ALMA Construction Project Book, Chapter 3.1: Calibration Issues

Calibration Issues for the ALMA

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Summary

The precision imaging to be attained by the ALMA will be achieved through accurate calibration. The types of calibration are summarized in Table 3.1.

Table 3.1 ALMA Calibration Requirements.

Pointing	0.6" absolute
Primary Beam	2-3%
Baseline Determination	0.1 mm
Flux Calibration	1% absolute flux accuracy goal
Phase Calibration	0.15 radian at 230 GHz
Bandpass Calibration	10000:1 to 100000:1
Polarization Calibration	10000:1
Single Antenna Calibration	Employed

Calibration strategies will be developed and implemented on the OVRO and BIMA arrays. The principal goals to be achieved by the end of the ALMA Design and Development (D&D) Phase are to demonstrate radiometric phase correction at 22 GHz, including demonstration of correction algorithms at OVRO and BIMA; and to demonstrate improved instrumental amplitude calibration.

3.1.1.0 Introduction

Calibration is the process by which the astronomer converts electronic signals from the telescope into meaningful astronomical data. Calibration is crucial for the ALMA. As millimeter and submillimeter wavelength radiation will be adversely affected by the atmosphere and the electronic signal path in a variety of ways, and as the antennas will also be affected by the observing environment, we must understand how we will correct for or remove these various effects. The calibration strategy interacts heavily with the science requirements, the system design, the receivers' functioning, the antenna's physical behavior, the site conditions (*i. e.*, site characterization), the scheduling of the telescope, the real time computing, and the post-processing software which will take most of the burden of implementing the required calibration schemes.

Never before has a radio astronomical instrument been built with such a detailed understanding of the site and its impact on the telescope. With this knowledge in hand, we can optimize the full calibration strategy to produce the maximum scientific output for the ALMA.

We are convinced that all the calibrations that are required can be effectively achieved, but we have not yet made all the decisions as to how to achieve these calibrations. Furthermore, many of the options which we lay out for the various calibrations interact with each other, so we have a long way to go yet before we have a coherent picture of all calibration systems and their interdependencies. This chapter tries to express the astronomical requirements for the various calibrations which need to be performed, as well as the hardware and software requirements for the competing methods for performing these calibrations.

3.1.2.0 Pointing

3.1.2.1 Astronomical Requirement for Pointing

Cornwell, Holdaway, and Uson (1993) show a requirement of 1 arcsec for pointing accuracy, based on the requirements of good mosaicing image quality with 8m diameter primary aperture. Observations at the highest frequencies (900 GHz) will also require this pointing accuracy for even single pointing observations, and high frequency mosaics would often benefit from even better pointing. However, a large fraction of the ALMA observations, such as single pointing observations at frequencies up to 500 GHz, mosaic observations at 115 GHz or lower frequency, or low SNR mosaics at millimeter wavelengths will not require this precision pointing spec.

With an increase in D from the ALMA 8m to the ALMA 12m, the pointing spec should tighten to 0.6 arcsec. Holdaway (1997; Memo 178) performed a more detailed analysis, showing the effects of pointing errors ranging from totally random to totally systematic. While we do not divide up the 0.6 arcsec pointing error specification into various systematic and random terms here (but see Table 3.4.3-2 of the ALMA Antenna RFP), we note that the effects of any pointing error budget with various systematic and random terms could be translated to an estimated image quality. We do note here that random errors have less effect than systematic errors, but we also assume that systematic errors can be calibrated out.

With only minor exceptions, pointing calibration must be performed prior to astronomical observations or the data are useless. This also means that we cannot generally interpolate pointing solutions backwards in time. This makes pointing calibration all the more crucial.

3.1.2.2 What Affects Pointing?

The antenna pointing will be affected by several slowly varying terms such as systematic imperfections of the antenna and the pad, gravitational forces, and thermal loading from the sun. Depending upon the strategy of the astronomical observations, much of these slowly varying effects can be removed by frequent offset pointing observations Some active corrections might also be incorporated into the antenna design. Thermistors have been employed on existing antennas to monitor solar thermal response. Lamb and Woody investigated the use of tiltmeters and a carbon fiber reinforced plastic (CFRP) pointing reference structure in their investigation of a 12m antenna design. Lugten (ALMA Memo 232) discussed implementation of a CFRP reference structure in detail, showing that use of such a structure might improve pointing performance.

