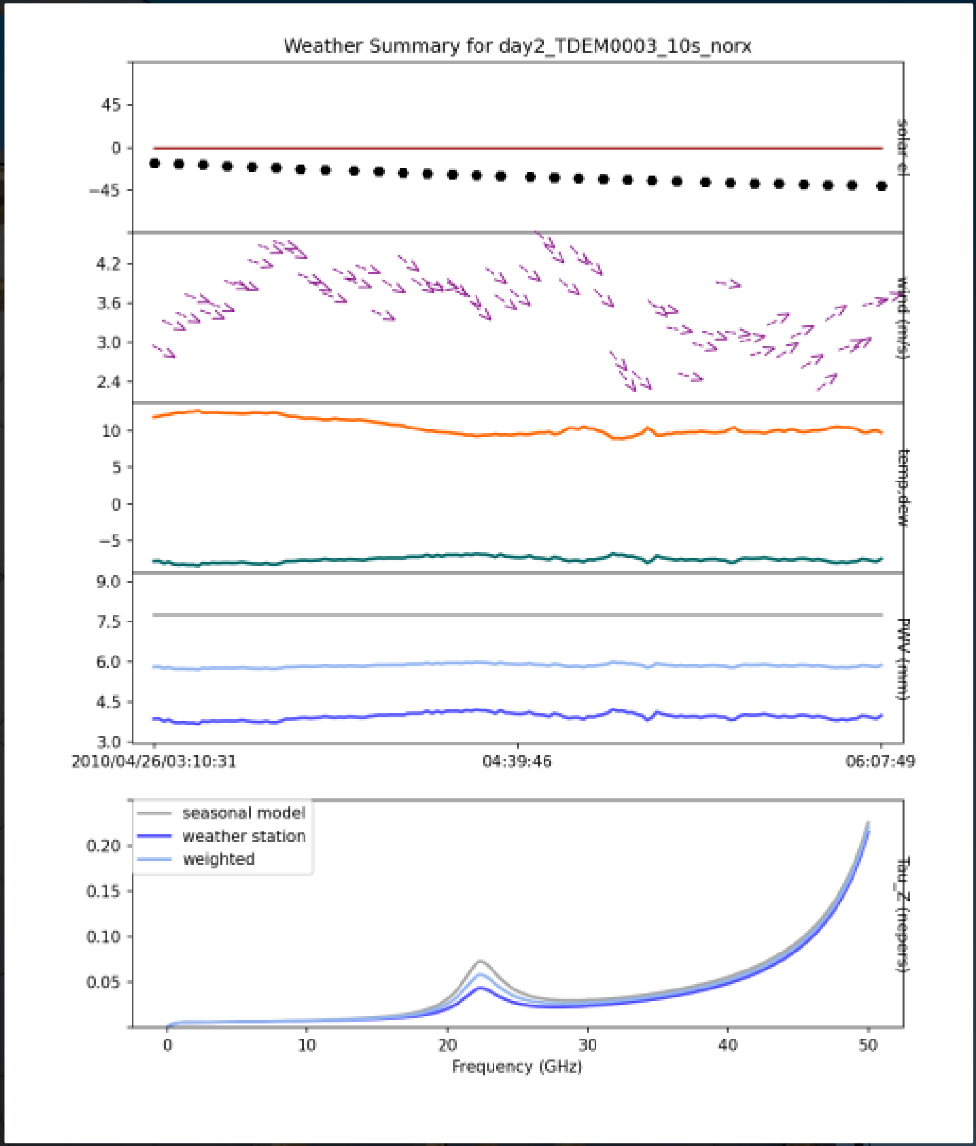


For the JVLA, the following data processing steps are applied to the data:

