Atacama
Large
Millimeter
Array

ALMA Calibration Plan

ALMA-90.03.00.00-007-A-PLA

2006–09–06

Specification Document

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Change Record

Revision	Date	Author	Section/ Page affected	Remarks
1	2005-10-01	Jeff Mangum	All	Initial Draft
2	2006-02-04	Jeff Mangum	All	Added some content to all sections
3	2006-04-11	Jeff Mangum	All	Reformatted to couple better to example documents
4	2006-06-10	Jeff Mangum	All	Modifications following first few example document reviews
5	2006-08-27	Jeff Mangum	All	Modifications following further example documents reviews
6	2006-09-01	Jeff Mangum	Optics	Added Optics calibration content following review
7	2006-09-01	Jeff Mangum	ACA	Added ACA calibration coordination content
8	2006-09-03	Jeff Mangum	Polarization	Updated Polarization calibration section
9	2006-09-06	Jeff Mangum	Polarization	Another update of Polarization calibration section

`$Id: CalibrationPlan.tex,v 1.8 2006/09/06 14:00:23 jmangum Exp $`

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Table 1: Calibration Examples/Descriptions

Document	Author(s)
Amplitude and Flux [1]	Lucas & Mangum
Phase [2]	Holdaway
Bandpass [3]	Lucas
Polarization [4]	Fomalont, Myers & Holdaway
Pointing [5]	Mangum & Lucas
Antenna Location [6]	Mangum, Fomalont, & Holdaway
Antenna and Electronic Delay [7]	Lucas
Optics [8]	Vila Vilaro
Primary Beam [9]	Mangum & Holdaway
ACA Calibration Coordination [10]	Fomalont

1 Calibration Road Map

The development of the ALMA calibration system is described in Figure 1. The major input categories in this diagram are:

– *ALMA Design Documentation and Experience*: The development of each calibration measurement starts with the low-level science, system, and calibration requirements augmented with experience from the development and use of other radio and millimeter interferometers.

– *Calibration Examples/Descriptions*: Atomic level descriptions of each type of calibration based on the science requirements and system characteristics. These descriptions list the measurements made during a calibration sequence and any issues or options to be considered in their development.

– *Hardware/Software Calibration Observation Sequences*: In collaboration with the Computing, Frontend, Backend, and Systems IPTs the example descriptions of each calibration type are collected into an observation sequence. These then represent "scheduling block" level definitions of a calibration measurement.

– *Observing Modes*: Using the observation sequences developed for each type of calibration, appropriately sequenced calibration measurements (with input from the "calibration matrix" of predecessors) are coupled to the various ALMA observing modes.

2 Calibration Example Overview

In the following subsections we list the goals and describe some of the details entailed with each type of calibration measurement. The full description of each calibration example is left to the associated example document (see Table 1).

2.1 Amplitude

The goals of an amplitude calibration measurement are:

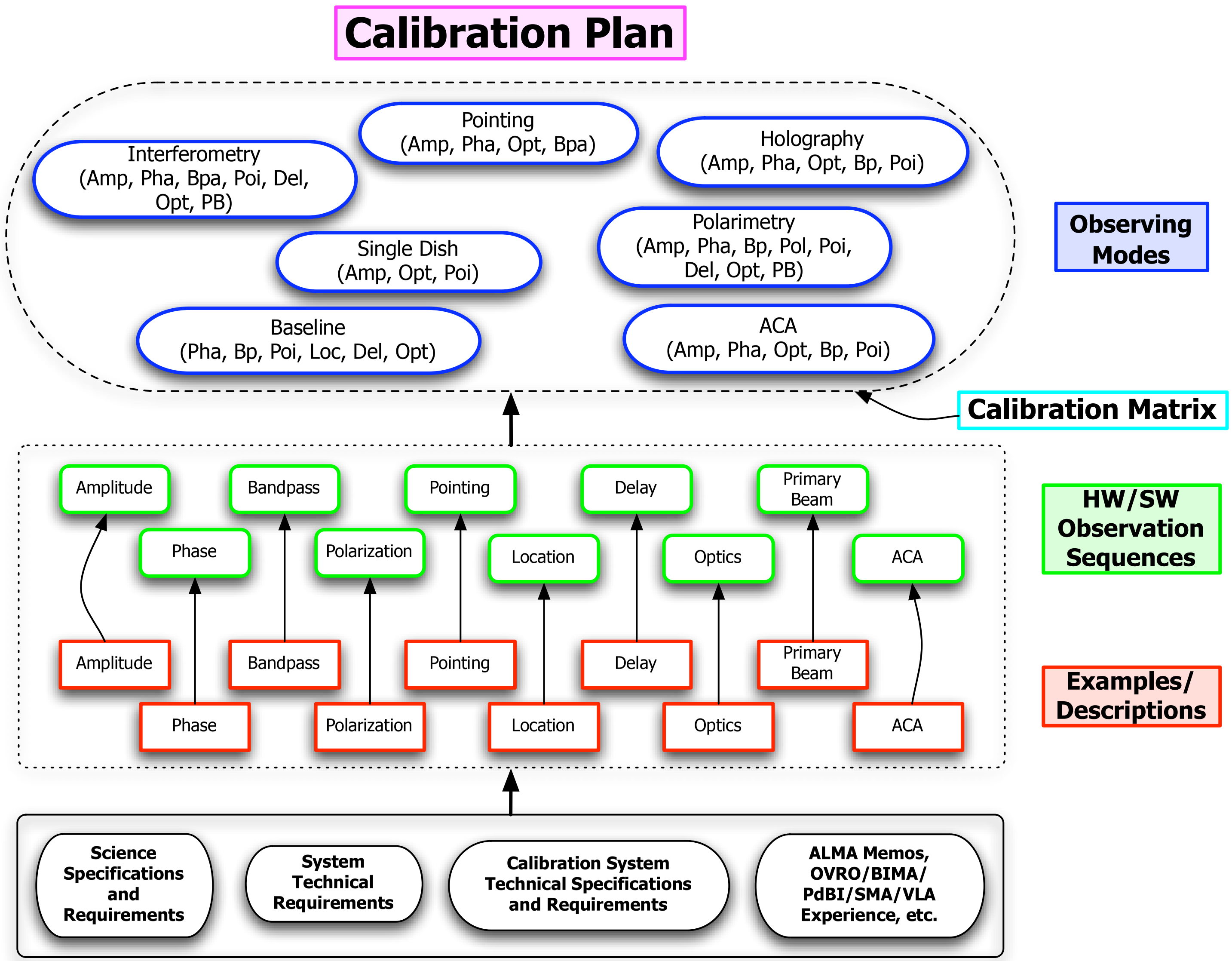

Figure 1: Calibration plan organization. The flow of requirements and information starts at the low-level science, system, and calibration requirements augmented with experience from the development and use of other radio and millimeter interferometers. This information feeds detailed descriptions (“examples”) of each type of calibration, which in-turn drive the development of hardware/software observation “sequences” for each type of calibration. The hardware/software observation sequences are then used to develop observing modes which incorporate one or more calibration measurements. Calibration measurement sequencing is dictated by the “calibration matrix”.

- **Establish the T_A^* scale** for ALMA observations, both in interferometry and single-dish mode, for continuum and spectral line data. Conversion to T_A^* ensures that the main effects of variations of atmosphere absorption are taken out, so that emission from sources at different elevations can be compared. See [11] for details. Note that this is a *relative amplitude calibration* scale.

  As specified in [12] (SSR 2.3-R11) the visibilities are stored as cross-correlation coefficients. The option has also been taken to store the auto-correlations (recorded in all cases, both interferometry and single-dish) in similar units (see [13], [14]). Thus the integral of the autocorrelation spectrum is 1.0 (the raw value of the zero-lag channel is kept too). We refer to this data as "raw data". However remember that the following corrections have already been applied:

  · correlator quantization correction,
  · WVR path length correction (optional)
  · residual delay error correction.

