Atacama
Large
Millimeter
Array

Location Calibration Steps

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Specification Document

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1	2005-09-14	Mark Holdaway	All	Initial draft
2	2006-07-17	Jeff Mangum	All	Rewrite following review
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Contents

1 Goals

1. To determine the antenna positions to within 65 μm relative to the ICRF. This specification leads to a < 3 degree baseline phase offset at 300 GHz for a phase calibrator-to-target separation of 5 degrees.
2. Note that whenever antennas are moved their initial positions will at first need only be determined to < 2 cm accuracy. This accuracy will produce negligible decorrelation (< 3 deg change) over 5 seconds of integration time or over a frequency bandwidth of 120 MHz ($\frac{1}{16}$ of a 2 GHz band). See §2.
3. The approximate position of these newly-moved antennas will be determined by a baseline observation involving these antennas and at least one unmoved antenna. The maximum baseline between the unmoved antenna and any newly-moved antenna be < 1 km.
4. Ultimately the antenna positions will need to be accurately determined. The timescale over which accurate baseline measurements will be made will interact with the execution of the ALMA pipeline and the needs of specific observations. For example, only science observations requiring the most accurate absolute positions will require the most accurate baseline measurements.
5. Since pointing model derivation for newly-moved antennas must also be made before including them in any science observations, it would be most efficient to interleave all-sky pointing measurements with baseline measurements.

2 Impact of Antenna Position Errors

There will be three different errors which occur when we get the baselines incorrect:

1. *Initial Antenna Position Measurement Requirement:* Since it may take several days to determine accurate antenna positions to correct the data, the interim baselines must be sufficiently accurate to not degrade the quality of the data. We interpret this as meaning that the baseline-induced phase drift over 5 sec for the calibrator or target should be < 3 degrees, or the baseline-induced phase change over a 125 MHz channel should be < 3 degrees (*i.e.* the baseline error will produce insignificant decorrelation). The baseline error that will produce a 3 degree change at 300 GHz (1 mm PWV) over 5 seconds ($B(t)_{error}$) and the baseline error that will produce a 3 degree change over a channel bandwidth of 120 MHz ($B(\nu)_{error}$) are of the same order-of-magnitude, given by the following:

$$\begin{aligned} B(t)_{error} &= \frac{1mm * 3^\circ}{360^\circ} \times \frac{1rad}{5sec} \\ B(\nu)_{error} &= \frac{3^\circ}{360^\circ} \times \frac{c}{120MHz} \\ &\simeq 2\ cm \end{aligned} \tag{1}$$

2. *Phase Decorrelation Across the Bandwidth:* Lets say we can tolerate 10° of phase error across the 8 GHz band. Then, the component of the baseline error parallel to the vector to the observed source must be less than

$$B_{error} < \frac{10^\circ}{360^\circ} \times \frac{c}{8GHz}$$

$$< \quad 1\ mm \tag{2}$$

Hence, if we don't make the 100 μm specified accuracy for baseline calibration, there is an extra factor of 17 over the spec before we will start to see bandpass decorrelation.

3. *Phase Errors Due to Fast Switching:* Fast switching between a target and a nearby calibrator is an excellent method for removing phase errors associated with geometric delay errors like the antenna position error, and large-scale tropospheric model errors. As the target source and the cal source are very close together, they will have nearly identical delay errors due to the geometrical error, so using the cal source's phases will correct for most of this error.

   The specification of the 65 μm for antenna position error (95 μm baseline error) will produce a residual 3 degree phase error at 300 GHz for a calibrator-source separation of 5 degrees. For observations of 50 antennas over several hours, we estimate that this phase error will give an rms dynamic range limit of about >200:1 ($\sim \left(\frac{5deg}{1radian}\right)\sqrt{\left(\frac{1}{50}\right)}$). The dynamic range limit varies inversely with the mean antenna position error; hence a significant increase in the antenna position error will decrease the dynamic range limit. The image dynamic range will also be limited by the short-term phase fluctuations which will depend on the accuracy of the WVR corrections. However, if the target can be self-calibrated, then the effect of baseline errors are must less important in determining dynamic range limits.

4. *Using the Incorrect (u,v) Coordinate for Imaging:* At the levels we are talking about, using the incorrect (u,v) coordinate is not an issue at all. It would take a few meters of (u,v) error to make a difference.

3 Performing Baseline Calibration Observations

Determining the antenna positions, also known as baseline calibration, is a service observation, and the results of this service observation will be automatically applied to the data in the on-line or reduction software. Much of the strategy for baseline calibration comes from [1].

3.1 Common Issues

We will give example observations for a few different situations, but several elements will be common among these situations.

Antenna and Electronic Delay: Baseline calibration requires good antenna, electronic, and tropospheric delay measurementa and calibrations (see [2]).

Calibration Frequency: Because of the combination of a low noise system and relatively small instrumental (including bandpass time variations) and tropospheric errors, the baseline calibration will be performed at 90 GHz.

Phase and Delay Determination: The antenna-based phase and phase gradient across the 8 GHz (or larger) frequency span will be measured from each 30-sec calibrator scan. These data will be analyzed to determine accurate baselines.

Pointing Issues: At 90 GHz, the pointing is fairly good. Furthermore, sizeable pointing errors can be tolerated in baseline calibration, as we are observing point sources and the main effect of pointing errors on such obervations will be small amplitude errors. The visibility phases will contain all the information we are interested in. As baseline and pointing observations will be done at the same frequency and with the same sources, it will be most efficient to interleave baseline and pointing measurements.

Calibration Sources: We will need a list of 100-200 point-like calibration sources, each about 0.1 Jy or brighter at 90 GHz. Furthermore, we need to know the positions of these sources to sub-mas accuracy. Suitable calibrators south of declination −30 deg are needed.

