Atacama
Large
Millimeter
Array

Phase Calibration Steps

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Specification Document

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Change Record

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Contents

1 Goals

1. To calibrate the atmospheric and electronic phase fluctuations, effectively reducing them to the smallest values we can. Based on an analysis of the phase stability of the entire ALMA system [1], *the corrected visibility phase fluctuations must be* < 1 *radian at 950 GHz*.
2. 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]
3. Fast Switching (FS) and Water Vapour Radiometry (WVR) correction systems will be used to meet this phase calibration requirement.
4. 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).
5. 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 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 amplitude fluctuations due to variable decorrelation.

Note that the following description of fast switching phase calibration represents only a summary of the details given in [2].

2 Three Regimes of Target Observations with regards to Phase Calibration

No matter what we do with phase calibration on ALMA, we will always have some residual phase errors. The main effects of phase errors on interferometry are the loss of sensitivity due to decorrelation and the degradation of image quality due to scattering of flux throughout the image. (The degradation of resolution is a classic effect caused by phase errors which increase with baseline length, as would result if no aggressive calibration were attempted. ALMA will probably not experience a loss in resolution, just a loss in sensitivity and a degradation of image quality.)

We indicate three regimes of target observations with regards to imaging errors caused by incomplete phase calibration:

— SNR is very low, say below 5:1 over the time which the phase errors are randomized. Here, the flux scattered about by the phase errors will be masked by the thermal noise.

— If the SNR is moderate, we may be in a regime where the imaging is limited by residual phase errors which cannot be self-calibrated.

— If the SNR is high, we can self-calibrate and solve for the residual phase errors.

[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.

3 Calibration Strategies

We will consider three different strategies for phase calibration:

— No WVR, only fast switching with cycle times of 10-60 seconds.
— WVR with 1 second integration time, and fast switching cycle times of 10-300s.
— Self calibration.

Note that fast switching can handle phase fluctuations on timescales of less than half the switching cycle time (via interpolation), and WVR can effectively deal with changes in the phase on 1 second time scales, but has trouble with determining the absolute phases. Hence, the two methods are largely complimentary. The exact manner in which these two techniques will fit together will depend upon the performance details of the WVR units and the realities which the atmosphere above the site provide us with, and we will fine tune the phase calibration strategy when we arrive on site with four ALMA antennas. Since the fast switching calibration process results in lost sensitivity while observing the calibrator source, we would really like to perform fast switching with the longest possible cycle times (*i.e.*, 300-600s). As WVR does not correct for any electronic phases, the phase stability time scale of the electronics (*i.e.*, 300-600s) will set the upper limit to the fast switching cycle time, though other problems may push that time scale down.

4 Calibration Steps

4.1 Calibration Steps for All Fast Switching Measurements

1. *Select a Calibrator Source.* In order to optimize phase calibration, the dynamic scheduler is expected to control some of the details of the calibration scheduling. The most obvious detail is the choice of the phase calibrator. We must select which source will make the best calibrator, which means a combination of the brightest and closest calibrator. Details of choosing the best calibrator are included in §A. We presume that many of the potential calibrators have not been observed recently and will need to be reobserved. For example, any calibrators with flux observations more than 30 days old (this number will be tweaked through experience) will need to be observed. The flux observations will take about 1.5 seconds of move time and 1 second of integration time. If we have 10 potential calibrators, the whole process could take about 30 seconds. The calculation which determines the optimal calibrator from their fluxes and positions is computationally fast. The results of the flux determination will be written into the calibrator data base.
2. *Calibrate at 90 GHz or the target frequency?* Observations below some critical frequency ν_c (which will be about 300 GHz) will usually be more efficiently calibrated at the target frequency. Observations above that critical frequency will usually be more efficiently calibrated at 90 GHz, but these will require a second cross-band calibration to determine the cross-band instrumental phase drift, approximately every 300-600 seconds. If we are calibrating at 90 GHz, then a second calibrator which is bright at both 90 GHz and at the target frequency must be found within 10-20 deg of the target source, and a short list of potential cross-band calibrators may also need to be observed at the target frequency to evaluate which one is optimal. However, as this cross-band calibrator grid is fairly coarse, these calibrators will be well monitored by other recent observations. During commissioning, we will need to ensure that there are no systematic residual phase errors introduced from the cross-band calibrator being distant from the target source and the regular fast switching phase calibrator.
3. *What Cycle Time?* After the optimal calibrators have been chosen, we need to calculate the optimal cycle time and the integration time on the calibrator source, which will be set by the required SNR of the phase

solutions. These details are addressed in the [2].

