VLBA Scientific Memo 40

# Towards VLBA Absolute Bandpass Determination

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**Abstract** Interferometric bandpass determination methods are sensitive only to differences between the phases of two antennas rather than allowing definitive phase assignment to individual antennas. For the vast majority of use cases this distinction is immaterial. However, there are certain use cases for absolute phase[1] determination. This memo outlines a prescription for estimating individual antenna bandpass phase response by augmenting the interferometric bandpass with pulse calibration measurements. The effectiveness is demonstrated using a test observation.

## 1 Interferometric bandpass determination

This section describes interferometric standard bandpass determination on an array of $N_{\text{ant}} \geq 3$ antennas.

Interferometric bandpass determination is a standard part of interferometry data processing. It is critical when performing spectral line observations and helps improve precisions and repeatability of measurements even for continuum observing. Typically one or more dedicated calibration scans on a very bright compact object is used as the source of data. Initial phase, delay, rate calibration is first performed by fringe-fitting. The solutions are then applied to the calibration scan. The net effect of this is to remove any constant and linear phase terms from the visibility measurements. Bandpass responses can then be determined separately for each baseline by averaging the calibrated visibilities on a per spectral channel basis and then dividing by an overall normalization value to enforce zero net gain across the passband. If the calibrator source is heavily resolved it might make sense to first determine a source model and then divide the calibrator scan visibilities by those predicted by the model. If the calibrator source has a large spectral index, this could influence the gain slope across the band.

It is desirable, when possible, to determine calibration on a *per antenna* basis, rather than on a *per baseline* basis. There are three reasons for this: 1. almost all calibration errors in modern interferometric arrays with digital correlators are due to antenna-specific effects; 2. this preserves closure relationships which might be important for downstream processing; and 3. there are fewer total degrees of freedom (for any array with more than 3 elements), meaning the same amount of data can likely yield calibration values with higher signal-to-noise ratios.

A linear least-squares process can be used to decompose the baseline-measured gain (amplitude) and phase as a function of frequency into antenna-measured values. For reasons which will become apparent, it is best to perform this process separately for gains and phases rather than as complex numbers.

Given a set of baseline-based gains, $g_{kl}(\nu)$ for $k \neq l$ and each of $k$ and $l$ ranging from 1 to $N_{\text{ant}}$, one desires to find a set of antenna-based gains, $g_k(\nu)$ such that $g_k(\nu)g_l(\nu) = g_{kl}(\nu)$. Taking the logarithm of this expression yields $\log g_k(\nu) + \log g_l(\nu) = \log g_{kl}(\nu)$ which lends itself to a simple, well-posed, linear least squares solution.

Given a set of baseline-based phases, $\phi_{kl}(\nu)$, one seeks to determine antenna-based phases, $\phi_k(\nu)$ such that $\phi_k(\nu) - \phi_l(\nu) = \phi_{kl}(\nu)$. While this superficially resembles the above problem of solving for $\log g_k(\nu)$, the "$-$" replacing the "$+$" makes the linear least squares problem degenerate. This can be seen by noting that any function $c(\nu)$ can be added to each $\phi_k(\nu)$ with zero effect on the difference between any two. It is traditional practice to choose one antenna to be the "reference" antenna and for that antenna to be assigned $\phi_{\text{ref}}(\nu) = 0$. This makes the least squares problem well-posed.

[1]The word "absolute" is perhaps not the perfect word. In this document it is meant to represent a meaningful assignment of phase to one antenna rather than either arbitrarily choosing a reference antenna or only considering phase to be a property of a baseline.

This prescription is used widely in radio interferometry. As can be seen, with the measurements being considered it is not possible to determine any single antenna's phase response.

## 2 Use cases for absolute bandpass phases

Within radio interferometry, application of bandpass calibration to measured visibilities always results in applying the phase difference between calibration values for the two antennas comprising the baseline.

In cases where the individual antenna voltage streams are of value, the absolute phase calibration is important. Some examples are noted below. No further description of these use cases is provided in this memo.

1. **Radar processing.** This is the most important use case. In radar processing, the voltage streams from individual antennas are processed using a matched-filtering procedure which is effectively cross correlation of the individual antenna voltage stream with a template voltage stream representing the transmitted waveform.

2. **Antenna diagnostics.** Clearly isolating suspicious phase responses to specific antennas may help with understanding of the root cause.

3. **Pulsar processing.** The coherent dedispersion processing that is central to high accuracy pulsar timing can be improved if the receiving antenna passband phase response is known. Improvements to pulsar scintillometry observations may also be possible.