  Converting the raw data into T_A^* data requires only multiplying by the system temperature T_{SYS} for the proper observing frequency. This scaling factor is derived from measurements made with the relative amplitude calibration device (*c.* f. [11]).

- **Convert T_A^* into flux density units (Janskys)**. This scale is appropriate for interferometric aperture synthesis and single-dish observation of point sources. Note that this is an *absolute amplitude calibration* scale. All measurements will ultimately need to be converted to flux density units.

  This step will remove the antenna gain, residual atmospheric antenna and receiver gain variations, receiver passbands, *etc.*

- **Convert the T_A^* into brightness temperature units**. This step is appropriate for single-dish observation of extended sources. Note that this is an *absolute amplitude calibration* scale.

For the conversion of the relative T_A^* amplitude scale to an absolute brightness temperature (T_R) or flux (S) "traditional" means will be used. Measurements of astronomical objects whose fluxes are known or well-predicted by modelling are used to connect the absolute and relative amplitude scales. As the current state-of-the-art in amplitude calibration at millimeter and submillimeter wavelengths is generally larger than the 5% absolute calibration specification, the characterization of a set of absolute amplitude calibration standards will be an early and high-priority research project for the ALMA operation.

To this end, one of the first development projects that ALMA should pursue will be an adaptation of the absolute amplitude calibration scheme using interferometry proposed by Jim Gibson and Jack Welch (UCB RAL). A description of this next-generation absolute amplitude calibration system can be found in [1].

Finally, since the ALMA amplitude calibration requirement is a rather complicated specification with many facets, we have produced a document designed to clarify this requirement. [15] seeks to consistently define and explain the contributions to the amplitude calibration specification and relate these definitions to existing reports and documents.

2.2 Phase

The goals of a phase calibration measurement are:

- To calibrate the atmospheric and electronic phase fluctuations, effectively reducing them to the smallest values possible. Based on an analysis of the phase stability of the entire ALMA system [16], *the corrected visibility phase fluctuations must be* < 1 *radian at 950 GHz.*

– This phase stability requirement is designed to allow ALMA to reach its imaging specification of "noise limited imaging down to 0.1% brightness features"[1]
– Fast Switching (FS) and Water Vapour Radiometry (WVR) correction systems will be used to meet this phase calibration requirement.
– The residual phase errors we will be able to achieve will depend strongly on the atmospheric conditions (which vary by a factor of 20), the observing frequency (which varies by a factor of 30), and the specific demands of the project (*i.e.*, detection, mapping, or high fidelity mapping, which will have a factor of 3-10 difference in required phase stability).
– In addition to achieving very low phase errors for each visibility, we must also achieve very low phase errors across each integration to minimize phase decorrelation. The relative amplitude calibration is required to be better than 1% for millimeter wavelengths and better than 3% for sub-millimeter wavelengths, and decorrelation will need to be a small part of that specification. However, the imaging specification of "noise limited imaging down to 0.1% brightness features" may require an even tighter requirement on the relative amplitude fluctuations due to variable decorrelation.

A number of issues are addressed in [2]:

– *Solar Observations*: Fast switching during solar observations will require the insertion of the solar filter when target (Sun) observations are made at the target frequency.
– *Decorrelation Correction When Using WVR*: Visibilities corrected by the calibrator's phase solutions and the WVR phase increments will suffer from some degree of decorrelation, due to the WVR thermal noise and any residual phase errors not accounted for by the phase solutions and the WVR measurements. This decorrelation is expected to be minor and only an issue for the highest ALMA frequency bands. If there are other residual phase errors at play, a more complicated decorrelation correction scheme will need to be applied, and this is a research topic for ALMA commissioning.
– *Calibrator Database*: There will need to be a calibrator catalog which will likely contain a few ten thousands of sources. For all observations, then, there are several potential calibrators within a few degrees of the target source. This database will be updated with flux measurements whenever a calibrator is observed. More accurate positions will also be added when available.
– *Monitor Calibrator Phase Solutions in Real Time*: During the fast switching observations, we will need to monitor the phase solutions on the calibrators to make sure that the phase conditions are indeed what we thought they were when the dynamic scheduler started this current observing project. WVR data should also be monitored and displayed, along with a statistic on the WVR-brightness to phase conversion which is appropriate to the current observations. An estimate of residual phase errors and resulting dynamic range limitations and phase calibration efficiency would also be useful. In addition to being available to the scheduling software, the phase solutions should be available to the astronomer as a quick look tool to help evaluate the success of the observations.
– *Offline Processing for Fast Switching*: In the offline data reduction system, the phase solutions will be determined again and interpolated (including the less frequent cross-band phase solutions, if applicable), and applied to the data. Some fancy interpolation schemes, such as:
    · Time-delayed or time-advanced interpolation, to deal with a calibrator which is up or down stream from the target source.

[1] Note that if an object is bright enough for features at 0.1% peak brightness to be seen in a reasonably short amount of time, we will be able to self-calibrate to remove the effects of phase errors, but this is a small fraction of the observations.

· Wet delay interpolation between the target frequency band and the calibration band (usually Band 3). If we calibrate at 90 GHz and scale the phase solutions up to the target frequency, we will need to construct a lookup table or use a transmission model like ATM to calculate a scaling factor (convert the WVR brightness fluctuations into phase fluctuations at the target frequency) which is more accurate than the target frequency divided by the calibration frequency. These additional calculations must be performed quickly, simply, and in an automated fashion, as they need to be available to the calibration and imaging pipeline.

will need to be developed.

– *Integration Times and Subsequent Self-Calibration*: If just fast switching is used on a weak source, there will be a fair amount of decorrelation and no recourse to self-calibration, so an averaging time equal to the time on the target source for each switching cycle will be used. The variable decorrelation could be estimated from the calibrator gain solutions to achieve a more correct amplitude scale, but at the expense of dynamic range (our correction can make the flux scale correct on average, but will make errors on specific visibilities which will scatter flux around the image). If just fast switching is used on a strong source, short (1 s) integration times should be used. The short integrations will permit self-calibration to be used to correct for the short time scale phase fluctuations which take place between 1 s and the fast switching cycle time.

– *Offline Application of WVR and Fast Switching Data*: Conversion of WVR fluctuations to phase fluctuations can be made theoretically based on measurements of the water vapor and temperature profiles. Alternatively, examination of the detailed correspondence between WVR data and the calibrator phase solutions could determine the details of how the WVR data gets converted to phase increments. The best way to convert the WVR fluctuations to phase fluctuations will be a research topic for ALMA commissioning. The presence of liquid water or ice crystals will impact this conversion.

2.3 Bandpass

The goal of bandpass calibration is to correct the science data for all frequency-dependence of the telescope gains. Specifically:

– **Correct for the Frequency Dependence of the Atmospheric Attenuation**: This is a pure amplitude calibration, using a dual load system: ambient and warm loads, at $T_1 \sim 293$ K and $T_2 \sim 350$ K (about 80 C). This is described in [1]. Using a suitable linear combination of the two load signals allows to have T_{CAL} very much independent of frequency (as well as of changes in atmospheric optical depth).

  These steps correct also for frequency dependence of the amplitudes of antenna-based gains in the electronics. However it does not correct for antenna and optics losses, prior to the amplitude calibration device.

– **Measure the Relative Phases (and Amplitudes) of the Basebands on a Point Source**: This is required to improve the signal-to-noise ratio for the various on-line calibrations, like pointing, focus, which are done on point sources (quasars), and for which we will average basebands, side bands and polarizations. For them one frequency point for each baseband is only required.

