ALMA Memo 491
Does the ACA Need Phase Compensation?

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Abstract

We analyze the phase monitor data from Chajnantor over the period 1996 - 2001 and infer the level of phase fluctuations that would be seen on 10-30 m, typical baseline lengths for the Atacama Compact Array (ACA). On baselines of 10-30 m, fast switching phase compensation will be useless, but water vapor radiometry (WVR) could improve the phase stability marginally. We consider the effects of phase errors on imaging and on the flux scale, and determine that (a) the ACA will require dynamic scheduling in order to meet the ALMA scientific objectives, (b) given dynamic scheduling, the ACA will likely not require any sort of active phase correction such as WVR, and (c) by permitting high frequency ACA observations during conditions with the lowest opacities and less than optimal phase stability, WVRs could increase the ACA's efficiency, especially for high frequency observations, and can probably be justified on a cost-benefit basis.

There is another reason why we would want phase calibration on the ACA – the 12 7 m dishes cannot calibrate themselves to the required accuracy in a reasonable amount of time. In order to calibrate accurately, we need to correlate the 7 m dishes with the four 12 m dishes dedicated to the ACA, or even better, with the full ALMA array. If we are correlating with the four nearby 12 m dishes, we do not need phase compensation on the ACA antennas, but if we plan to correlate with the full ALMA, we absolutely need WVR and fast switching capability.

1 Introduction

The current concept for measuring short baselines for permitting ALMA to image objects larger than the 12 m dishes' primary beam is to supplement the ALMA data with both total power from the 12 m dishes and with interferometric data from an array of 12 7 m antennas, called the Atacama Compact Array (ACA).

Calibration of the ACA will be demanding, as the sensitivity of this smaller array will be much less than the sensitivity of the ALMA. To help, four 12 m ALMA dishes will be dedicated to calibrating the ACA and providing total power measurements. (The existence of four dedicated 12 m total power antennas does not imply that the other ALMA antennas won't need to perform total power measurements.) However, there is also the possibility that the full ALMA will need to be correlated with the ACA for calibration purposes in some cases.

Phase calibration may be particularly difficult for the ACA: fast switching won't work because the array doesn't have enough sensitivity and the calibration time scales required to effectively remove the atmospheric phase fluctuations will be on the order of a second, much too fast for fast switching.

We take a look at the archived site testing data from Chajnantor to infer how large the phase fluctuations are likely to be to determine if the ACA needs WVR of not.

2 What is the Phase Specification on the ACA?

There is no formal specification on the phase requirements of the ACA. There are phase stability requirements for the 12 m ALMA antennas, but the ACA may be in a different regime because errors on the shortest baselines can have severe consequences on imaging.

2.1 Phase Spec Based on the Flux Scale Spec

ALMA has a specification to achieve 1% accuracy in the flux scale. There is also talk of relaxing the flux scale accuracy to 3% or even 5% in the sub-millimeter. The desired flux scale accuracy implies a specification on what sort of phase errors are acceptable: phase errors will result in decorrelation, which will result in errors in the flux scale.

The coherence is given by

$$e^{-\sigma_\phi^2/2},$$

where σ_ϕ is the rms phase error in radians. Hence, to limit the flux scale errors due to decorrelation to 1% (ie, 99% coherence), we can tolerate rms phase errors as large as 8 degrees. Limiting the flux scale errors to 3% implies we can tolerate phase errors as large as 14 degrees, and 5% errors implies phase errors as large as 18 degrees. The rms path length fluctuations which result in 99, 97, and 95% coherence are indicated for a range of observing frequencies in Table 1.

Decorrelation can be corrected by WVR or by estimating each baseline's rms phase error from frequent observations of a nearby calibrator source. This is similar

	rms path length [microns]		
freq (GHz)	99% (8 deg)	97% (14 deg)	95% (18 deg)
90	74	130	167
230	29	51	65
345	19	34	43
650	10	18	23
850	8	14	18

Table 1: RMS path length fluctuations, in microns, at which observing at a certain frequency will result in a certain coherence.

to fast switching, but the phase is not applied to the target source, instead the rms calibrator phase is used to correct the amplitudes for decorrelation. Since we are not actually tracking the phase, but measuring the statistics of the phase, we don't need the calibrator to be so close, and we can use calibrators which are bright enough. The details of this method would need to be developed: how bright a calibrator do we need, are there enough, how often should we observe a calibrator, and for how long, and what are the residual imaging errors after the method has been applied?

Atmospheric phase decorrelation will be only one component of the flux scale budget. We assume that the improvement in the flux scale from a decorrelation correction method makes room for any additional contributions to uncertainties in the flux scale. Hence, if we require a 3% flux scale accuracy, we will consider the phase fluctuations which result in 97% coherence, and the decorrelation correction might take that number up to 99% (ie, 1% flux scale error from decorrelation), and other factors will increase the flux scale error up to about 3%. Note that the decorrelation-based *phase specification* is independent of frequency (except that the flux scale specification is relaxed to vary with frequency), so the *atmospheric path length* specification then gets stricter with increasing frequency.