WVR Use: Atmospheric phase errors will translate into uncertainty in the antenna positions. WVR is designed to track relative changes, but we need absolute phase information. So WVR will likely not be used during baseline observations until the long-term phase stability of the WVRs is understood.

3.2 Preliminary Baseline Calibration After Antenna Reconfiguration

1. Current operations planning calls for the reconfiguration of four antennas each day.
2. Using a subarray which includes the newly-reconfigurated antennas and at least one unmoved (reference) antenna, a series of sequenced all-sky pointing/baseline calibration measurements will be made. The maximum baseline between any newly-moved antenna and the reference antenna should be < 1 km. The sequence will be as follows:
   (a) Select a list of at least 10 bright (> 0.1Jy at 90 GHz) point sources with good (Az,El) sky coverage.
   (b) For each point source in the list:
      i. Make a pointing measurement.
      ii. Apply derived pointing offsets for each antenna.
      iii. Perform phase measurement.
   (c) In order to separate temporal electronic phase drifts from elevation dependent baseline phase effects, a suitable observing sequence must be designed.
3. Suitable software must be available to analyze the phase and delay (phase slope with frequency) to determine the three baseline coordinates. A determination of the residual zenith-path delay may be another parameter that must be determined.
4. After the pointing and preliminary baseline observations have been completed, the four newly moved antennas can be used in regular observations. However, as the baseline solutions will have significant errors, we must consider what to do with the data. If the observations are demanding, for exampe, if they are high frequency observations, long baseline observations, or high fidelity imaging observations, we cannot reduce the data in the calibration and imaging pipeline yet, but we need to wait until better baselines are determined (see §3.3. If the observations are not very demanding, we will often be able to proceed with the calibration and imaging pipeline.

3.3 High Quality Baseline Calibration at Night

The preliminary antenna positions solved for shortly after the reconfiguration has been completed will usually be limited by the poor daytime phase stability. To correct this, we will wait until the phase stability improves during the night and perform a better baseline calibration. Again, for these observations we form a subarray from the four newly-moved antennas and at least one other antenna with previously well-determined positions.

1. Perform baseline measurements as described in §3.2.

2. There may be times when daytime conditions are either so windy or the phase stability so poor (and refractive pointing jitter so high) that the pointing run will be unreliable. In these cases, we may want to perform the interleaved all-sky pointing observations to improve the a-priori pointing model. Generally, though, we won't need to repeat the pointing observations, and can go straight to the baseline measurements.
3. Baseline calibration should be done when the phase stability is excellent. During periods of excellent phase stability (25% of the time) the phase error over a 30-sec calibrator scan is 175 μm over a 1 km baseline. Hence, about 20 observations of calibrators over the sky should produce an rms baseline of about 65 μm.
4. At the start of the baseline measurement run the measured phase jitter should indicate at what level the atmosphere is limiting the measurements. At this point an automated decision could be made as to how many times we repeat the observations to average down the atmospheric phase errors.
5. After the baseline solutions have been succesfully made, the antennas are returned to the main array for astronomical observations. The new antenna positions and baseline information will be taken into account for all future observations, and past observations can be corrected for the improved baselines. The corrections will include a phase gradient across the band (this correction will usually be quite small) and updates to the (u,v,w) coordinates of the visibilities. These corrections will be applied in the calibration and imaging pipeline.

3.4 High Quality Full Array Baseline Calibration

Full array baseline calibration will be needed to prevent errors from propagating through the iterative reconfiguration and calibration process. These observations will look very much like the subarray observations described in §3.2 and §3.3, but will include all antennas and should be made at night to take advantage of superior phase stability. The timescale over which these accurate baseline measurements will be dictated by the actual measured stability of the antennas. The antenna position stability requirement of 65 μm applies over a timescale of 2 weeks (a fortnight). Therefore, at least initially, baseline runs will be required at least every two weeks in the beginning.

4 Issues Requiring Consideration

1. Baseline errors produce a systematic phase difference between the calibrator and target for which fast switching (with or without the WVR) cannot remove.
2. The inherent systematic phase error between target and calibrator resulting from fast switching at 90 GHz will be multiplied when tranfering this phase calibration to higher frequency. Hence, at 800 GHz with 65 μm accuracy and a 10 degree separation between a strong calibrator and the target/fainter calibrator, a systematic phase error of < 10 degrees is likely (which is pretty good).
3. The array clock error and astrometric/geodetic model (Calc) can impact the apparent antenna position error. This and the above effects may determine how often baseline observations have to be made, even with no configuration change. Note that using a the USNO (Calc) astrometric model in the correlator (< 0.2 mas accuracy) will introduce an apparent baseline error on a 20-km baseline which is less than 20 μm.
4. Interaction of the baseline observations with WVR observations and tropospheric modeling will be important, and can only be determined with the first few years of ALMA observations. As with present

VLBI, global tropospheric properties may be determined directly from the observations more accurately than meteorological monitoring.

5. For ALMA astrometric proposals (*e.g.* determination of the accurate absolute position of faint stars), the proposal itself probably should include more accurate baseline calibration observations to supplement the normal ALMA baseline monitoring.
6. The frequency of baseline observations (other than the obvious when antennas are reconfigured) depend on the structural stability of the antennas and other electronic phase effects which are associated with the pointing location of the antennas.
7. ALMA will probably be used to search for suitable calibrators for relevant future targets and determination of the flux density of quasars. These searches could be combined with antenna position determination observations.
8. Coordination of a-postiori baseline corrections into the ALMA pipeline must be developed.

References

[1] Conway (2004), “Antenna Position Determination: Observational Methods and Atmospheric Limits”, ALMA Memo 503

[2] Lucas (2006), “Antenna and Electronic Delay Calibration Steps”, Lucas