Basics of Baseline Calibration and Sanity Checks

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Summary:

Probably the simplest sanity check on the validity of the adopted antenna locations is to simply (1) choose a data set with bright continuum sources, (2) apply the usual phase corrections for geometric delay, (3) do an antenna-based calibration using an analysis package such as AIPS, (4) inspect the phases for each antenna as function of time, looking for distinctive variations as function of hour and and declination.

Most analysis packages have routines to do automated fits for antenna locations. These routines need to be given data sets that provide adequate constraint on the parameters, in order for the fit to converge and be meaningful. A suitable data set must cover several sources that have been observed at a wide range of hour angle and declination. The telescope instrumentation should not have been reset or restarted in a way that would alter the instrumental phase offset during the period of the acquisition of the data set.

More Detailed Look at the Underlying Logic:

The fundamental equations that relate the antenna locations fixed to the rotating Earth to the coordinate system used for phase calibration and imaging are contained in the matrix formulation:

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} \sin H & \cos H & 0 \\ -\sin\delta\cos H & \sin\delta\sin H & \cos\delta \\ \cos\delta\cos H & -\cos\delta\sin H & \sin\delta \end{pmatrix} \begin{pmatrix} X_\lambda \\ Y_\lambda \\ Z_\lambda \end{pmatrix}, \qquad (1)$$

(c.f., Thompson, Moran & Swenson, *Interferometry and Synthesis in Radio Astronomy*). Here, the U, V, W orthogonal coordinate system is oriented with W aligned in the direction of the celestial radio source (at hour angle H and declination δ). The baseline coordinates $X_\lambda, Y_\lambda, Z_\lambda$ are computed from the relative locations of the antennas that are fixed to the Earth, with Z_λ aligned parallel to the Earth's rotation axis in the Northerly direction, X_λ is aligned toward $H = 0, \delta = 0$ and Y_λ points toward $H = -6^h, \delta = 0$.

The observed visibility phase, ϕ in radians is:

$$\phi = 2\pi W + \phi_{instr}, \qquad (2)$$

where ϕ_{instr} is the frequency-dependent, instrumental phase contribution due to differential cable lengths and phase offset in the instrumentation. The W term is the projection of the baseline onto the line of sight in the direction of the source. It represents the geometric delay that must be corrected as a function of time (or hour angle H in the formulation here, where $H = LST - RA$) in order to compensate for the Earth's rotation and thereby "stop the fringes."

Errors in the relative antenna locations $X_\lambda, Y_\lambda, Z_\lambda$ lead to errors $\Delta x, \Delta y, \Delta z$ in the baseline coordinates, which in turn couple to errors in the observed interferometer phase, $\Delta\phi$:

$$\Delta\phi = \Delta x \cos\delta \cos H - \Delta y \cos\delta \sin H + \Delta z \sin\delta + \Delta\phi_{instr} \ . \tag{3}$$

Note that an error in time keeping by the "station clock" would give rise to error in the assumed hour angle, and this error would create distinctive errors in the observed phase,

$$\Delta\phi = X_\lambda \cos\delta \cos(H + \Delta H) - Y_\lambda \cos\delta \sin(H + \Delta H), \tag{4}$$

but application of an algorithm to solve for baseline errors would compensate for the clock error by assigning the phase offsets to errors in the location of the antennas.

Diagnostic Behavior of Interferometer Phases in the Presence of Baseline Errors:

Figures 1 and 2 illustrate the Hour Angle and Declination dependencies of how phase errors depend errors in antenna positions. Either study of Equation 3 or inspection of these figures makes it clear that there are degeneracies (or near degeneracies) that can make automated baseline fitting tricky.

For example, in Figure 1, it is clear that a dataset that contains only a single source or a dataset that has only sources at similar declinations will have a degeneracy in between the parameters for Δw and ϕ_{instr}; both appear as constant, flat lines in the figure. An automated fit would not be constrained and would diverge. Furthermore, a dataset dominated by observations within a couple of hours of $H = 0$ will find that Δx is also nearly degenerate with Δw and ϕ_{instr} due to the flatness of the $\cos\delta$ function around $H = 0$. And,... if all measurements were made at positive hour angles, (say 0 to 4 hours for MWA), then Δx and Δy become roughly degenerate, since they have similar slopes, and their difference could be offset by adding a scaling of either Δw and ϕ_{instr}.

Similar sorts of arguments can be made for the Declination dependencies illustrated in Figure 2.

The bottom line here is that data sets suitable for automated fits must cover a wide range of both hour angle and declination. Acquisition of a suitable dataset encounters added difficulties with an instrument like the MWA that is constrained to observe at zenith angles less than 60 degrees.

Sanity Checks on Baseline Validity:

A couple of sanity checks can be made on the baseline validity. These are outlined below. They rely on stability of the data acquisition system throughout the period of the observations, so that the instrumental phase offsets are constant. A further assumption is that the ionospheric refraction (and other similar external factors) are reasonable steady; this assumption is probably very reasonable given that the MWA Early Deployment observations made during a period of violent solar flares were still stable enough to allow a baseline fit to be made, and these observations demonstrated repeatability over approximately two days of observation.