In addition to these slowly varying systematic pointing errors, there will also be highly random pointing errors caused by wind loading and anomalous refraction. Measurements of the wind indicate that a great deal of the power in the wind is often in a constant speed and direction, so it is only the gusts about this mean speed and direction which will result in differential pointing errors between the calibration and the target source (see Holdaway 1996, Memo 159). The refractive pointing will usually not be a severe problem, but will sometimes limit the pointing (Holdaway, 1997, Memo 186; Butler, 1997, Memo 188; Holdaway and Woody, Memo 223, Lamb and Woody Memo 224). Since the refractive pointing is random on time scales of the antenna crossing time of the atmosphere (ie, 1 s), we mainly need to have statistically many different atmospheric instantiations for each of the five points of a pointing calibration to ensure that we are not applying an erroneous pointing position when we collect data on the target source.

Finally, at some level there will be a limit to the mechanical repeatability of the antenna pointing. At this level, we are left with completely random pointing errors which cannot be calibrated. If these purely random errors are too large, they will spoil the imaging characteristics of the ALMA and will not be correctable. If they are small to moderate in magnitude (ie, < 0.5 arcsec), we can tolerate them quite well as these random errors are the least damaging of any pointing errors.

3.1.2.3 Pointing Calibration Strategy

Our basic goal is to have systematic pointing errors which can be calibrated and removed completely so we are left with purely random pointing errors which are small enough not to bother us.

3.1.2.3.1 Pointing Model

The first step in removing the systematic pointing errors is to determine the systematic imperfections of the antenna and pad and the effects of gravity. Most radio telescopes periodically undergo a pointing routine which samples the sky with pointing measurements on about a hundred astronomical sources taken at night to minimize thermal and wind pointing errors. The ALMA will take about 60 minutes to perform 100 pointing calibrations across the sky. The results of these pointing measurements are then used to fit about 10 parameters in a pointing equation which accounts for various physical terms, such as misalignment of optical axes or four fold sag due to the antenna base being supported at four locations. Some experimenting will go into determining the optimal form for the ALMA pointing equation (see Mangum Memo 288).

The ALMA will probably rely heavily upon a lower frequency (e.g. 90 GHz or below) system for determining the pointing model. The wider beam at this low frequency and the high sensitivity and bright astronomical sources will facilitate pointing measurements, even after a reconfiguration. However, precise pointing offsets among the different frequencies will also need to be determined. It is our hope that the blind pointing after application of the pointing model is on the order of 2 or 3 arcsec rms. To achieve the precision pointing specification, frequent (i.e. every 30 minutes) offset pointing calibration will be required, to remove local deviations from the pointing model, or systematic slowly varying effects due to wind and/or thermal gradients.

3.1.2.3.2 Offset Interferometric Pointing on Quasars

Holdaway (1996; Memo 159) and Lucas (1997; Memo 189) have both demonstrated the feasibility of performing pointing calibration on quasars close to the target source; adequate SNR can be obtained with sufficient speed. The minimum calibrator flux, and hence the typical minimum distance to a pointing calibrator for pointing calibration, is a function of both the collecting area and the number of elements in the array.

A key question concerning the efficiency of these offset pointing calibrations: what are the differential pointing errors as a function of distance between cal and target sources? This depends upon the direction of wind, the sun angle, etc, and probably needs to be answered experimentally. Also, we must understand the stability of the pointing offsets among the different frequency bands, as the pointing calibration will usually be done at 30 or 90 GHz.

Both the pointing model solution and the offset interferometric pointing will require an extensive, up-to-date catalog of pointing calibrator sources, and the observing schedule program should allow for automation of the choice of a pointing calibrator and the pointing calibration strategy.

3.1.2.3.3 Infrared Pointing

The ALMA prototype antennas, and perhaps the production antennas will be outfitted to perform infrared or optical offset pointing. Offset interferometric pointing should work well enough. However, infrared pointing will increase the overall efficiency of the instrument, may improve the antennas' pointing and may help characterize mount components in the pointing equation. The infrared pointing will be largely immune to refractive pointing. Since our main strategy concerning refractive pointing is to minimize its random effect on the pointing measurements, the infrared pointing is not at a disadvantage because it is not affected.

3.1.2.3.4 Scheduling and Editing

A particular experiment's demands for precision pointing need to be combined with the current site conditions (phase stability for refractive pointing, wind and wind stability, and solar loading and variability) and qualitative rules of thumb for the success of pointing calibration and pointing stability in various conditions to determine when that experiment should be scheduled. Records of the pointing solutions, phase stability, wind fluctuations, and solar loading can be used to locate times when the pointing solutions are suspect, and the astronomical data during these times can be edited accordingly. If the pointing solutions show large drifts with time, but all antennas are behaving similarly, the mean array pointing position as a function of time can be corrected in post-processing.

