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Antenna Position Calibration

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ABSTRACT

This memo summarizes the antenna position calibration used at Hat Creek, and discusses its application to the CARMA and ALMA telescopes. Observations of quasars over wide range of HA and DEC provide data from which the antenna positions are determined. If the antenna positions are in error by many wavelengths, 2π phase ambiguities may make this process difficult, especially when the atmospheric phase coherence is poor on long baselines. In this case the antenna positions can be first determined from the phase difference between the sidebands in a double sideband system, or across a wideband single sideband. In addition to the antenna positions, there may be axis offsets on the antennas which can be fitted from the quasar data or measured mechanically. These offsets should be stable and not change when the antennas are moved.

1. Introduction

An interferometer measures the geometrical phase delay, $\phi = 2\pi/\lambda\ b.s$, where b is the baseline vector between each pair of antennas, and s is a unit vector in the source direction. After each antenna move, the antenna position must be determined to an accuracy $\sim \lambda/10$. An initial guess for the antenna positions is obtained from the array geometry, surveyed and historical record of station positions, and measurements of antenna offsets from the station positions. Observations of quasars then provide data from which the antenna position is determined. For an unresolved source, the observed residual phase is $\delta\phi = 2\pi/\lambda\ (\delta b.s + b.\delta s) + phase(time)$, where $phase(time)$ includes thermal noise and uncorrected phase drifts in the instrumental phase. We determine δb by rapidly observing quasars with accurately known positions, over a wide range of HA and DEC, and fitting the residual phase, $\delta\phi$ to solve for δb. Errors in the quasar positions propagate into errors in δb. For $\delta s \sim 1$ mas, the error in the baseline $\sim b/(2\ 10^8)$. For a 10 km baseline at 1 mm, the error, $\delta b \sim \lambda/20$. The baseline fitting process also identifies errors in quasar positions. Because of the limited SNR and large atmospheric phase, baseline fitting is an iterative process at millimeter wavelengths. The antenna position calibration is often called the baseline calibration, but should not to be confused with a spectral baseline calibration (which is usually called a passband or bandpass calibration). We derive antenna based phases from the observations using SELFCAL, since we wish to determine antenna positions. SELFCAL can include known source structure in the quasars. The baseline observations are usually made at night when the atmospheric phase stability is good, and at a frequency around 90 GHz where the sky opacity is minimum and the best system temperatures are obtained. At this frequency there are sufficient strong quasars that a good baseline can be obtained in 2-3 hours.

2. The fitting procedure

The Miriad task BEE has evolved over the last 20 years to cover the procedures we have needed for determining the antenna positions at Hat Creek on baselines to 2 km. BEE is an interactive task with a number of different fitting, data selection, flagging, editing, and display routines. We determine the antenna positions and the residual instrumental phase iteratively. One must remove 2π wraps from the data. We do that with cursor options, using either a phase extender algorithm, or manually defining boxes in which to add or subtract 2π. A 4-parameter fit determines δb and a constant phase offset. A 3-parameter fit determines δb from difference phases over a specified time interval. A 2-parameter fit can be used to fit the equatorial components of δb from the HA dependent phase on a single quasar, followed by fitting the polar component (δb_z) using sources over a wide range of DEC. The fits to the antenna positions can be improved by fitting and removing a polynomial versus time to the residual phase and iterating if needed. Another fitting routine makes a best fit to a matrix of b_x b_y b_z space for the minimum residual. This works well if the SNR is good and the baseline error is within the search box. For each fit, BEE calculates a covariance matrix and the errors on each fitted term.

3. Long Baselines

In the largest array configurations, the station positions are less well determined and the atmospheric phase fluctuations are large, so we have to work harder. Ideally, we would first correct the observations for atmospheric phase fluctuations before fitting the antenna positions. However, the antenna positions are determined from the phase changes between widely separated sources observed through very different air masses, and these atmospheric phases are more difficult to correct than the atmospheric phase fluctuations observed on a single source. Instead, we fit the phase difference between the two sidebands, effectively fitting the baseline at the difference frequency, where the atmospheric phase fluctuations are smaller. We first calibrate using the LSB and then USB, so that the derived antenna phases are USB - LSB. We can also fit the phase difference across a single sideband. Either way, this determines the baseline to about $\lambda/10$ at the difference frequency. We then determine the baseline more accurately in the usual way. For CARMA and ALMA, the bandwidths are 4 GHz and 8 GHz. Fitting the phase gradient across the band is effectively measuring the antenna positions from the geometric delay as a function of source position. These methods could also be used on more compact antenna configurations, but are usually not needed. Bandpass errors rather than instrumental phase drifts are a source of error in these methods.