– **Measure the Sideband Amplitude Ratios as a Function of IF Frequency**: This is needed for proper calibration of the atmospheric amplitude attenuation, and conversion to T_A scale, as this gain ratio g enters the formula for T_{CAL} , in both two-load and single-load schemes. (See [1]).

– **Correct for Bandpass Shape in Science Data**: This is done in both amplitude and phase using the signal of a strong point source. This is needed to correct for:
  · The phase response of all the analog receiving system, with the exception of the effect of delay offsets which have to be corrected before observing (see [7]). The phase response of the digital Tunable Filters is corrected for in real-time by the correlator software.
  · The amplitude frequency response not corrected by the amplitude calibration above. Two effects should contribute:
    ◦ The amplitude response of the antenna beam (antenna gain).
    ◦ The decorrelation, due to averaging in time (atmospheric or instrumental phase fluctuations), which should not be frequency dependent, or frequency (the latter should be small except may be at the very edge of filters).

2.4 Polarization

Polarization calibration essentially determines the cross-talk between the two measured orthogonal source polarizations (see [4] for details). The cross-talk terms are generated in the feeds, by the antenna structure and blockages, and from the receivers. Assuming polarization types X and Y, the cross-talk can be parameterized for each antenna at a specified frequency, time, and at the beam center by:

d_X = amount of Y polarization signal in X polarization channel.

d_Y = amount of X polarization signal in Y polarization channel.

Both of these terms are complex numbers giving the amount and relative phase of the leakage signal. Other parameters which tie the phases between all of the X and Y polarization channels are:

ϕ_{XY} = phase difference between all X and Y polarization channels

δ_{XY} = delay difference between all X and Y polarization channels

It is expected that the d_X and d_Y terms will be about 2% for the lower frequencies, but perhaps up to 10% at the highest frequencies. Calibration accuracy, based on VLA experience, should be relatively easy to the 0.5% level per antenna at the lower frequencies. Thus, even at this level, polarization image artifacts should be less than 0.1% of the peak on the total intensity image.

The calibration steps outlined in [4] should cover most cases that the baseline ALMA will encounter. However, there are still a number of issues that are as yet unresolved and will likely require investigation as part of ALMA commissioning:

– Single-dish determination of polarization parameters.

– Time dependence of **D** and **E**.

– **D** determination using extended sources.

– Optimal factorization of **D** into more physical terms.

– Application of the calibration parameters during processing.

2.5 Pointing

The goals of pointing calibration are to establish the antenna-based pointing offsets at several levels:

– **Global Pointing Model Parameters** for all ALMA antennas. This will generally be done with a linear least-squares fitting algorithm applied to a sequential series of randomly-distributed radiometric pointing measurements of $\sim$ 100 or more radiometric point sources. This global pointing model characterization should be necessary not more than once per month.

– **Reference Pointing Offsets** for each antenna and receiver band. This pointing measurement tracks shorter timescale variations in the pointing performance of each antenna. These pointing variations can be tracked with either single (Az,El) offset measurements or derivation of a "local pointing model" in the region around a target source.

– **Relative Receiver Band Pointing Offsets** for each antenna and receiver band. Necessary to monitor longer (several month) timescale variations in the relative pointing between receiver bands for each antenna.

Investigations of alternate, and potentially more time-efficient, pointing measurement techniques should be a priority for ALMA commissioning. For example, if stronger sources and thus shorter integration times (smaller than 2 seconds) are used, it may be more efficient to observe a circle around a pointing source at the half-power point to minimize the slew time between discrete integrations at half-power points. Also, the local pointing model scheme will need some validation. As sensitivity is a key factor which will determine the ultimate utility of this technique, its real efficiency can only be tested on the full ALMA array. Tests on actual telescopes are quite valuable as the main uncertainties here are the actual telescope thermal and mechanical properties.