4. *Make all Measurements with Fixed Focus and Subreflector Positioning.* Subreflector positioning and focus should be optimized for the *target* observing band.

4.2 Fast Switching Only

As noted in [2], the most general way to view fast switching is to break the problem up into a "target sequence" and an "instrumental sequence":

Target Sequence: Over a period of 15–30 seconds the following measurement sequence is observed involving the target source and a phase calibration source located typically $\lesssim 2$ degrees away from the target source:

1. Tune to the calibration frequency if cross-band calibration required.
2. Phase calibrator measurement ($t_{int} \lesssim 1$ second).
3. Tune to the source frequency if cross-band calibration required.
4. Target source measurement ($t_{int} \lesssim 25$ seconds).
5. Tune to the calibration frequency if cross-band calibration requrired.
6. Phase calibrator measurement ($t_{int} \lesssim 1$ second).

Instrumental Sequence: This cycle of measurements is required for cross-band calibration of dual-frequency fast switching measurements. Over a period of 10–25 seconds a strong phase calibrator source which can be detected at both the target and calibration frequency is used to provide the phase scaling from the target (usually higher) frequency to the calibration (usually 90 GHz) frequency:

1. Tune to calibration frequency.
2. Phase calibrator measurement ($t_{int} \lesssim 1$ second).
3. Tune to target frequency.
4. Phase calibrator measurement ($t_{int} \lesssim 1$ second).
5. Repeat this sequence.

A graphical description of these observing sequences is given in Figure 1 (from [2]).

4.3 WVR on 1s Timescales with Fast Switching Cycle Times of 10-30s

The main problem with fast switching is that it misses the phase fluctuations which occur on time scales between about 1 s (the time it takes for the atmosphere to cross the antenna dish) and the fast switching cycle time. Interpolation will improve fast switching down to about half the cycle time. WVR is designed to track phase increments, and should be able to remove most of the phase fluctuations missed by fast switching. For this example, we assume that fast switching is performed as described in §4.2.

4.3.1 Optimal Smoothing Time for WVR Data

During the best phase stability conditions, the atmospheric phase fluctuations on short time scales will be less than the WVR thermal noise equivalent phase errors. Hence, during the best conditions, we will want to average the WVR data over an interval of about 5 s. This averaging time will be determined by monitoring of the atmospheric phase errors, either made with the site testing interferometer or with the calibrator phase solutions.

