Draft of phase calibration plan

Phase errors originate in various components of the ALMA instrument, including the antenna and the electronics, and also in the atmosphere. These errors limit ALMA's resolution, the dynamic range of its images, its sensitivity and they may introduce artifacts into ALMA images. Phase calibration aims toward reducing these errors to enable ALMA to achieve full scientific productivity. Chapter 3.1 of the ALMA Project Book gives ALMA specifications on calibration, including that on phase, which is discussed in 3.1.6 of that document. The project book presents a view which is based on several earlier documents, notably the phase calibration working group report (Woody 1995; Memo 144). The present document presents a current view of phase calibration.

That report considered several levels of phase errors; from its recommendations arose the ALMA specification on phase errors. The specification for phase calibration on ALMA is that it will be accurate to 0.15 radian at 230 GHz. The phase error budget may be distributed among several elements which contribute to it including the antenna, the electronics, and the atmosphere.

Phase Calibration	0.15 radian at 230 GHz

One goal of phase calibration is to measure instrumental phase for removal from the astronomical data. Instrumental phase should be stable on timescales of many minutes. Calibration to measure instrumental phase may be achieved by periodic observation of astronomical point sources. Contributions to instrumental phase include changes in the distance between the subreflector and the feed, and the stability of the LO and other electronics.

At millimeter wavelengths, the main atmospheric constituent which causes phase errors is inhomogeneously distributed water vapor. Up to about 300 GHz, atmospheric water vapor is very nearly non-dispersive. Above 300, water vapor can be quite dispersive, especially near the water vapor lines in the atmosphere. Submillimeter wavelength observations will need to account for this dispersion if the phase is being calibrated indirectly (*i.e.*, scaled from a lower frequency or determined by scaling the differential water vapor column as determined by water vapor radiometry).

Comments go here summarizing site characterization statistics for Chajnantor, and how much of the time active correction will be needed.

The dry air results in a major contribution to the absolute phase. If there are appreciable temporal or spatial fluctuations in temperature or pressure in the dry air above the array, phase fluctuations will result. Furthermore, the absolute dry air phase depends upon the observing elevation angle and the topographical elevation, which will change from one source to another

1. Instrumental Phase Calibration Strategies

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2. Atmospheric Phase Calibration Strategies

2.1 Fast Switching

If a calibrator is sufficiently close and the telescope is sufficiently fast, fast switching between a calibrator source and a target source can effectively stop the atmospheric, electronic, and antenna phase fluctuations. If fast switching is used as the phase calibration method, it makes minimum requirements on the system sensitivity, the slew speed and settle down time of the antennas, and the online and data taking systems. Fast switching has been studied extensively, put into practice at the VLA and elsewhere, and we are fairly confident that it will work for the ALMA.

2.1.1 Sensitivity Requirements

The basic criteria for fast switching to work is that the phase calibration source needs to be detected with sufficient SNR and the target source be observed for some amount of time within the coherence time and distance of the atmosphere. This translates into a requirement that there be sufficiently many calibrator sources which are sufficiently bright (Memo 123), and a requirement on the sensitivity of the array. In practice, this means that the calibrator source will typically be within a degree of the target source, the calibrator will usually be detected in less than a second, and the entire cycle time will be about 10 s, though the details vary with observing frequency. Spectral line observations will need to use wide bandwidth continuum observations of the calibrator.

With the current sensitivity of the ALMA and our understanding of the quasar source counts and their dependence on frequency, we will not always be able to perform fast switching calibration at the target frequency, but often we will get a higher SNR phase solution by observing the calibrator at a low frequency (e.g. 90 GHz) and scaling the solution up to the target frequency using an atmospheric model.

2.1.2 Scaling the Phase to High Frequency Observations

The falling source counts and sensitivity at high frequency will often require fast switching to observe calibrators at low frequencies and scale the phases up to the observing frequency of the target source. This requires a much more accurate phase solution at the lower frequency. Since the dry atmosphere and the electronics terms are non-dispersive, this extrapolation basically relies upon the wet differential delay to be non-dispersive as well. In the submillimeter, the wet differential delay is dispersive, which will either limit the effectiveness of fast switching or require more complications in the fast switching observing strategy, such as less frequent multi-frequency calibrator observations to help separate out the non-water vapor phase contributions.

2.1.3 Requirements on Antenna Movements

The antenna movement requirement is currently a slew of 1.5 degrees and settle down to 3 arcsec pointing in 1.5 seconds.

2.1.4 Requirements on Antenna and Electronics Stability

At the very least, the antenna needs to be mechanically stable to within a small fraction of a wavelength (ie, 5-10 degrees at the target frequency) over a calibration cycle time, even when the antenna is moved by a few degrees on the sky. Similarly, the electronics need to be equally stable over the calibration cycle time. However, if we are to succeed in the submillimeter, the antenna and electronics need to be stable over much longer times, such as the cycle time between the multifrequency observations required to separate the wet and dry phase errors.

2.1.5 Requirements on Computing

The on-line system needs to control the antennas gracefully enough to move them quickly without exciting the lowest resonant frequency. Also, the quanta of integration time and scan length need to be sufficiently small so as not to restrict the integration time spent on the target source and calibrator or the time spent between sources. Flexibility at the 100-200 ms level is desirable. Fast switching data can be calibrated with existing software, but some extensions in spatial-temporal interpolation will be useful.