2.2 Phase Spec Based on Imaging Arguments

The ACA scheme for measuring short baseline information is replacing the earlier *homogeneous array* concept, in which the 12 m dishes were measuring both total power data and interferometric data *without* anything like the ACA. We could perform a very detailed analysis of the effects of phase errors in the ACA data on imaging with the full ALMA + ACA, but instead we will make simple arguments based on the assertion that the phase errors on the ACA baselines should be no more than the equivalent phase errors produced at the edge of a 12 m dish by the pointing error specification of 0.60 arcseconds. A pointing error of 0.60 arcseconds on a 12 m antenna results in a path length of 35 microns, which is independent of observing frequency. Phase errors will be much more random than typical pointing errors, so we should be able to tolerate a higher path length error than the equivalent from the pointing specification, perhaps as much as 2-3 as large, or 70-100 microns.

On the other hand, the people who were overly bothered by the homogeneous array concept may not feel easy about the 35 micron phase error at the edge of the 12 m dish caused by the 0.6 arcsecond pointing error. Those people might choose to divide by 2-3 prior to multiplying by 2-3, ending up with 35 microns.

3 What Phase Errors will the ACA Experience?

With 12 7 m antennas, the ACA will have baselines ranging from about 10 m to 40 m. The key baselines are the 10 m ones, but we'll perform the analysis on 10, 20, and 30 m baselines.

The phase monitor uses a 300 m baseline to observe an 11.2 GHz satellite beacon at 30 degrees elevation. We convert the observed rms phases

- to rms path length in microns
- to a canonical 60 degree elevation, assuming the phase fluctuations vary as the square root of air mass
- to the appropriate baseline b assuming the rms phase varies as $(b/300)^{\alpha}$, where α is the root structure function exponent, which is determined alongside of the rms phase by the phase monitor data reduction software. We use the actual α for each measurement rather than an average value.

The deciles of the rms path length for the 6 years of concatenated site testing data are presented in Table 2 for 10, 20, and 30 m baselines.

4 Interpreting the ACA Phase Error Specifications and the Site Testing Data

We compare the phase error specifications in Table 1, which are derived from the flux scale error specification, to the estimated phase errors. Let's look at the 20 m baselines, and consider the 99% coherence for frequencies up to 345 GHz and the 97% coherence for frequencies above 345 GHz. For the lower frequencies, we see that the ACA phase fluctuations will not generally be a problem. For the higher frequencies, we see that we will need to observe during the better phase conditions to result in sufficiently small decorrelation losses and flux scale errors. This indicates that the ACA will probably require dynamic scheduling in order for

percentile	rms path length [microns]		
	10m	20m	30m
10	7.2	10.7	13.6
20	10.2	15.4	19.6
30	13.6	20.7	26.5
40	17.9	27.4	35.1
50	23.7	36.4	46.7
60	31.7	48.7	62.5
70	43.7	66.7	85.3
80	63.6	95.4	120.9
90	108.6	154.2	190.6

Table 2: RMS path length fluctuations in microns, due to atmospheric turbulence on 10, 20, and 30 m baselines based on Chajnantor site testing data from 1996-2001, adjusted to a 60 degree elevation angle.

the observations not to be compromised by the phase errors. However, we already knew that dynamic scheduling was required in order for the atmospheric opacity to not compromise the observations.

Lets compare the estimated phase fluctuations in Table 2 with the phase error which corresponds to the pointing spec at the edge of a 12 m dish, or 35 microns. First, it is probably not fair to compare the phase errors on a 30 m baseline with this 35 microns, as the ACA is being built to measure data on 8-15 m baselines, the "dip" between the 12 m total power and the shortest 12 m interferometric spacings. Data from much longer baselines (ie, 30 m) may be tapered or discarded, especially if they are more contaminated by errors. So, on 20 m baselines, for almost half the time the phase errors will be less than the 35 micron limit. This indicates that during moderately good atmospheric conditions, the phase errors which the ACA experience will not limit mosaic imaging as much as the 12 m dishes' pointing errors do. In all probability, as the phase errors are more random than pointing errors are likely to be, we will be able to tolerate more like 70 micron phase errors, and the fraction of time that phase errors would not dominate imaging on 20 m baselines will likely go up to 70%. What happens when the phase errors are greater than 70 microns? This just indicates that the phase errors which the ACA experiences will be more problematic in imaging than the 0.6 arcsecond pointing errors. However, if the phase stability is that bad, the residual phase errors from the rest of ALMA may end up being pretty bad too, bad enough to dominate imaging errors. Viewed another way, if the phase errors were that bad, we would probably be observing at a low frequency. At 90 GHz or 30 GHz, the pointing errors are "overspec'ed" because the beam is much wider, and the imaging is likely to be limited by something other than pointing errors. Hence, having somewhat worse path length errors at these lower frequencies will not be at all bad.