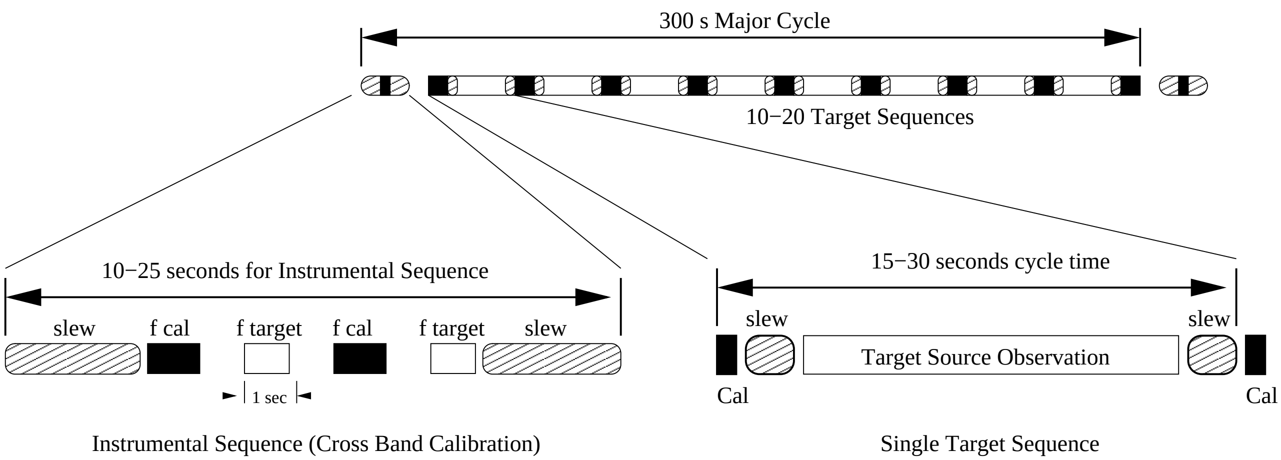

Figure 1: Instrumental (left) and targe (right) phase calibration observation sequences.

4.3.2 Data Averaging

On time scales shorter than 1s, the air crossing time of the 12m dishes when the velocity aloft is 12m/s, the phase fluctuations are strongly damped by the smoothing of the atmosphere by the 12m air column. The WVR are designed to have sufficient sensitivity on 1s timescales to detect the atmospheric phase in most cases. However, we do not want to store the raw visibilities with 1s averaging, as this would be very expensive. (u,v) smearing does not require anything like 1s integrations even in the largest arrays.

So, the scheme is to observe with something like a 1s correlation time, convert the 1s WVR brightness measurements to incremental phase estimates, apply those incremental phases in near-real time, and average up in time to something like 20-60s. These phase-corrected and averaged visibilities will have much of the decorrelation removed, and these are the visibilities which will be imaged and archived.

As the WVR phase application and averaging is irreversible and the 1s integration visibilities will be thrown away, the commissioning team will have to demonstrate that this process is working correctly before we can introduce this averaging into the pipeline.

5 Self Calibration

A fraction of observations will see target sources which are bright enough to permit self-calibration on 1-30s time scales. If the source is only bright enough to be adequately detected on longer time scales, fast switching will be more effective at correcting the phase errors.

Self-calibration is problematic in that the absolute source position and the flux scale start to float. However, for bright sources, self-calibration will be the best way to make a high fidelity image. All problems such as WVR to phase transfer, phase transfer from 90 GHz to the target frequency, dispersive water vapor, spatial dependence of the phase, etc, will go away with a strong target source.

If the primary phase calibration strategy is self-calibration, then we still must have some concern for other phase calibration methods. In VLBI, most sources are dominated by a point source, and a simple point source model can be used. However, many millimeter and sub-millimeter wavelength sources will be dominated by extended structure, and a simple starting model may not be available. So, at the very least, some amount of fast switching phase calibration will be required. We don't want to do fast switching very much, just often enough so that there is some data which will be well calibrated to permit us to make a low SNR starting model to get the self-calibration cycle started.

Even if the target source is not extremely bright, we will often be able to perform self-calibration on data initially calibrated by fast-switching. This can act to decrease the residual phase errors and perhaps increase the fast switching cycle time, both of which will increase the fast switching efficiency. If WVR works as well as we hope, self-calibration won't need to be used to improve the efficiency of fast switching, as WVR will fill that role, independent of source brightness.

6 Issues

6.1 Solar Observations

The fast switching sequences described above will also be used for the phase calibration of solar observations. The only additional condition involved will be the insertion of the solar filter when target (Sun) observations are made at the target frequency.

6.2 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. If residual errors are dominated by the WVR thermal noise, then the decorrelation correction will be simple to achieve, just scaling the visibilities up by an easily calculated factor which may be baseline dependent if the WVR's do not all behave identically. Furthermore, as the decorrelation is expected to be minor, this correction would only need to be performed at 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.

6.3 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.

6.4 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 when the dynamic scheduler started this project. Phase conditions can deteriorate or improve with time, and phase fluctuations can also vary across the array. These phase stability changes can impact the next project to be chosen, or could lead to the termination of the current observation. 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. An estimate of residual phase errors resulting from the current atmospheric conditions and the details of the phase calibration strategy should be displayed along with an estimate of the resulting dynamic range limitations.

6.5 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, may be developed in the future to deal with a calibrator which is up or down stream from the target source. Such time-delayed or time-advanced interpolation will work best if the turbulence is mainly confined to a single layer in the atmosphere.