1. *Most basic calibration and visibility data inspection.* The most basic sanity check is to apply the corrections for geometric delay in order to stop the fringes. This involves the adoption of a set of antenna locations, which in the case of the MWA 32T come from high precision GPS measurements. If the phases of the cross-correlation spectra are reasonably flat across the frequency bands, then it is not necessary to compute and apply passband corrections before averaging the data across the band to obtain a single complex visibility for each time step (sometimes called a *continuum channel*). Here a "time step" means a scan average (of say 5 min, not individual 1 second integrations). (Polarizations should be kept separate.) Then, take one time step of high signal-to-noise ratio for a bright source and solve for the phase calibration. Apply those phase offsets to the entire data set (all sources, hour angles, declinations, etc). If the baselines are correct and the geometric delays have been correctly applied, then the phases of all visibilities for the bright, compact, continuum sources should hover within the noise level around zero phase. These can be inspected with routines like LISTR in AIPS (either "list" or "matx" options).

2. *Next most basic approach: antenna-based phase calibration.* A more sensitive way to look for phase residuals due to possible baseline error is to apply the calibration routines to the continuum channel to obtain a table of phase calibration "solutions." In AIPS, CALIB writes tables called "SN" tables, and they can be viewed with LISTR in the "gain" option. Examination of these tables would reveal trends as function of hour angle or declination that would appear as some combination of the dependencies shown in Figures 1 and 2. The advantage of looking at these calibration tables over simply the phases of the complex visibilities in method 1 is that the signal-to-noise ratio should be greatly improved and the errors are isolated according to each antenna.

3. *Automated baseline fitters.* Automated fitters that put out tables of antenna location errors are probably the most elegant solution. However, as emphasized above, a fair bit of effort must go into planning the observations to obtain a suitable data set that spans the full range of possible hour angle and declination.

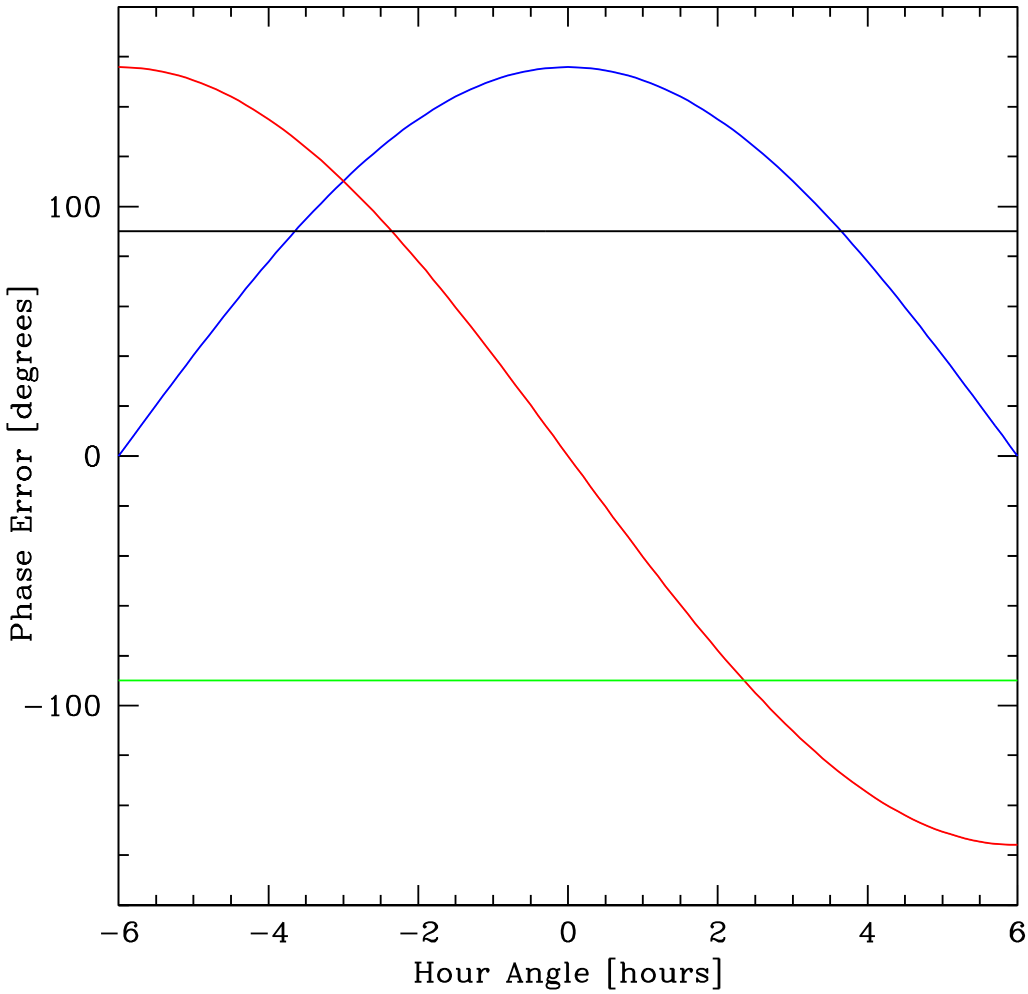

Fig. 1.— Observed Phase Errors versus Hour Angle arising from errors in the adopted baselines, assuming a source at declination of $-30^{\odot}$. Blue: $\Delta X = 0.5\lambda$. Red: $\Delta Y = 0.5\lambda$. Green: $\Delta Z = 0.5\lambda$. Black: $\phi_{instr} = 0.25\lambda$.

