Does the ACA Need Phase Compensation?

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Abstract

We analize 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 Attacama Compact Array (ACA). 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 water vapor radiometers (WVRs), 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 be justified on a cost-benefit basis. In order to make an informed decision about the necessity of WVRs on the ACA, we need to know more about how over- or undersubscribed the ACA is likely to be to keep pace with ALMA's observations of objects larger than the primary beam.

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 Attacama Compact Array (ACA).

Calibration of the ACA will be demanding, as the sensitivity of this smaller array will be 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.)

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 atmopheric 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 submillimeter. 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 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

	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.

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.

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.

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 satelite 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 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 tappered 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 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 succesful 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.