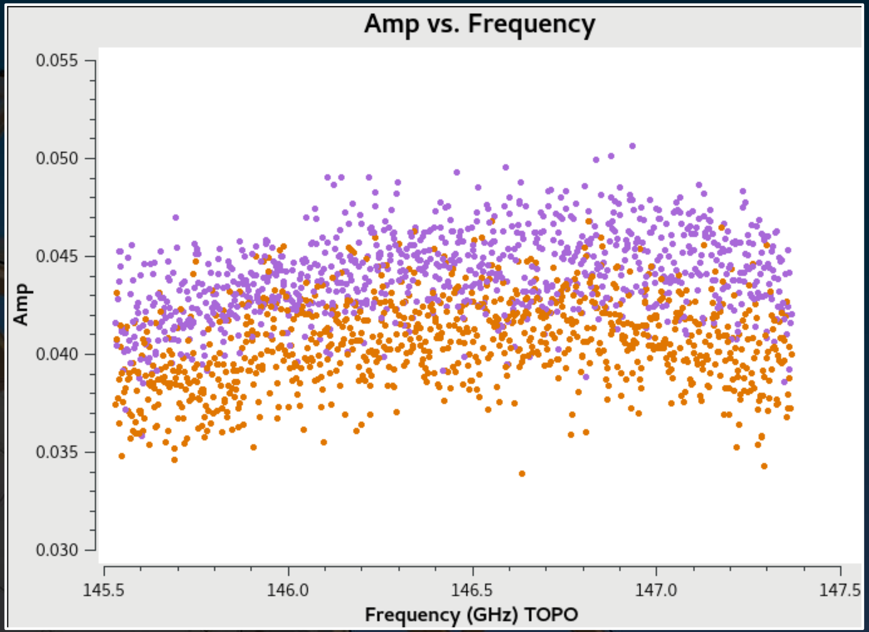
1. Corrections to the amplitudes are applied based on the target elevation.

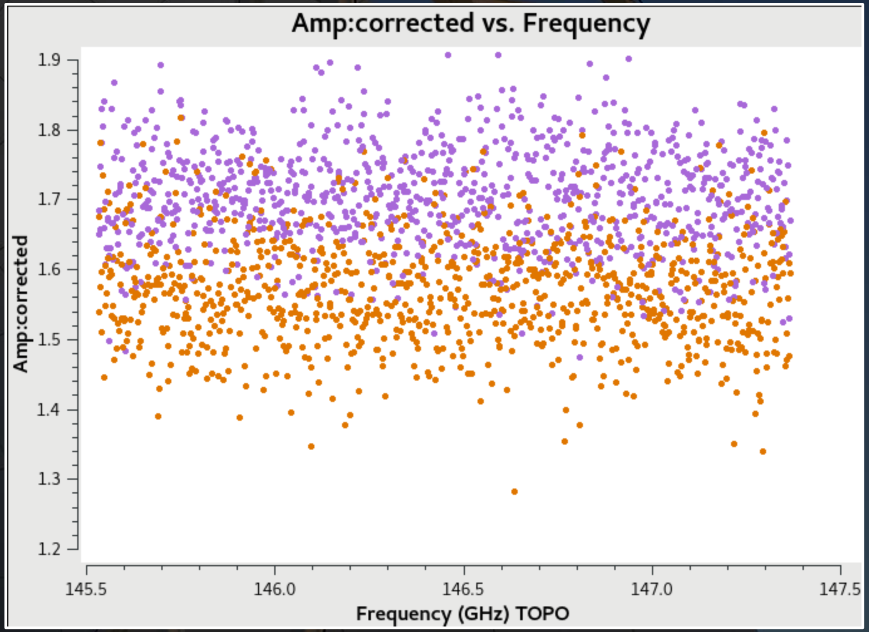
2. Opacity corrections are applied to higher frequency bands.



The bandpass calibration uses observations of a pointlike source with a flat spectrum to make amplitude and phase corrections as a function of frequency.

The bandpass calibrator is usually a very bright quasar that may not be located near the science target.