5 Calibration of the ACA

We consider five different telescope setups with which we could calibrate the ACA:

- **ACA alone**, meaning just the 12 7 m dishes cross-correlated among themselves.
- **ACA+4**, meaning adding cross correlations with the four dedicated 12 m total power dishes, and gains must be solved for the 12 m dishes as well as for the ACA dishes.
- **ACA+4***, which is the same as the previous case, but in this case we assume we do not need to solve for the gains for the four 12 m dishes. In this case, all that extra sensitivity of the four 12 m dishes goes straight into improving the gain accuracy for the 7 m dishes.
- **ACA+64**, meaning we cross correlate the ACA dishes with all 64 12 m ALMA dishes. The extra sensitivity gets used to improve the accuracy of both the ACA gains and the AMA gains.
- **ACA+64***, meaning we cross correlate the ACA dishes with all 64 12 m ALMA dishes, but we somehow already know the ALMA gains, and all the extra sensitivity gained by adding ALMA goes into improving the accuracy of the ACA gains.

Note that the modes with "*", where we don't solve for the gains of the 4 or 64 12 m antennas, are unproven modes, and it is uncertain exactly when they would be useful.

Table 3 gives estimates of the sensitivity increase and time savings relative to the ACA (12 7 m dishes) alone. While adding the four 12 m dishes will help out a lot, there will be cases, especially at high frequencies, when we may just want to add the entire ALMA to improve the calibration.

If we only add the four dedicated 12 m dishes, we must look at the phase fluctuations on 15-50 m baselines, which will not be so much larger than the 10-30 m baselines considered for the phase fluctuations seen by the ACA. In other words, we won't need active phase compensation for those four dedicated 12 m dishes. However, if we ever plan to correlate the ACA antennas with the rest of the ALMA antennas, which could be spread all over the plains of Chajnantor and Pampa la Bola, we will absolutely need to address the phase calibration issue.

Currently, there are no plans to cross-correlate ACA and ALMA antennas, even though there is good reason to do so. If that plan changes and we decide

Array	Sensitivity w.r.t. ACA	Time factor
ACA	1	1
ACA+4	1.42	2.0
ACA+4*	2.17	4.7
ACA+64	4.27	18
ACA+64*	34.8	1200

Table 3: For the calibration of the ACA elements, how does the sensitivity of the gains improve as you add more antennas? The "*" refers to the case where you don't need to solve for the gains on the extra 4 or 64 antennas – for example, if we are solving for the pointing for just the ACA antennas. This mode has not been proved, and may not be applicable for some calibrations.

we need to cross-correlate ALMA and ACA antennas, we also need to provide the ACA antennas with the means of performing phase calibration, ie, WVR and fast switching capability. And right after that, we have to warn the SSR that things are now much more complicated than they were already.

6 Conclusions

As in other considerations, the atmosphere above Chajnantor is not perfect. However, with a judicious choice of the astronomical project to fit the observing conditions, we should be able to get good ACA data for the complete distribution of observing frequencies.

In specific, phase fluctuations on 10 m baselines will permit better than 99% coherence at 345 GHz over 40% of the time, or 97% coherence at 650 GHz over 40% of the time. As there are other types of phase fluctuations leading to decorrelation and flux scale errors, we may not want to fill the flux scale error budget completely with atmospheric decorrelation errors. Using the same atmospheric conditions, we can reduce the decorrelation significantly (to essentially zero) using a fast switching scheme which estimates the rms phase errors on each baseline and applies an *amplitude* correction to the target source visibilities.

Another way to gauge the severity of phase errors is to compare them to the equivalent phase error caused by the 0.6 arcsecond pointing spec at the edge of the 12 m dish. In this case as well, there are amble atmospheric conditions which will meet this criterion.

The atmosphere will not always cooperate. By being flexible in our scheduling, and by being complete and honest in the requirements of each astronomical project, atmospheric phase fluctuations will probably not prevent the successful completion of any project on the ACA.

An alternative strategy would be to try to conquer the atmosphere. Water vapor radiometers on the ACA would probably increase the flexibility of the ACA, permitting high frequency observations during times when the phase stability was not otherwise good enough. This would result in some improvement in the ACA's efficiency, as there are times when the opacity is very low, appropriate for the highest frequency observations, but the rms phase errors are too large. Similarly, WVR installed on each ACA antenna would eliminate the need for any sort of decorrelation correction, increasing the efficiency of the array by something like 5%.

So, it is my belief that the ACA will be able to do everything required of it without any active phase correction, but it will be able to do everything a bit faster and more efficiently if it had WVRs.

If we need to cross-correlate ACA antennas with ALMA antennas, then we absolutely must have the means of phase calibrating the ACA antennas – ie, WVR and fast switching.