2.6 Location

The goals of antenna location (baseline) calibration are as follows:

– 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.

– 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).

– 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.

– 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.

– 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.

We note that there are several issues regarding antenna location calibration should need to be considered when developing an operations strategy:

- Baseline errors produce a systematic phase difference between the calibrator and target for which fast switching (with or without the WVR) cannot remove.
- The inherent systematic phase error between target and calibrator resulting from fast switching at 90 GHz will be multiplied when transferring 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).
- 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.
- 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.
- 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.
- 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.
- 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.
- Coordination of a-postiori baseline corrections into the ALMA pipeline must be developed.

2.7 Delay

The goal of antenna and electronic delay calibration is to measure the delay offsets induced by the hardware in the antenna, fibers, cables, *etc.*. These delays have to be compensated by appropriate delays in the correlator to limit amplitude losses due to de-correlation across the observing bands. Note, however, that small (*i.e.* a fraction of a nanosecond) and constant delay errors will be efficiently removed by bandpass calibration.

Since there are several components to this measurement, we briefly describe the basic measurement technique and its application:

- The *basic experiment* is simple enough: measuring the delay on a strong point source is done simultaneously for each base-band and polarization, having the correlator producing the two parallel products (XX and YY).

  The delay is determined by fitting a linear dependence on frequency for the antenna-based channel phases. It might be wise to exclude a few edge channels in each base-band. The band with should be 2GHz for each baseband to optimize sensitivity.

  However if the delay is totally unknown and can be high, a narrow band on a strong source is preferred, as a strong delay could produce too much de-correlation in wide channels; for instance in 1MHz channels the delays are measured with an ambiguity of 1ms. With BBC 7 (2 GHz and 2 polarizations), the resolution is 15.625MHz and the ambiguity is 64ns. This is the equivalent of 20 m distances. If the fiber lengths are not known from construction to that accuracy, we will have to use use higher frequency resolutions.

– There are in fact three kinds of parameters to be measured:

Quantity	Description	Number	When?
$\tau_{\rm R}$	Receiver delay	$N_{\rm ANT}N_{\rm BAND}N_{\rm POL}N_{\rm SIDE} = 2560$	Receiver or down converter change
$\tau_{\rm IF}$	IF delay	$N_{\rm ANT}N_{\rm POL}N_{\rm BB} = 512$	Antenna move, back-end change
$\tau_{\rm XP}$	Cross Polarization delay	$N_{\rm BAND}N_{\rm SIDE}N_{\rm BB} = 80$	At least once, but should be checked from time to time.

This is a simplified list as tracking all the parameters is probably needlessly complex and error-prone. For example, it has been proposed to keep track of the differential delays between base-bands independently of the station-dependent delays due to fiber lengths. However the possibility of rather frequent use of ACA antennas with the 64-station correlator made this even more complex. It is not very costly to measure all the baseband delays whenever the interferometer configuration is changed.

– The same set of $\tau_{\rm R}$ for an antenna should be valid whether it is connected to the 64-station correlator or to the ACA correlator. But the set of $\tau_{\rm IF}$ is correlator dependent (there is one such set for each correlator). This also applies to the set of cross correlation delays $\tau_{\rm XP}$.

2.8 Optics

The goal of optics calibration is to measure and where appropriate correct for misalignment of all optical components. Misalignment of the optical components on each of the ALMA antennas, including primary dish surface, subreflector, mirrors, and receiver feeds will result in loss of sensitivity and image quality degradation. This is due to overall gain loss, beam-shape distortion, excess pickup noise from spillover, and polarization property changes caused by the misalignments. Optics calibration then includes optimization of the following optical components of each antenna:

– **Surface Setting**: Significant deviation of the main reflector shape from an ideal parabolic surface will result in severe loss of collective power/gain of an antenna. The main dish surface of the antennas will be segmented into multiple movable panels whose shape with respect to that of an ideal parabola can be adjusted. The goal is to set the panels as close to the ideal main dish shape as possible. Two forms of holography will be used to make these antenna surface measurements: near-field (transmitter) and interferometric (astronomical) holography.