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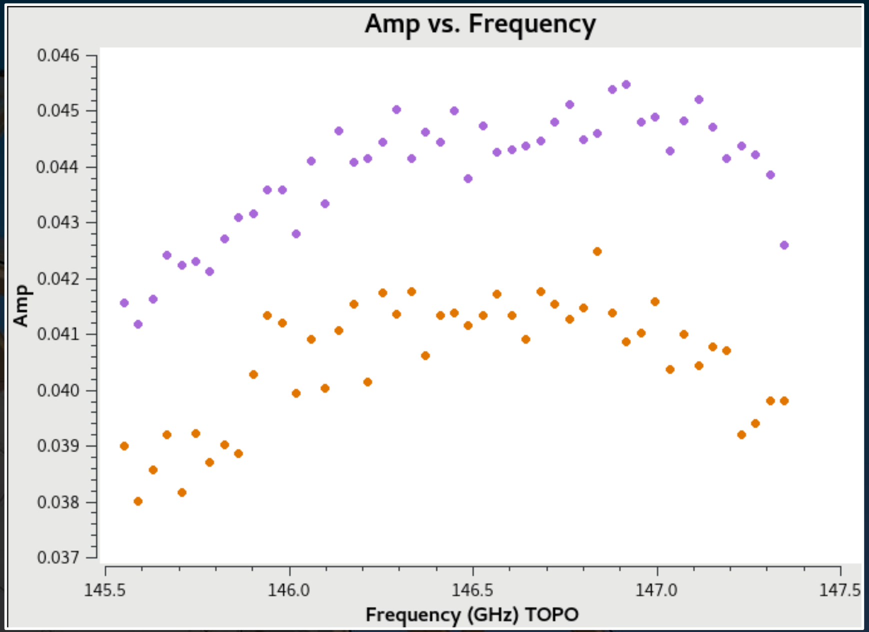