## 3 Pulse calibration

The VLBA (and many other VLBI) antennas employ a pulse calibration system. This system injects a train of pulses into the receiver, in most cases ahead of the first active components, allowing measurement of the propagation delay through the receive system up to the point of digitization. Special algorithms in the correlator and real-time system "extract" the amplitude, $a_k(\nu)$ and phase $\psi_k(\nu)$ of the pulse calibration tones which are usually spaced every 1 MHz of sky frequency. These pulse calibration measurements are fundamentally made on a *per antenna* basis. A set of pulse calibration phase and amplitude measurements can be formed into a bandpass-like entity by following similar procedures.

Pulse calibration data can suffer from local oscillator contamination. Because certain exact integer frequencies are being extracted, leakage of oscillator tones and their harmonics can render some pulse cal tones unusable. Any known contaminated pulse cal tones should be removed from consideration. The pulse cal amplitudes can be used to identify tones that are overwhelmed by contamination. More subtle contamination is difficult to detect. Then an overall phase offset and phase slope is subtracted from $\psi_k(\nu)$. Finally, $\psi_k(\nu)$ can be interpolated and extrapolated to cover the full baseband channel bandwidth. A similar treatment can be performed to the amplitudes, but this is not needed as the interferometric gains are unambiguous and absolute.

## 4 Combining interferometric and pulse calibration phases

The relative merits of the interferometric (IM) and pulse calibration (PC) phases should be considered:

- The PC phases are measured absolutely (relative to a linear function, over frequency).
- The IM phases are measured across the full baseband channel bandwidth whereas the PC phases are only measured at discrete frequencies.
- The IM phases are relatively robust to radio frequency interference and local oscillator leakage.

- The IM phases are measured on exactly the same signal path as the science data; in contrast, the PC phases are not sensitive to propagation through the feedhorn or antenna optics and do potentially have contributions from the calibration coupler and comb generator that are not common to the science data signal path.

Noting the above, it should not be expected that the pulse calibration and interferometric bandpass result in identical measurements. That said, it is plausible that the pulse calibration data can be used to provide some degree of absoluteness to the bandpass phase. This is done by constructing a function $c(\nu)$ which is to be added to each of the interferometrically determined $\phi_k(\nu)$ values. Since there is only one degree of freedom per frequency (that is the value of $c(\nu)$ at the specified value of $\nu$) one can insist that

$$\sum_{k=1}^{N_{\text{ant}}} (\phi_k(\nu) + c(\nu)) = \sum_{k=1}^{N_{\text{ant}}} \psi_k(\nu) \tag{1}$$

leading to

$$c(\nu) = \frac{1}{N_{\text{ant}}} \sum_{k=1}^{N_{\text{ant}}} (\psi_k(\nu) - \phi_k(\nu)) \,. \tag{2}$$

This function is then added to each antenna's phase response

$$\phi_k(\nu) \longleftarrow \phi_k(\nu) + c(\nu). \tag{3}$$

# 5 Initial validation

This technique was tested on VLBA test project TR040L, a project that was executed as a test of the VLBA real-time data transfer system. It consisted of five 150 s scans on bright calibrator source 4C39.25, observed in a single 16 MHz S-band baseband channel. Data from seven antennas (BR, FD, HN, LA, OV, PT, SC) were available for testing. Figures 1 through 3 and their captions show the derived bandpasses and compare against the pulse cal data itself.

# 6 Conclusion and next steps

The approach outlined here appears to improve absolute bandpass phase determination to a level of about 1° to 2° on a specific 16 MHz bandwidth observation. Bandpass phase excursions are expected to be larger when observing with wider bandwidths, so this procedure may have more value in those cases.

Following an apparently successful initial test sequence, the software used will be made more robust and will be generalized to handle more complex observations. Testing will then be done with wider bandwidths and larger arrays. An interesting self-consistency check will come from two correlation passes: one using all of the antennas in one subarray (and thus making use of measurements on all baselines), and the other using two disjoint subarrays. In theory the resultant bandpasses should be identical, excepting for the contribution of the cross-subarray baselines that would not contribute in the second case.

# 7 Acknowledgements

Thanks to Patrick Taylor and Paul Demorest for helpful suggestions and corrections.