– **Subreflector Positioning**: The subreflector of each antenna will be movable along 3 axes (*i.e.* optical axis of main reflector and in a plane perpendicular to it). The optimum position of the focus along any of these axes is a function of elevation (homologous mount focus displacement) and environmental parameters. The goal is to position the subreflector so that there is a maximum transfer of the power collected by the main dish into the off-axis ALMA receiver system. Traditional astronomical single dish astronomical holography measurements will be used to determine the appropriate subreflector positioning.

– **Receiver Feed Setting**: The ALMA Receivers will be placed off-axis with respect to the main dish. If the plane of the aperture of the feeds is inclined with respect to the focal plane (defined by the optimized subreflector position defined above), the shape of the beam will become elongated (*i.e.* coma aberration).

The same techniques used to measure the subreflector positioning will be applied to the receiver feed setting calibration.

– **Beam Squint Determination**: Some of the ALMA Receivers will observe simultaneously two orthogonal polarizations through re-direction of the signal from the subreflector using various beam-splitting mechanisms/devices. The goal of the beam squint measurement is to set the planes of the feed apertures as close as possible to being perpendicular to the optical axis of the subreflector and to match the orientation of both polarization channels on the sky.

2.9 Primary Beam

The goal of primary beam calibration is to accurately measure the primary beam response for all antennas. Specifically:

– **Determine Antenna Power Pattern**: Must determine the antenna power pattern response of each ALMA antenna to a measurable and repeatable precision of better than 1% (for $\nu \leq 400$ GHz) and 2% (for $\nu > 400$ GHz) of the boresight power response at all points within the -10 dB contour of the beam pattern, for each polarization. This means that at the -10 dB point the precision of that measurement is 10%/20%, respectively.

– **Measure Antenna Voltage Patterns with Interferometric Holography**: From these measurements a primary beam model will be constructed from the statistical properties of the voltage pattern.

– **Primary Beam Model Use in Imaging Software**: The primary beam model derived from these measurements will need to be incorporated into any imaging software, including pipeline and offline analysis tools.

A number of ancillary calibration measurements will be required for accurate primary beam calibration:

– *Absolute and Relative Amplitude Calibration*: We don't need to worry about absolute amplitude calibration when mapping the primary beam as the beam map will be normalized to the peak value, though a precise understanding of the noise level will benefit from knowing how bright the source is. So, we count absolute flux calibration to be of secondary importance. It *is* important to track relative amplitude fluctuations, as they could otherwise limit the accuracy of the beam's measurement.

– *Phase Fluctuations and Decorrelation*: It will be important to track phase fluctuations: phase errors will lead to errors in the voltage pattern's phase, and phase fluctuations and decorrelation will lead to low amplitudes in the voltage pattern.

– *Pointing Errors*: Pointing errors will translate into amplitude errors in the beam measurement, so we need to make our beam measurement during conditions with good pointing.

– *Frequency Dependent Beam Variation*: There will be significant beam variation over the 8 GHz bandwidth, especially at low frequencies such as 90 GHz. We could consider either mapping the average beam for the entire continuum bandwidth, or we could observe in spectral-line mode, in which case we will need to perform bandpass calibration. Presumably, the methodology of spectral line holography needs to be developed.