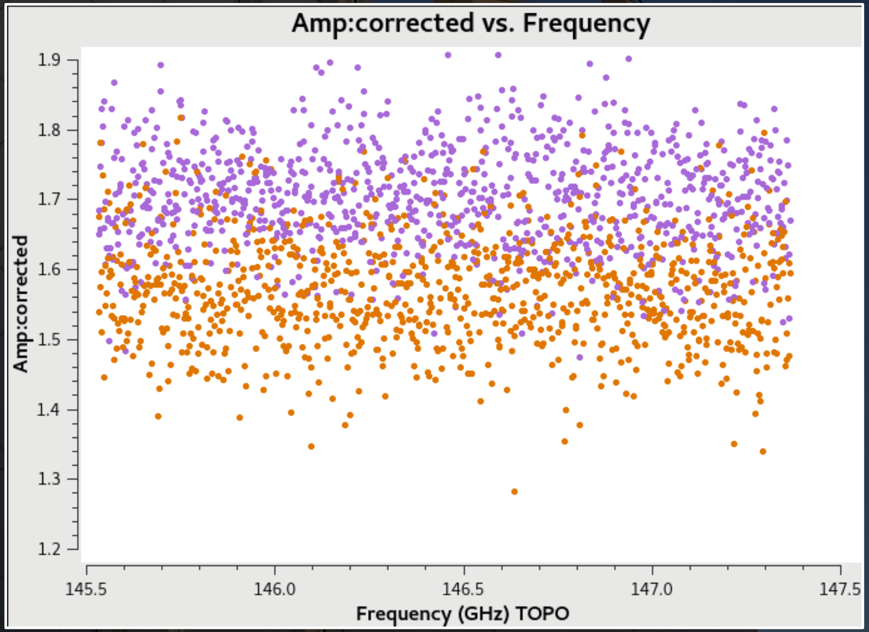

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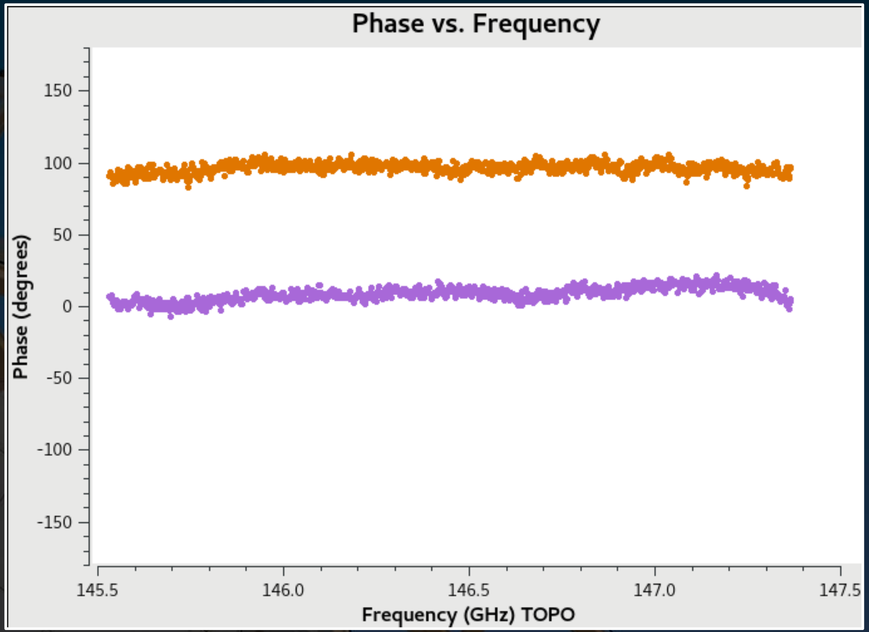