3.1.2.3.5 Pointing Self-Calibration

Pointing self-calibration, an unimplemented algorithm, may not work well at all unless there is at least one bright point-like source within the target area. Once the antenna pointing offsets have been determined, it is simple and not too cpu-expensive to apply the mean array offset as a function of time to mosaic or single pointing data and use that in the imaging. However, if there is significant scatter among the antennas' pointing positions at each time, imaging wide field sources considering the correct pointing data may be prohibitively expensive (Holdaway, 1993; Memo 95).

3.1.3.0 Primary Beam Calibration

A detailed understanding of the primary beam will be required to image wide field astronomical objects. At lower frequencies, pointing errors will tend to limit mosaic image quality, but at high frequencies, surface errors resulting in primary beam distortions will dominate the errors in mosaic image reconstruction (Cornwell, Holdaway, and Uson, 1993). Early simulations (Holdaway, 1990; Memo 61) indicated that an understanding of the primary beam down to the 2-3% level is desirable. If this cannot be achieved, mosaic dynamic range will be limited by primary beam uncertainty more than pointing errors.

The desired primary beam information will result naturally from the low frequency holography campaigns. While the high frequency primary beams will not simply scale like the frequency, we can estimate them from a surface error model and the feed placement. However, we will probably want an independent measurement of the beam at several frequencies. At the highest frequencies where we expect the most problems with the primary beams, the primary beams will be hardest to measure due to decreased sensitivity and a lack of appropriate sources.

We may require primary beam models with different levels of complexity to achieve different scientific goals. The simplest primary beam model, which will suffice for low to intermediate dynamic range observations, will be a mean rotationally symmetric primary beam, measured out to the first or second sidelobe. The next level of complexity may be a mean 2-d (*i.e.*, non rotationally symmetric) beam. It is conceivable that we would someday require the use of different 2-d primary beams or voltage patterns for each antenna, for several different elevation angles, or even for both.

3.1.4.0 Baseline Determination

The relative positions of the antennas must be determined accurately so the geometrical delay can be correctly applied to the antenna voltages prior to correlation. Residual delays will result in phase errors which change across the observing band and differential phase errors between two different sources on the sky. For the ALMA with, *e.g.* an 8 GHz bandwidth, a reasonable limit of 1/3 radian phase difference across the band requires a baseline accuracy of about 1 mm. Requiring the differential phase error between two sources 5 degrees apart on the sky to be on the order of 5 degrees results in a baseline accuracy of about 0.1 mm. Atmospheric phase errors of more than 5 degrees would not severely impact the imaging, as these errors are random in time and among antennas. However, baseline errors will be partially systematic as they will be slowly varying in time, so we need to be more conservative with them than with the atmosphere.

3.1.4.1 Baseline Measurement Strategy

The baselines, or delays, may be measured by determining the delay on each baseline for on order of a hundred observations of point sources sampling the entire sky. Individual delays can be fit across the spectrum, as in VLBI. The complete set of delays is used to solve for the three dimensional locations of all antennas relative to a reference antenna. The observing strategy is similar to that for the pointing model determination, and should take about an hour to complete. Signal to noise is not an issue for 0.1 mm accuracy, and the 1 hour time scale is set more by the minimum time to sample many sources around the sky. Atmospheric phase fluctuations may affect the baseline delays, so ideally the observing conditions should be excellent. In poor conditions, the delays can probably still be determined based on the statistics of many differential measurements, as the atmosphere should tend towards a zero mean in differential measurements.

Of some concern is the time scale over which we can expect the antenna positions to remain fixed to within 0.1 mm. Permafrost has been anecdotally reported on the ALMA site, which enables an entire class of soil movements. We can probably expect some amount of soil creep, especially after earthquakes. We will gain experience concerning the frequency of baseline calibration once the ALMA begins to be operational at Chajnantor.

3.1.5.0 Flux Calibration

3.1.5.1 Astronomical Requirements for Flux Calibration

Yun et al. (ALMA Memo 211) have written a white paper on flux calibration which addresses most of the issues mentioned here. The primary scientific requirement for accurate absolute flux calibration is the comparison of astronomical images made at different frequencies. While the current 10% estimated absolute accuracies permit many qualitative conclusions, 1% absolute flux accuracy will really open up new quantitative scientific possibilities. This flux calibration accuracy must apply to both total power and interferometric modes.