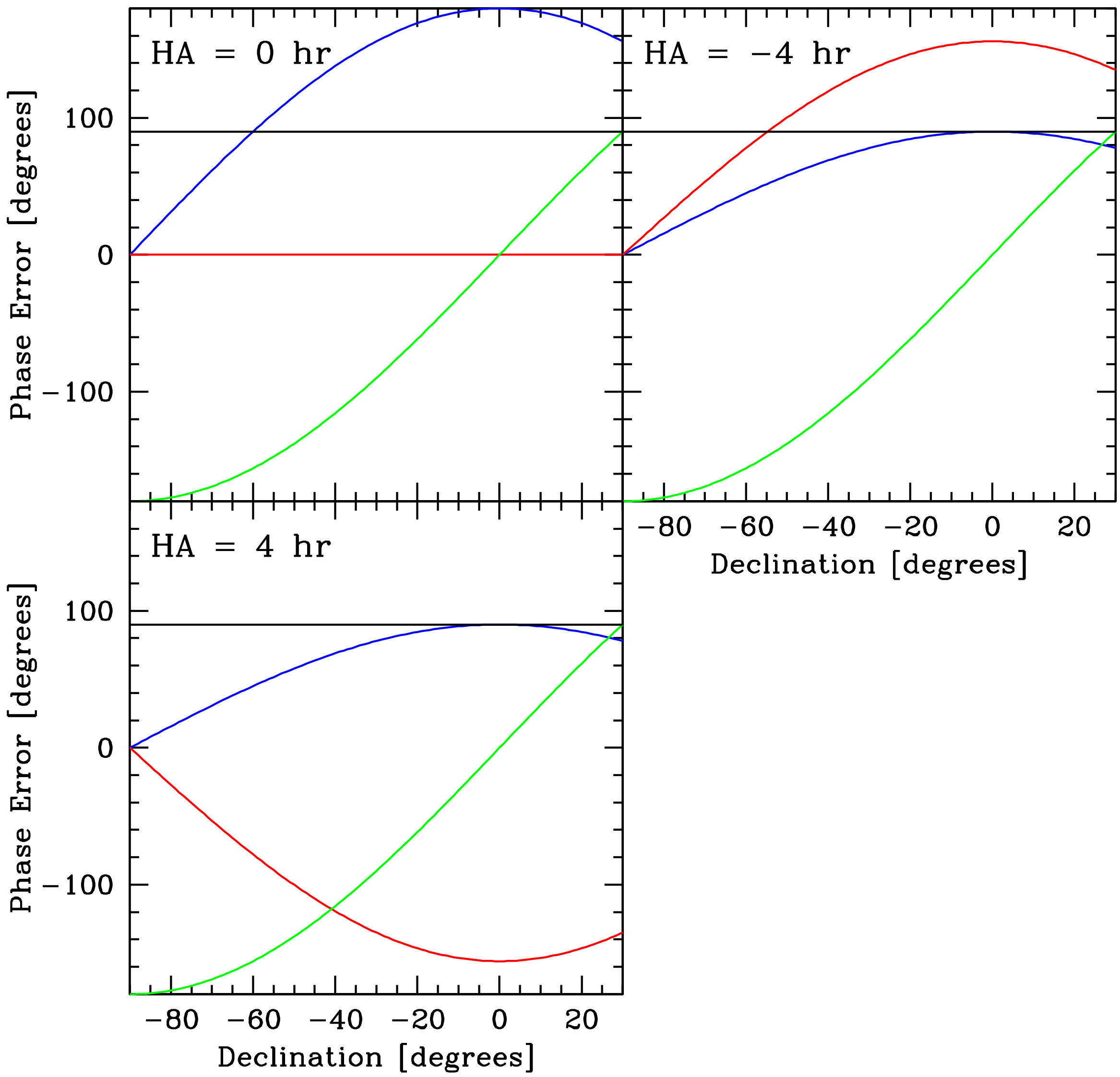

Fig. 2.— Observed Phase Errors versus Declination at Three Hour Angles arising from errors in the adopted baselines, assuming a source at declination of $-30^{\odot}$. Blue: $\Delta X = 0.5\lambda$. Red: $\Delta Y = 0.5\lambda$. Green: $\Delta Z = 0.5\lambda$. Black: $\phi_{instr} = 0.25\lambda$.