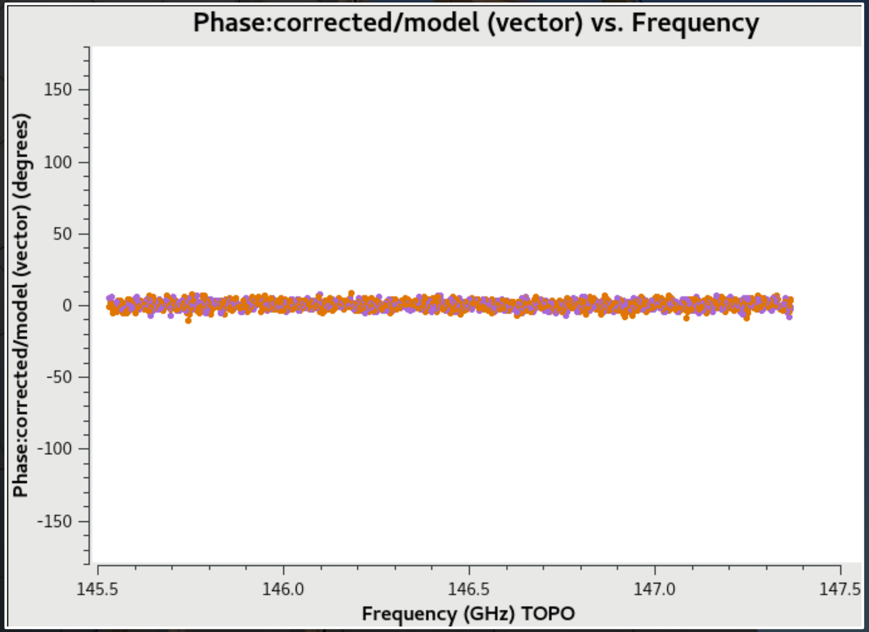
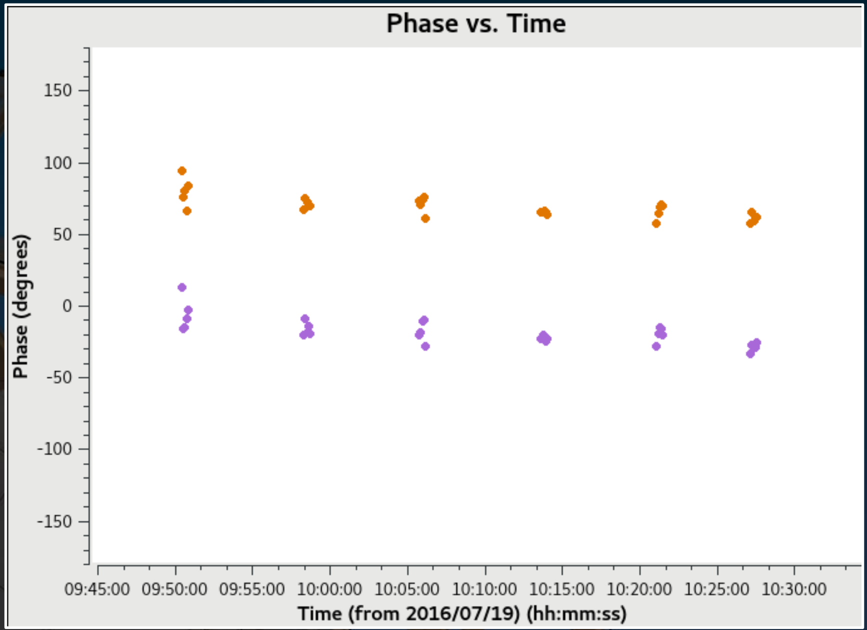
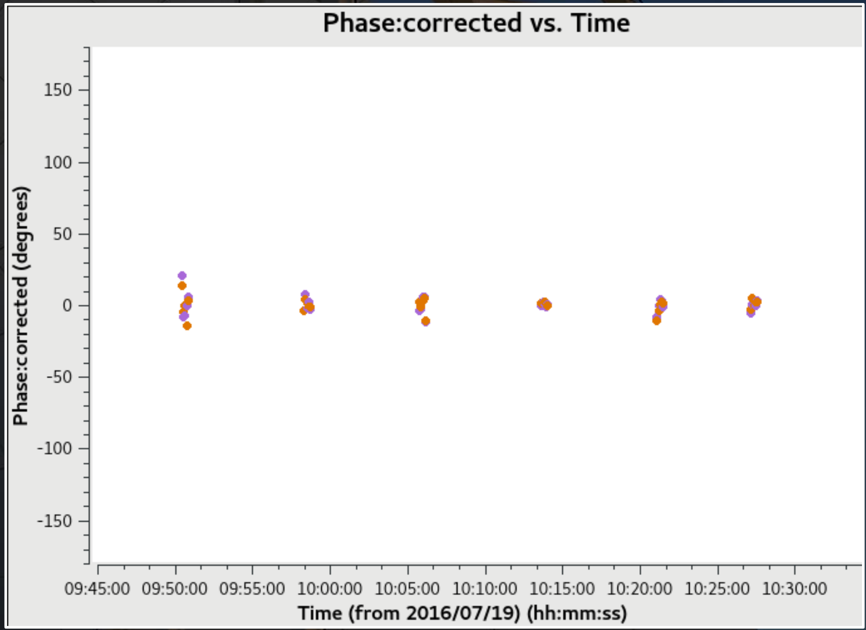