3.1.5.2 What Affects Flux Calibration?

Changes in the receiver temperature, electronic gain drift, variable atmospheric opacity and emission, variable ground pickup, decorrelation (atmospheric and electronic) and gravitational deformation at high frequencies are some of the parameters affecting accurate flux calibration.

3.1.5.3 Flux Calibration Strategy

3.1.5.3.1 Instrumental Amplitude Calibration

The currently used ambient load chopper wheel method is accurate to about 5% (see Ulich & Haas (1976), Kutner (1978)). Bock et al. (1998; ALMA Memo 225) are investigating a two load system located behind the secondary and viewed through a hole in the secondary; see also ALMA Memo #318 by Jeff Mangum: "Amplitude Calibration at Millimeter and Sub-millimeter Wavelengths". This system could theoretically achieve 1% amplitude calibration of a well understood antenna/receiver system, but would rely upon accurate ancillary measurements of the decorrelation and the opacity. BIMA is prototyping this system, and is evaluating how well it works. An accurate estimate of the atmospheric opacity will be required for accurate flux calibration. At frequencies at which the atmosphere is opaque at the low elevation angles and partially transparent at high elevation angles, it will be possible to solve for the sky temperature and the opacity with a sky tip. However, at frequencies at which the atmospheric transmission is excellent, a sky tip will only give the product of the opacity and the sky temperature, and the temperature must be assumed to calculate the opacity. Currently, atmospheric models are not sufficiently accurate to measure the opacity and sky temperature at a partially opaque frequency and accurately estimate the opacity at another frequency. The Water Vapor Radiometry (WVR) system should provide a measure of emission and absorption at its operational frequency of 183 Ghz. Actual measurement of the sky temperature and water vapor profiles via radiosonde are currently underway, along with modeling of the data. Continuous radiosonde monitoring, however, seems unwieldy and expensive. A more cost effective solution would be to float a tethered balloon over the site several times a day. The temperature, pressure, and water vapor information would also be useful for the radiometric phase correction schemes.

3.1.5.3.2 A Gain-Based Instrumental Amplitude Calibration

Larry D'Addario points out that tracking Tsys fluctuations may not be the easiest way to get good flux calibration. He points out that with a multi-bit correlator, we can measure the correlated power instead of the correlation coefficient; hence, we need to track the electronic gain from receiver to correlator. The electronic gain does not vary with atmospheric opacity, changing ground pickup, etc, and is therefore much easier to track, perhaps by injecting a broad-band signal through the system. Even so, we still need an accurate opacity measurement.

3.1.5.3.3 Astronomical Flux Calibration

While an instrumental amplitude calibration accurate to 1% is a desirable goal, it is unclear that we will be able to understand the antennas and the atmosphere well enough to achieve this ambitious goal, so it is important to find astronomical sources that could serve as flux standards. Currently, planets are used as astronomical flux standards for millimeter wavelength observations, but the estimated accuracy of the planets' fluxes is only about 10%, so new flux standards need to be found.

The ALMA will have the sensitivity to use much fainter sources as flux standards. At the highest frequencies (650 and 900 GHz windows), some stars will be bright enough to achieve the 1% flux calibration goal in a few minutes. A knowledge of their temperatures from optical data will determine the expected submillimeter flux, but this may be complicated by confusing emission from dust or even time variable gyrosynchrotron emission from sunspots or flares. Some efforts at stellar measurements are underway at BIMA to evaluate this possibility.

As the blackbody spectrum falls off very fast at lower frequencies, millimeter observations will not be able to use stars as astronomical flux standards. However, although still subject to the same blackbody spectral law, asteroids appear promising. Many are unresolved to many ALMA baselines, the bright ones are in the range of 50-1200 mJy, permitting fast detection at 1% accuracy, and they are fairly simple systems. One drawback is their non-uniform emission as they rotate and as they move with respect to the sun, which could change their flux by several percent. Observational tests are required on these prospective astronomical flux standards as the ALMA comes on line, and we can always hope for a less problematic class of sources for an accurate astronomical flux standard. See Yun et al. (1998) for a more detailed discussion of stars and asteroids for flux standards.

3.1.5.3.4 Phase Decorrelation

An uncorrected antenna based phase error of 10 degrees rms will result in a 3% decrease in the visibility amplitude due to decorrelation. As the characteristics of the phase noise change, the amount of decorrelation will also change. The primary defense against decorrelation is to try to correct the phase as much as possible. However, when the phase cannot be fully corrected, we can estimate the magnitude of the decorrelation and correct the visibilities. Decorrelation could be estimated from:

- phase calibrator data (fast switching)
- independent phase monitor (atmospheric) PLUS injected LO signal (antenna mechanical & electronic)
- radiometric data (atmospheric) PLUS injected LO signal (antenna mechanical & electronic)

For atmospheric coherence times, see Holdaway 1997 (Memo 169).