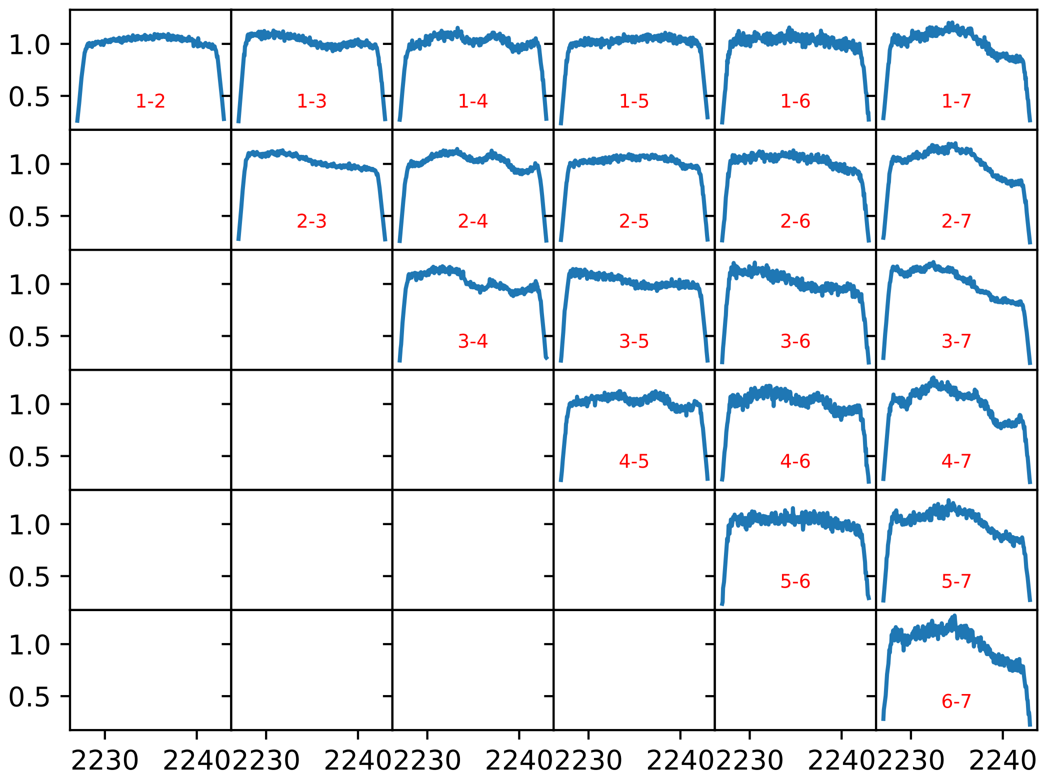


Figure 1: *Baseline-based amplitudes.* Bandpass amplitudes for all 21 baselines for the 7-antenna subarray are shown here. Frequency is in MHz and gain is unitless. Baseline numbers are printed in red. Antennas are: BR=1, FD=2, HN=3, LA=4, OV=5, PT=6, SC=7.