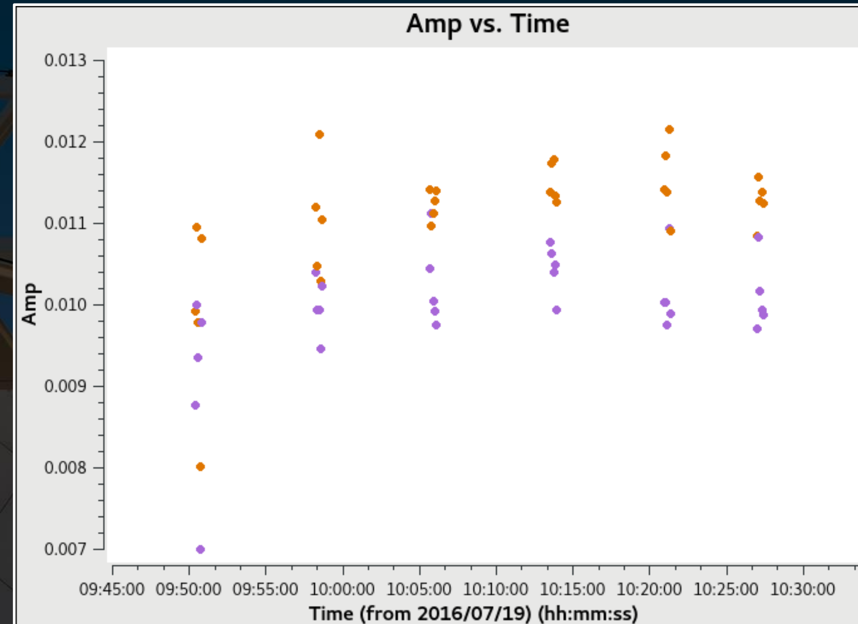


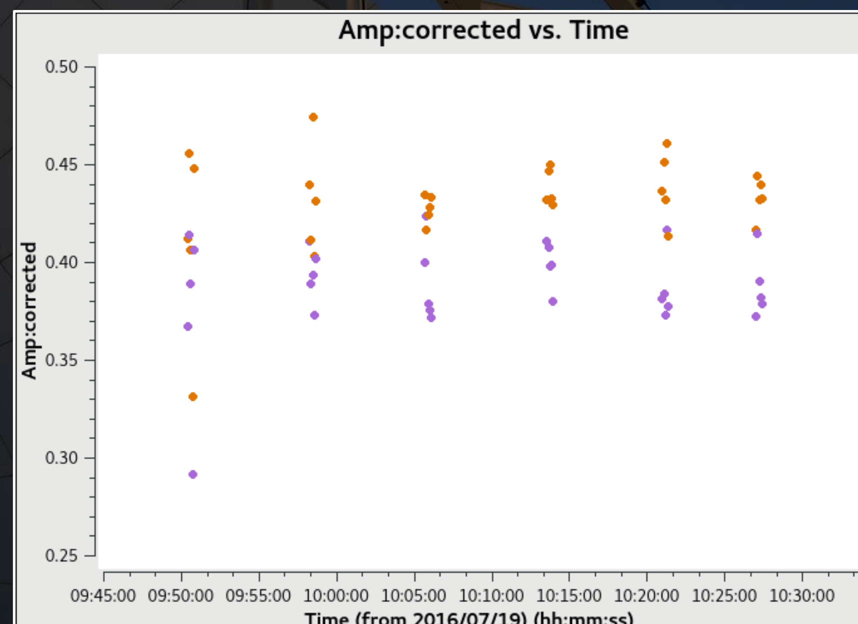
Corrections of the phases as a function of time are derived using a pointlike source, typically a quasar, located near the science target.





Corrections of the amplitudes as a function of time are derived from the phase calibrators after the amplitudes of the phase calibrators have been rescaled using a flux calibrator.