3.1.5.3.5 Changes in Transparency

At millimeter wavelengths, the changes in atmospheric transparency will be very modest, under 1% over 10 minutes about 80% of the time. Since the same amount of water vapor results in much larger opacities in the submillimeter, the transparency fluctuations in the submillimeter over characteristic calibration time scales will be much larger, typically several percent during median stability conditions. Due to the lack of submillimeter calibration sources available for fast switching and the current uncertainty in the transmission models, we will probably need to perform frequent tipping measurements to solve for the transparency at the observed frequency.

3.1.5.3.6 Polarization Complications

As mentioned below under polarization calibration, if a linearly polarized calibration source is used to track changes in the amplitude gain or opacity, a telescope with linear feeds will produce parallel hand visibilities which are modulated by the linear polarization. The extra signal varies as a sinusoid of the parallactic angle, so the errors are systematic. This will not be a problem for the astronomical flux calibrators mentioned here, but would be a problem for quasars.

3.1.6.0 Phase Calibration

Phase errors limit resolution, limit the dynamic range of images, introduce artifacts, and reduce sensitivity by decorrelation. Without effective phase calibration, the maximum usable ALMA baseline would generally be about 300 m. Amplitude errors would limit image dynamic range and skew the flux scale.

3.1.6.1 Astronomical Requirements for Phase Calibration

The phase calibration working group report (Woody 1995; Memo 144) considered three cases at 230 GHz: high quality imaging with 8 deg phase errors, median conditions with 19 deg phase errors, and poor imaging with 48 deg phase errors. The phase errors have a budget which includes the atmosphere, the antenna, and the electronics.

3.1.6.2 What Affects the Phase?

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).

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. It is believed that the dry phase is non-dispersive at millimeter wavelengths.

Any change in the distance between the subreflector and the feed will cause phase errors.

The stability of the LO and other electronics will also influence the phase.

3.1.6.3 Phase Calibration Strategies

3.1.6.3.1 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 (ALMA Memos 84, 123, 126, 139, 173, 174, 221, 262), and we are fairly confident that it will work for the ALMA.

3.1.6.3.1.1 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 (like 30 or 90 GHz) and scaling the solution up to the target frequency.

3.1.6.3.1.2 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 is 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.

On longer timescales, set by the phase stability of the electronics, it is necessary to measuring the instrumental phase offset between different frequencies, by observing a single source at both wavebands. See section 7.0.6 of the Local Oscillators chapter of this Project Book for a discussion of this point.

3.1.6.3.1.2 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.

3.1.6.3.1.3 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. These performance requirements are specified in the Anntena Request for Proposal.

3.1.6.3.1.4 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.

3.1.6.3.1.5 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. ALMA 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.

3.1.6.3.1.6 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?

3.1.6.3.1.7 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.

3.1.6.3.2 Radiometric Phase Correction

The most promising alternative to fast switching is radiometric phase correction (ALMA Memo 209, ALMA Memo 210: 'Radiometric Correction white paper', Weidner 1998 Ph. D. Thesis, Woody and Marvel 1998, ALMA Memo 252). 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 will be monitored on 1 s or better intervals through a water vapor radiometry (WVR) system. 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. The ALMA Science Advisory Committee has noted that the benefits of a cooled system in terms of stability and noise probably outweigh the costs. Stable, sensitive WVRs may also contribute to amplitude calibration via measurements of emission and absorption (e.g. ALMA Memo 300). When the PWV column w is under 4 mm, residual antenna based rms path errors of under $10(1+w)$ microns should be achievable on 1 s timescale over a period of 5 minutes and elevation change of 1 degree. Larger water vapor columns preclude high frequency observations, so the larger phase errors associated with high opacity conditions may not be critical.

In the ALMA Design and Development (D&D) Phase there exists an instrument present at Chajnantor to investigate but not implement radiometric correction at 183 Ghz (ALMA Memo 271). At existing sites this line will be saturated much of the time (e.g. Memos 237 and 238 estimate this for Kitt Peak and the VLA site). 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 operated a 183 GHz phase correction radiometer at Mauna Kea (Memo 252). 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? See Memo 271 for a report on this system, and Appendix E of the Report of the ALMA Scientific Advisory Committee March 2000 Meeting.

3.1.6.3.4 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.

3.1.6.3.5 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. See ALMA Memo 262 for results of VLA tests.