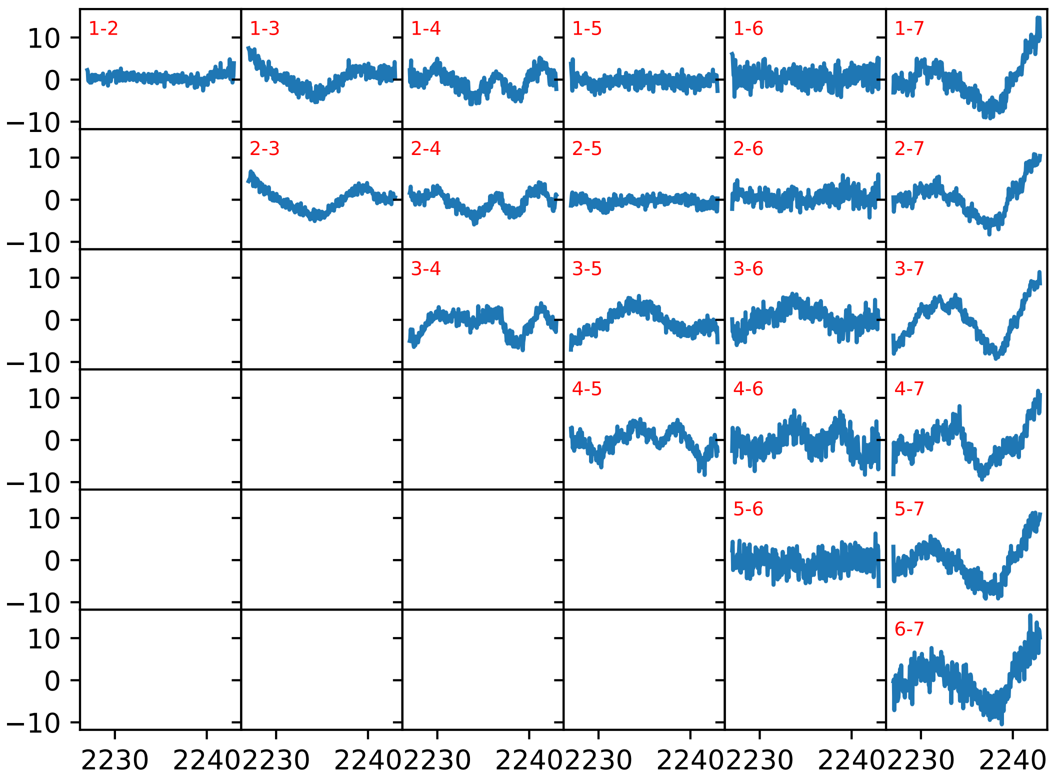


Figure 2: *Baseline-based phases.* Bandpass phases, $\phi_{kl}(\nu)$, for all 21 baselines for the 7-antenna subarray are shown here. Intuition can assign certain features to certain antennas (e.g., the large phase slope on the right can be assigned to antenna 7), but there is no formal mathematical mechanism to make this association.

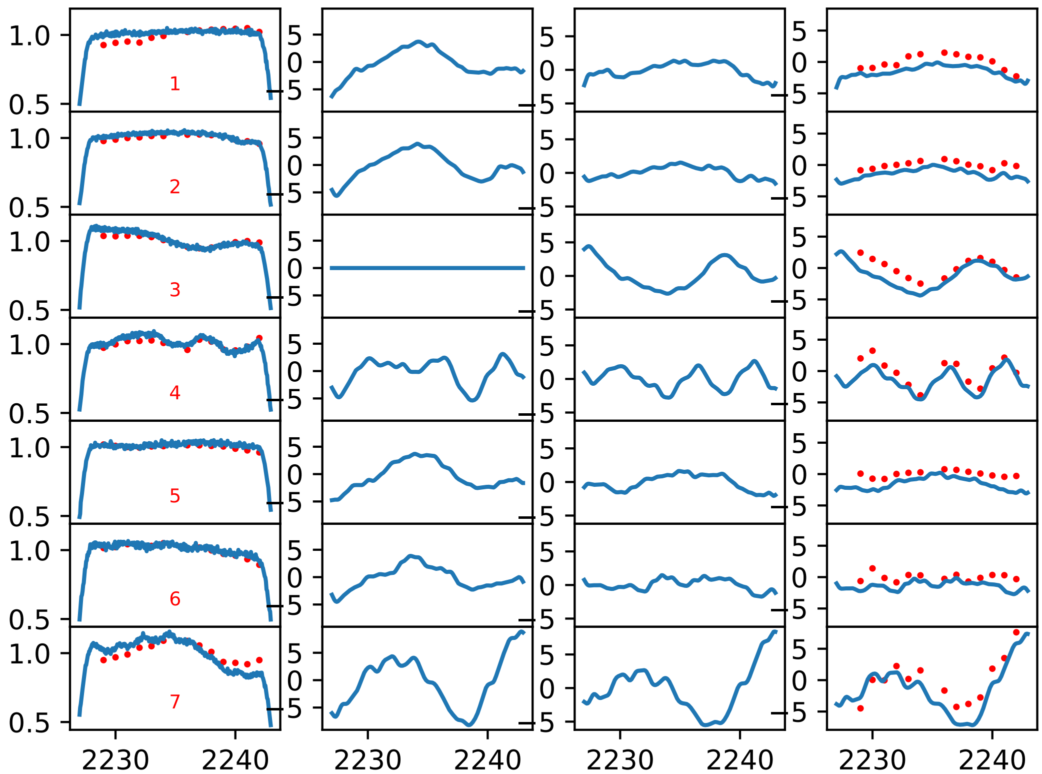


Figure 3: *Antenna-based bandpasses.* The left column shows in blue bandpass amplitudes for each antenna as determined interferometrically. Red points show the pulse cal amplitudes as a comparison. There are features common to the two, but they are not identical. The second column shows the antenna-based bandpass phases, $\phi_k(\nu)$, solved interferometrically using antenna 3 as the reference antenna. The third column shows antenna-based bandpass phases, but with the average phase across all antennas subtracted. The right column shows in blue the bandpass as determined through Eqn. 3. The red dots show the pulse cal phases (after removal of constant and linear trend), $\psi_k(\nu)$ for comparison. Like for the amplitudes, certain features match, but differences at the 1° to 2° level remain.