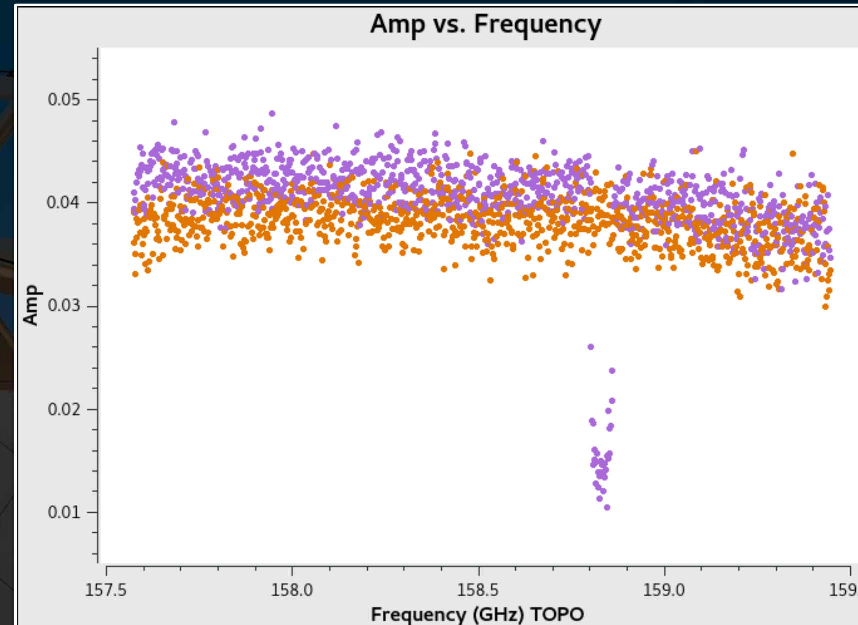
The flux calibration for any given observation is typically derived from measurements of a very bright quasar.

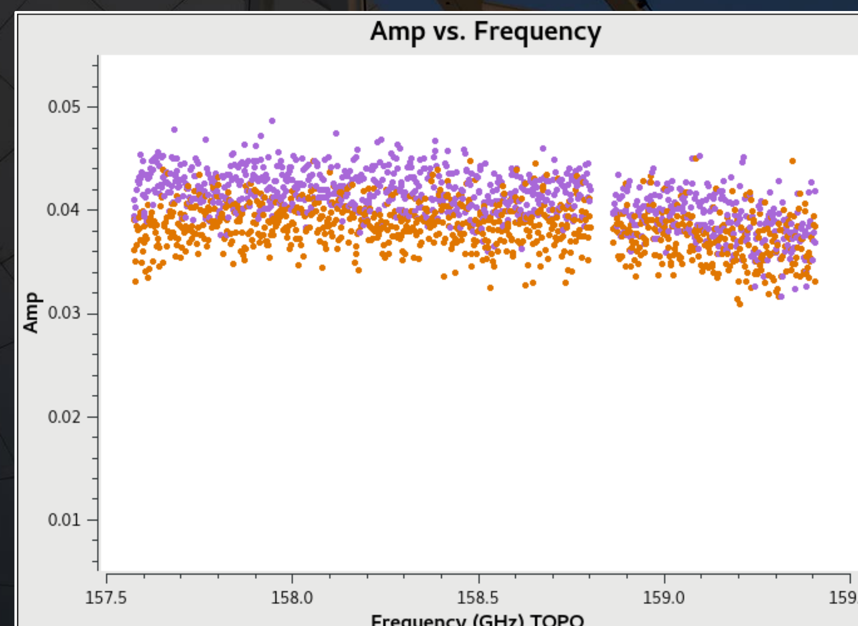
However, quasars vary in brightness unpredictably over time. Therefore, these sources' flux densities are usually calibrated with Solar System objects where the blackbody emission has been extremely well modelled and extremely well constrained by other instruments (especially satellites that have measured the cosmic microwave background).