2.1.6 Sensitivity Loss from Fast Switching

Fast switching will reduce the sensitivity of observations due to time lost observing the calibrator and moving the antennas, and due to decorrelation from residual phase errors. Both effects can be reduced by observing in the best conditions, which often result in very low residual phase errors at a minimum expense in time lost to the calibration process. However, not all projects can be observed during the best phase conditions. MMA Memo 174 concludes that fast switching will generally result in less than a 20% decrease in sensitivity for the phase conditions at the Chajnantor site.

2.1.7 Interaction with Scheduling

During poor phase stability conditions, fast switching won't work at the high frequencies. Also, a given target field may have a dearth of calibrator sources, requiring that the field be observed during better phase conditions than the average field. For reasons like these, dynamical scheduling is absolutely required to optimize the utility of the ALMA. We envision one or more phase stability monitors providing real time information to the array control center, and contributing to observing decisions - *e.g.*:

- what project should run on the telescope?
- do the present conditions permit the current project to continue?
- what is the optimal calibrator for the current project in the current atmospheric conditions and hour angle?

2.1.8 Calibrator Survey and Maintenance of a Calibrator Database

The quasars which will form the bulk of the fast switching calibrators will be highly variable at millimeter wavelengths, and a quick survey of a few square degree region about the target source will sometimes be required. The ALMA has the sensitivity to perform a blind search for calibration sources in a few minutes. Surveys directed with lower frequency source catalogs will be even faster. Whenever a potential calibrator is observed, the source information will need to go into a comprehensive calibrator database, which can also be used for choosing an appropriate calibrator.

2.2 Radiometric Phase Correction

The most promising alternative to fast switching is radiometric phase correction (MMA Memo 209, MMA Memo 210: 'Radiometric Correction white paper', Weidner 1998 Ph. D. Thesis, Woody and Marvel 1998). Radiometric phase correction utilizes the variable emission caused by inhomogeneously distributed atmospheric water vapor to determine the phase fluctuations caused by water vapor. While water vapor is not the only source of phase errors, it is the dominant source of short time scale phase fluctuations. This method has had several early successes, but the correlation between the radiometric fluctuations and the interferometrically measured phase fluctuations changes with time, and there are some times when the method does not work well at all.

The current plan for radiometric phase correction is that the 183 GHz water vapor line should be exploited. The partial saturation of this line, even in the driest conditions on Chajnantor, initially seemed problematic, but Lay (Memo 209) indicates the unique line shape helps to discriminate between water vapor and errors like spillover, water droplets, temperature fluctuations, height fluctuations, and gain fluctuations. A total of 16 channels each of 500 MHz bandwidth would permit good discrimination between the water vapor and these errors. A cooled system is desirable. When the PWV column is under 4 mm, residual antenna based rms path errors of under 50 microns can be achieved. Larger water vapor columns preclude high frequency observations, so the larger phase errors associated with high opacity conditions will not be critical.

In the ALMA Design and Development (D&D) Phase there will be an instrument present at Chajnantor to investigate but not implement radiometric correction at 183 GHz. At existing sites this line will be saturated nearly all of the time. Hence MDC partners OVRO and BIMA will build and demonstrate 22 GHz radiometric phase correction systems. This will include construction and deployment of hardware and development of algorithms for application of the correction to astronomical data. The CSO/JCMT interferometer operates a 183 GHz phase correction radiometer at Mauna Kea. We will monitor the progress of that system. ESO has duplicated this system at Chajnantor for operation with the 12 GHz interferometers at the site. Reduction of data from this system will help the project to decide how to implement the 183 GHz water vapor spectrometer on theALMA: do we use a standalone cooled or uncooled system, a dedicated radiometer in the receiver dewar, or do we simply use the 183 GHz astronomical receiver as a water vapor spectrometer? Or, if experience suggests, we may decide to instrument the ALMA with 22 GHz systems.

2.3 Calibration of the Electronic and Antenna Phase with an Injected Signal

Radiometric phase correction will only correct for those phase fluctuations which are caused by water vapor, and will not correct for any phase errors caused by variations in the dry atmospheric delay, mechanical instabilities in the antenna, or instabilities in the electronics. Therefore, radiometric phase correction requires some supporting observations or calibration technique to remove phase errors caused by these other sources.

It should be possible to periodically inject a stable signal, perhaps derived from the LO, into the feed to calibrate the electronic contributions to the phase errors. If the calibration signal is injected from the subreflector, then this calibration system will also track the most important mechanical phase drifts of the antenna. If the calibration signal is derived from the LO, and the LO itself has phase instabilities, they will either cancel or be doubled, depending upon the relative phase of the LO and the injected signal. In fact, by alternating the relative parity of the injected signal and the LO, we can solve for both phase errors in the LO and in the rest of the electronics and the antenna up to the subreflector. So, between a reference signal injected at the subreflector and radiometric phase correction, only fluctuations in the dry atmosphere will be unaccounted for.

The on-line system would need to control the details of the injected signal. Information about the injected signal would need to be recorded with the data, and an option for determining and correcting for the electronic phase errors in real time should exist.

The injected signal calibration scheme is an area of research for the design and development phase of the project and will be developed in coordination with the LO system.

2.4 Paired Array Phase Correction

It is possible to use some of the antennas to observe a calibrator and the rest of the antennas to observe the target source. At this time, no special plans are being made for this "paired array" phase calibration technique. Specifically, the array is not being designed in a way that closely pairs antennas to optimize paired array calibration. In the smaller arrays, the configurations will naturally permit paired array calibration.

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