The wet delay becomes significantly dispersive in the sub-millimeter windows. If we calibrate at the target frequency, there is no problem because the dispersive phase is measured directly. 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 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.

6.6 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.

6.7 Monitoring Phase Solutions and WVR Data

We will still need to monitor calibrator phase solutions for dynamic scheduling. WVR data should also be 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.

6.8 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.

As noted above, observations in the sub-millimeter windows will suffer from dispersion, and the phase will not be correctly calculated by scaling up linearly with frequency. Atmospheric transmission codes like ATM should be able to help us convert the WVR brightness fluctuations into phase fluctuations at the target frequency.

Combined with fast switching, this may be a bit tricky, and should be considered a research topic for ALMA commissioning.

6.9 Interpolation

When observing with fast switching only, we will have high SNR detections of the phase once every 20-40s when we observe the calibrator. The calibrator will be fairly close to the target source spatially. Part of the integration on the target source will be close to the phase solutions in time, but halfway between the calibrator observations the residual phase errors will be at a maximum. If the atmosphere were purely noise-like, interpolation between the calibrator phase solutions would not help. If the atmosphere were dominated by large scale structure, the phase errors would be nice smooth drifts, and phase interpolation would work very well at reducing the residual phase errors between the calibrator observations. In fact, the atmosphere lies somewhere between, and 2-pt interpolation can reduce the residual phase errors by a factor of about 1.5.

Immediately after the fast switching phase solutions are made on the calibrator, the residual phase errors will be close to zero, but as the atmosphere evolves and blows over the array, we can use incremental WVR phase correction to track these changes. In this case, we do not want to perform any interpolation of the fast switching phase solutions, as the WVR correction will effectively remove these changes. Interpolating the fast switching solutions in addition to WVR would essentially try to remove the incremental phase errors twice, which would approximately put those residual phase errors back in as the negative of the original. Hence, when performing fast switching together with WVR, we should not interpolate the fast switching phases, but just apply the nearest neighbor solution and the forward or backward incremental changes from the WVR data.

References

[1] D'Addario (2004), "System Design Description"

[2] Holdaway & D'Addario (2004), "Simulation of Atmospheric Phase Correction Combined With Instrumental Phase Calibration Using Fast Swiching", LAMA Memo 803

A Choosing the Details of Fast Switching Phase Calibration

We first focus on choosing *which* calibrator is the best one. The best calibrator will be bright and close, but how do we trade off between brightness and proximity? This turns out to be a complicated process, but since the residual phase errors are dominated by time terms rather than distance terms, we can approximate this process by selecting the calibrator which minimizes the time it takes to detect the calibrator with sufficient SNR plus the time it takes to slew to and from the source. "Sufficient SNR" (the time required to observe the calibrator will be proportional to SNR^2) is also complicated, as the calibration may be performed at 90 GHz or at the target frequency, and the required SNR should also reflect the level of residual phase errors as set by the atmospheric phase stability and the cycle time. The decision to calibrate at 90 GHz or at the target frequency will reflect which calibration frequency will result in the lowest phase fluctuations and the highest sensitivity. In comparing phase fluctuations and sensitivity, we can look at the overall efficiency of the calibration, defined as

$$\sqrt{t_{target}/(t_{target} + t_{cal} + 2 * t_{slew})} * \exp -\sigma_\theta^2/2. \tag{1}$$

The first term represents the sensitivity loss due to calibration, and the second term represents the sensitivity loss due to decorrelation from phase errors. The first term is maximized by choosing long times on the target source before calibrating, while the second term is maximized by calibrating more frequently, so maximizing the product of these two, or the overall sensitivity, will find the optimal calibration cycle time.

The residual phase errors in the decorrelation term can be estimated via the phase structure function, which is measured by the site testing interferometer.

$$\sigma_\theta \simeq \gamma \sqrt{D_\theta(v t_{cycle}/2)} \tag{2}$$

γ represents an improvement factor due to interpolation. It is dependent on the phase structure function exponent, and will be between 0.5 and 1.0. D_θ is the phase structure function. v is the atmospheric velocity and t_{cycle} is the fast switching cycle time. The expression above neglects spatial factors in the residual phase, and we will have to verify if spatial factors are important when we begin commissioning at Chajnantor.