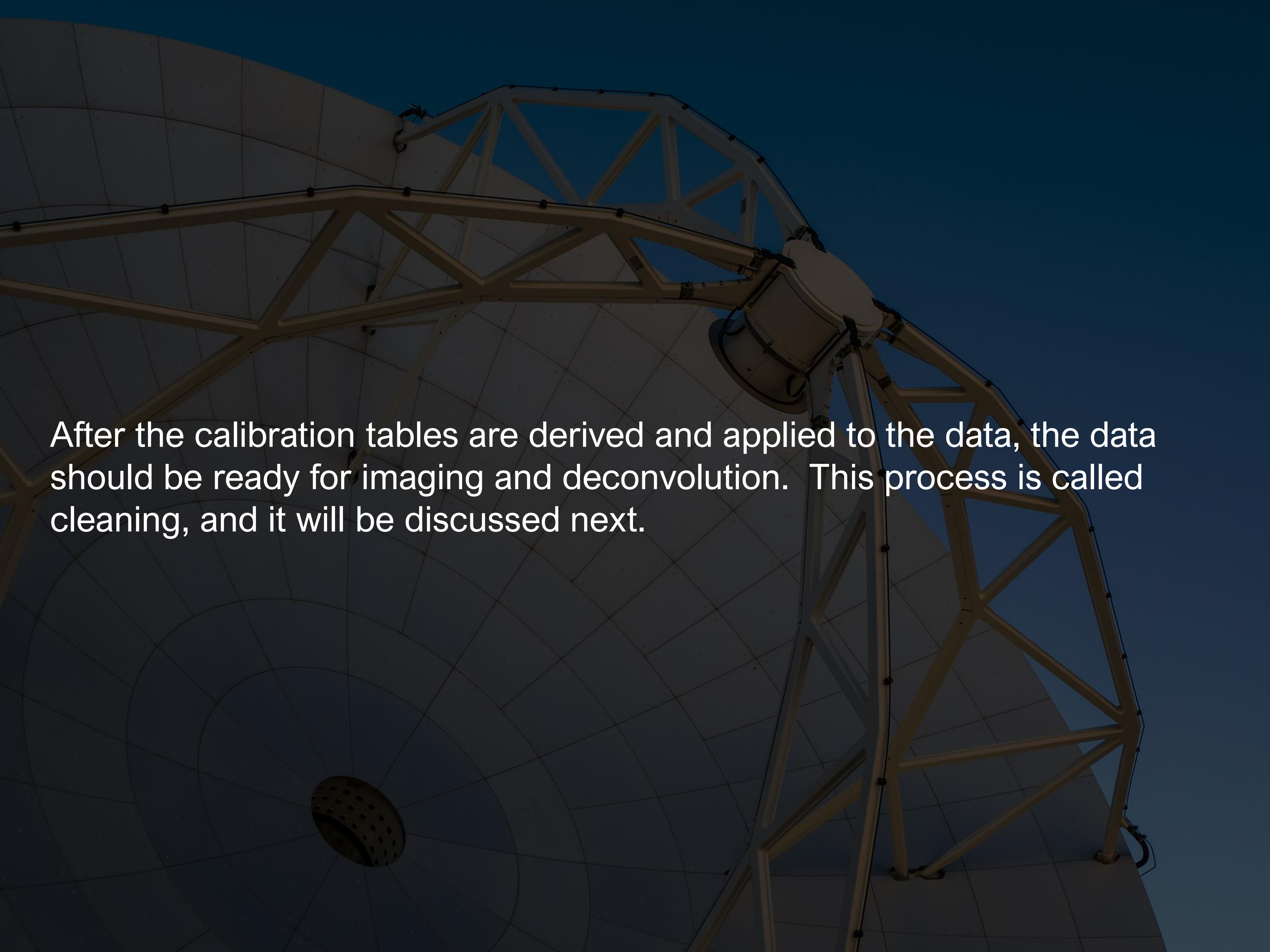
Solar System objects are not routinely used for calibration in large part because they are not always visible in the sky. Additionally, their spectra include absorption lines, and relatively long baselines may be insensitive to the extended emission from these objects.

In addition to these steps, it may be necessary to flag data that appear as outliers, which means that they will not be used either for deriving the phase or amplitude calibration or for creating the final images.

This flagging should be done before deriving the phase and amplitude calibration.







After the calibration tables are derived and applied to the data, the data should be ready for imaging and deconvolution. This process is called cleaning, and it will be discussed next.