3.1.7.0 Bandpass Calibration

In rough terms, the dynamic range of a single spectral channel which is limited by errors in continuum subtraction caused by bandpass errors will be

$DR=(S_{line}\ sqrt(N))/(S_{cont}s_{BP})$

where S_{line} is the strength of the line, N is the number of antennas, S_{cont} is the continuum strength of the target source, and s_{BP} is the rms error in the bandpass. For the spectral line observations to be limited by thermal noise and not by bandpass errors, and assuming the bandpass errors are themselves due to thermal noise in the observations of the bandpass calibrator, we have the condition that N $sqrt(t_{cal})/sqrt(t_{line}) > S_{cont}/S_{cal}$ where S_{cal} is the flux of the bandpass calibrator.

3.1.7.1 Scientific Requirements

A majority of the spectral line observations made with theALMA will probably have no problem meeting the condition of being limited by thermal noise before they are limited by bandpass calibration. Observations of weak spectral lines in the host galaxy of a bright flat spectrum quasar will be about as demanding on the bandpass calibration as these experiments currently are for the VLA or the AT. However, observations of spectral lines on planets in the solar system will be extremely demanding.

For example, the continuum brightness temperature of a planet might be 200 K, and the thermal noise for a bandwidth of 20 m/s and a 1 hour observation at 200 GHz with a T_{sys} = 40 K would be about 0.006 K, requiring a lot of time on a very bright source free of spectral emission to provide a good bandpass calibration. Furthermore, a large fraction of the ALMA's targets will be galactic, and it will be difficult to find bandpass calibrators which are not affected by galactic emission or absorption given the large bandwidth of ALMA.

3.1.7.3 Bandpass Calibration Strategy

We will always have the capability of calibrating the bandpass in the current manner, by observing a strong source for a sufficiently long time. However, injection of a strong noise signal which is flat over the observed frequency range would be an ideal solution to both the planet problem and to the galactic confusing line problem. The injection can be made directly into the feed, or can be part of the ancillary LO system which has been proposed to be injected from the subreflector. The injected noise will need to be much stronger than the 400 K signal at a few percent coupling mentioned in the flux calibration section.

At millimeter and submillimeter wavelengths, the atmosphere will also contribute to the bandpass for wide bandwidth observations, so we must either perform an independent determination of the bandpass astronomically to solve for the atmospheric bandpass component, or we would measure the precipitable water vapor from opacity measurements made at a fiducial frequency and determine the atmospheric contribution to the bandpass through the use of an atmospheric transmission model. Currently, the atmospheric transmission models are probably not good enough for this sort of work, but the ALMA would provide enough data for an ad hoc model or to improve the theoretical models. We will be concerned with changes in the atmospheric component of the bandpass on reasonably short time scales and among the different antennas.

There is an implicit specification placed on the system design that the electronic bandpass be either stable or that it vary linearly with time to something like 10000:1 to 100000:1. If the bandpass changes are mainly linear, we can remove them through interpolation if we calibrate often enough.

3.1.8.0 Polarization Calibration

Linearly polarized feeds have a wider usable bandwidth than circularly polarized feeds, and the ALMA will most likely use linear polarization in order to get complete coverage of all millimeter wavelength atmospheric windows with a reasonable number of receivers. Sault et al. (1991) and Cotton (1998, Memo 208) have both treated the problem of polarization calibration with linear feeds in detail (see also Appendix C to the Report of the ALMA Science Advisory Committee March 2000 Meeting. The main details that we must be concerned with here are that linear polarization leaks into the "parallel hand" visibilities, and that it is not easy to distinguish circular polarization from the instrumental polarization terms.

Because the linear polarization is entangled with the total intensity in the parallel hand visibilities, there are times when all four cross correlations per baseline will need to be performed, which will probably result in halving the bandwidth and cutting the sensitivity by root two. We consider several cases which could come up with the ALMA to demonstrate when we may need to consider all four cross correlations and when we may use approximations to make use of just the two parallel hand cross correlations:

- Amplitude calibration is performed instrumentally and phase calibration is performed on a quasar (or a combination of radiometric plus a quasar). The quasars will generally be a few percent linearly polarized, but may be as much as 10-20% polarized, and hence Stokes Q and U will influence the parallel hand visibilities. These sources have almost no circular polarization. For a point source, the calibrator's linear polarization will not affect the phase, only the amplitude. If the amplitude calibration is performed instrumentally, as in the scheme of Bock et al., there is no problem with a polarized calibrator and linear feeds. We further consider two subcases:
    - Total intensity imaging with no polarization in the target source. Many millimeter spectral line sources will have little or no linear polarization. Nothing special needs to take place, as the parallel hands will basically contain Stokes I.
    - Total intensity imaging with appreciable linear polarization in the target source. The linear polarization in the target source will corrupt the parallel hand visibilities in a systematic way. However, when the XX and YY visibilities are added together, the linear polarization corruptions cancel out. This is acceptable for low to moderate dynamic range total intensity observations, but may not be sufficient for high dynamic range total intensity observations, as residual gain errors will limit the cancellation of the linear polarization and adding the XX and YY correlations results in a condition in which gain errors no longer close, limiting the use of self-calibration. High dynamic range total intensity imaging of a source with appreciable linear polarization may require full polarization calibration and imaging.
    - Polarization imaging. A bright calibration source must be observed to determine the instrumental polarization leakage or "D" terms. If the calibrator has known (or zero) linear polarization and no circular polarization, the D terms can be determined in a single snapshot. If the calibrator has unknown linear polarization, the calibrator must be observed through sufficient parallactic angle coverage to permit separation of the calibrator and the D terms. Application of the D terms will permit the polarization imaging.
- Amplitude calibration is performed astronomically. If the amplitude calibrator is not polarized, there is no problem. If it is linearly polarized, then the parallel hand visibilities will vary systematically with parallactic angle, the XX and YY visibilities varying in opposite senses. There are several options:
    - For total intensity observations of a target source at low to moderate SNR, the array-wide XX and YY gain ratios can be determined and corrected for.
    - High SNR total intensity observations will require accounting for the different parallactic angles of each antenna, which will result in imperfect cancellation when using the array-wide gain ratios. In this case, the full polarization calibration will need to be performed, even if there is no interest in polarization.

In all cases in which the cross hand visibilities are explicitly used, the X-Y phase offset must be monitored for each antenna. As there is no simple way to determine the X-Y phase offset astronomically, the ALMA could inject a tone into the feeds, as the AT does. Cotton (1998) points out that it is difficult to generate a millimeter RF tone, and that injecting an IF tone further downstream in the electronics is simpler, though not as good instrumentally. On the other hand, we could derive an RF signal from the LO and inject it into the feeds for the X-Y phase calibration.

The choice of a flux calibrator may also interact with the polarization calibration. Unresolved asteroids which are not azimuthally symmetric will have some time dependent linear polarization, which will complicate the flux calibration. If stars are used for a flux standard, they may display some circular polarization, which would require that another source be used for the D term calibration.

As stated above, the full polarization calibration requires good coverage in parallactic angle to separate the constant instrumental polarization (D term) signal from the sinusoidally varying astronomical polarization signal. This causes some concern since the ALMA is envisioned to be predominantly a near-transit instrument with real time imaging capability. If instrumental polarization calibration is required for many observations, it may be prudent to keep a database of the instrumental polarization solutions at the various frequencies and bandwidths and rely upon that whenever possible. Unlike the VLA, the ATNF compact array shows essentially no time variability in the instrumental polarization (less than 1:10000 over 12 hours, with variations of 0.1% over months). Given the constraints of the ALMA, time constant instrumental polarization may be a good design goal for the feeds, but not a strict requirement.

One way around the complication of good parallactic angle coverage is to use sources of known polarization (ie, unpolarized sources). Holdaway, Carilli, and Owen (1992, VLA Scientific Memo 163) have demonstrated that it is possible to solve for the instrumental polarization for a single snapshot, (ie, a single parallactic angle) if the source polarization is known in advance. So, it would be beneficial to ALMA observing to identify bright, compact sources with known polarization or no polarization for use as polarization calibrators.

3.1.9.0 Special Single Dish Calibration Issues

The ALMA differs from any other aperture synthesis array in that, from the outset, the instrument will support no-compromise single-dish observing modes in addition to the more usual interferometric modes. Some of the issues are discussed in ALMA Memo 108 (*"Single Dish Observing and Calibration Modes"*, D.T. Emerson, P.R. Jewell). Receiver stability and other issues are addressed in ALMA Memo 289, and in Appendix D of the Report of the ALMA Scientific Advisory Committee March 2000 Meeting.

Because single-dish observing is in total power, albeit it switched against, for example, blank sky, there are extraordinary demands on instrumental gain stability. In addition, the extra, variable emission from the sky comes in directly, and tends to mask the much weaker (by perhaps 4 orders of magnitude) astronomical emission. This is in contrast to interferometry, which of course by the use of cross-correlation rather than self-correlation, is relatively immune to these factors.