4. Axis Offsets

In addition to the antenna positions, which must be determined every time the antennas are moved (or change due to station movement), there are mechanical axis offsets which can be determined from the quasar observations. The axis offsets can be measured directly from the antenna structure, but are identified and measured more accurately from quasar observations. The task BEE includes a 1-parameter fit to determine an axis offset. A 5-parameter fit includes antenna positions and axis offsets, but these are not orthogonal and the axis offsets are more accurately determined from special observations. The BIMA antennas are able to observe over an elevation range 5 to 175 degrees for these measurements. For the original Hat Creek 3-antenna array, the axis offset was a function of the antenna azimuth. These measurements led to improvements in the structure for the new BIMA antennas. The axis offset measurements are made over a range of antenna azimuth, but this is a small error on the current antennas.

5. Sensitivity, Sub-arrays and Error Propagation

5.1. Sensitivity

Thermal noise contributes an error $2\pi/\lambda\ \delta b.s \sim \Delta S/S$ radians, where ΔS is the thermal noise for the antenna-based phase. For the BIMA array with ten 6-m antennas, 800 MHz bandwidth and Tsys=200 K, $\Delta S \sim 30$ mJy with 4 minute integrations. This gives an error $\delta b < \lambda/100$ for quasars $>\sim$ 1 Jy which we use for the baseline calibration. A 4-minute integration gives good observing efficiency with the long slews (80 deg min^{-1}) used for the baseline observations. The quasars observed are arranged with wide angular separation to give good separation of instrumental phase drifts and baseline errors in the fitting procedures. We also re-observe each quasar over a range of HA in order to improve the determination of the equatorial components of δb. For ALMA, with a sub-array of ten 12-m antennas, 8 GHz bandwidth and Tsys=40 K, the thermal noise for the antenna phase $\Delta S \sim 3$ mJy with 10 second integrations. Errors from thermal noise are less than $\lambda/100$ for quasars brighter than $\sim$ 100 mJy, but long slews are still required to separate instrumental phase drifts and antenna position errors.

5.2. Sub-arrays

The antenna position calibration can be obtained from a sub-array. Since the antenna positions are relative to a reference antenna used to determine the antenna based phases, we need to include at least one unmoved antenna in order to find the antenna positions relative to the rest of the array. For small arrays like BIMA, it is convenient to use the whole array for baseline calibration. CARMA and ALMA sub-arrays may be comprised of combinations of different sized antennas. The calibration sensitivity is greatly enhanced by using correlations with larger antennas. These issues are discussed in more detail for the CARMA telescope in BIMA memo 85.

5.3. Error Propagation

The ALMA telescope will be reconfigured often; $\sim$ 3 antennas will be moved per day, and a sub-array can be used to calibrate the antenna positions. If different sub-arrays and reference antennas are used after each re-configuration, then errors in the antenna positions will propagate through the array. The antenna positions are used to determine the station positions which are used to calculate the initial antenna positions after a move. Error propagation can be minimized by using a set of reference antennas which are moved least frequently. The choice of sub-array should also consider atmospheric phase errors on the longer baselines. A periodic antenna position calibration using all the antennas will prevent errors from building up.

Antenna position errors cause phase errors in the uv-data, $\delta\phi \sim 2\pi/\lambda\ \delta b.\Delta s$, where Δs is the difference in position between the target source and the phase calibrator. For a phase calibrator, we must often balance the choice between a weaker calibrator close to the source position, and a stronger more distant one. For the BIMA telescope, it is usually possible to find a strong enough phase calibrator within 10 deg, giving a $\sim$ 6 deg phase error in the uv-data. This is smaller than the typical atmospheric phase fluctuations and adequate for sensitivity limited aperture synthesis imaging, but for accurate position measurements we must use several nearby calibrators. E.g. SiO maser positions (Wright and Plambeck, ApJ 267, L115). For CARMA and ALMA, with the higher sensitivity, we can observe weaker calibrators closer to the target source using shorter integrations. Rapid switching to nearby calibrators will reduce the effects of antenna position errors as well as atmospheric phase fluctuations. For a phase calibrator within 1 deg and an antenna position error $\sim \lambda/10$, the phase error in the uv-data is < 1 deg.