2.10 ACA Calibration Coordination

The goals of ACA/ALMA calibration coordination are:

- Establishing common observation and software reduction strategy for the basic calibrations that may be done independently by the ACA and ALMA. Incorporation of this data into the ALMA pipeline and archive should be transparent to the array used.
- Placing independent and non-simultaneous ACA and ALMA interferometric observations on the same amplitude and position registration scale.
- ACA semi-stable calibration needing high sensitivity will incorporate some or all of the ALMA antennas; *e.g.* primary beam mapping.
- ACA and ALMA use of the WVR data should be treated in a compatible manner.
- ACA temporal amplitude, reference pointing, and phase calibrations may need addition sensitivity, especially at the highest frequency.
- The tracking of primary calibrator sources and bootstrapping of the flux density of secondary calibrators (quasars and galaxies) is best done using the ACA lower resolution array. However, accurate positions and structures will need the ALMA array.
- The gain calibration methods of the ACA four 12-m TP antennas needs more work. It will probably use occasional simultaneous observations of a bright calibrator using the TP antenna in the appropriate switching mode, compared with interferometric observations with some ACA and/or ALMA antennas. How often these simultaneous observations are needed is unclear.

3 Calibration Matrix

Proper sequencing of the various types of calibration measurement will be important. To clarify the necessary sequencing of calibration measurements we have developed a “matrix” which defines the predecessors of each type of calibration. The current version of this matrix is shown in Figure 2. In this figure we identify two types of predecessor:

- **Necessary Observational Predecessor**: This is a calibration measurement that *must* precede another calibration measurement.
- **Necessary Reduction Predecessor:** This is a calibration measurement which must be reduced before another calibration measurement, but need not be observed before that calibration measurement.

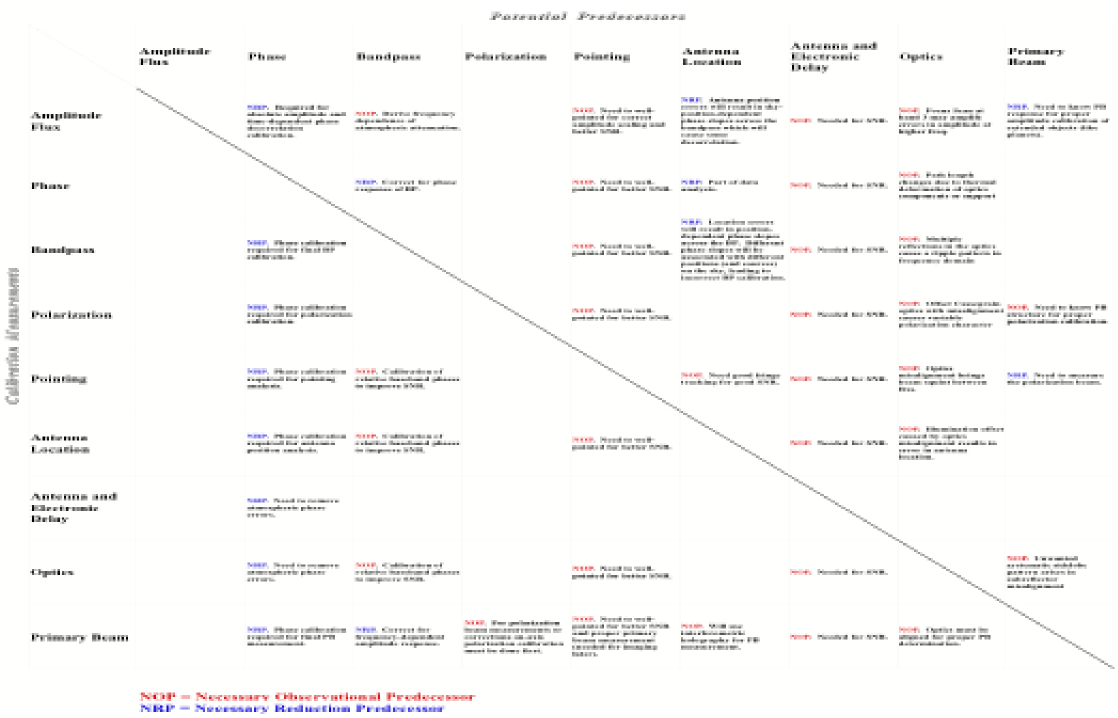

Figure 2: Calibration predecessor matrix.

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