Astronomical sensitivity calibration in single-dish mode has to be on a dish-by-dish basis; calibration sources need to be detectable with adequate signal-to-noise ratio by one single dish of the array. This is again in contrast to interferometric astronomical calibration measurements, in which the large collecting area of the entire array can contribute to the signal-to-noise ratio achievable in calibrating individual dishes of the array.

Polarization calibration of single dish observations has its own problems. At mm-waves, polarization measurements are conventionally made with a "widget" in front of the receiver feed. This "widget" introduces changes in the polarization response of the receiver - for example a rotating grid and screen combination can continuously rotate the incident plane of linear polarization. The astronomical polarization is then detected by synchronous changes in total power intensity through the receiver as the sense of polarization changes.

The ALMA may indeed have to provide such "widgets" for each of the antennas. However, the complexity and potential unreliability of such a device could be avoided if it were shown possible to measure polarization reliably, in single-dish mode, by cross-correlation of the signal from orthogonally polarized feeds. Tests of the feasibility of this techniques are planned by early 2000.

3.1.9.1 Atmospheric Emission Cancellation

The emission from the atmosphere is much stronger than the emission from most astronomical sources, and, even worse, the atmospheric emission is variable as well. The variable part of the emission is mainly due to inhomogeneously distributed water vapor, which also causes the phase fluctuations. Since we have excellent statistics of the phase stability on the Chajnantor site, we can infer the severity of the variable atmospheric emission at any desired frequency by using a transmission model or FTS measurements.

For an interferometer, the atmospheric emission above two different antennas is not correlated, so it does not affect the visibilities. In total power continuum observations, the variable atmospheric emission is a major problem which requires some sort of switching on the sky. The total power spectral line case is much less demanding, as large atmospheric fluctuations can be tolerated, considering the much smaller channel widths and much higher thermal noise and the possibility of fitting an average baseline to each spectrum. The spectral line data will have secondary effects, such as the bandpass changing in response to the changing atmospheric load. However, the spectral line observations are much easier than the continuum case, so if we can beat the atmosphere for continuum observations, the spectral line observations will be no problem. The detailed treatment of this problem is presented in an upcoming ALMA Memo (Holdaway, Lugten, and Freund, 2000). ALMA Memo 300 presents a novel method for calibration to remove atmospheric emission which makes use of the very wide bandwidths of ALMA.

3.1.9.1.1 Beam Switching

Traditionally, beam switching by nutating subreflector has been used to remove the variable atmospheric emission. Our study indicates that most beam switching is non-optimal. For any given observation, we would like to be roughly equally limited by thermal SNR and by the residual variable atmospheric emission. If the noise is dominated by the variable atmospheric emission, we need to switch faster. The faster we switch, the better the atmospheric cancellation, but the lower the duty cycle, so the thermal noise will increase. Furthermore, the distance of the throw also needs to be considered. In general, it is optimal to have the smallest throw which gets completely off source. However, in an unstable atmosphere, multiple short throws are better. Hence, the detailed use of a nutating subreflector needs to be fine tuned to match the atmospheric conditions and the observing frequency. As with fast switching, we hope that the observer does not have to perform the calculations to find the optimal switching strategy; the observer should provide high level guidelines, and the program which performs the micro-scheduling should calculate the optimal switching strategy for the current atmospheric conditions.

The nutator design (see specifications in paragraph 4.2.9 of the Antenna chapter of this ALMA Construction Project Book) for the ALMA prototype antenna allows for a maximum throw of about 1.5 arcmin for symmetric beam throwing. Maximum nutating frequencies of about 10 Hz are planned. If it is affordable, nutators with higher peak acceleration and larger maximum throws would be desirable for the production antennas. The two beams should be as similar as possible to reduce the level of systematic errors in beam switching.

The analysis of the On-The-Fly technique for total power continuum observations indicates that it will be as good or better than beam switching in all situations. However, there is considerable risk involved in relying on the On-The-Fly method to cancel all atmospheric fluctuations. For this reason, it is generally agreed that the prototype antennas need to have nutating subreflectors. Currently, this is planned according to the Payne design referred to above.

3.1.9.1.2 On-The-Fly

In On-The-Fly (OTF) observing, the antennas scan quickly across a source at constant elevation angle, using the off-source regions on other side of the source region to define the sky emission. Very large sources will need to be pieced together at some SNR expense. The OTF technique promises to be quite effective at removing the atmospheric emission for three reasons:

- each Nyquist sample on the sky is observed for a very short time, so the system noise is large and a larger amount of sky fluctuation noise is tolerable. (The large number of Nyquist samples observed in each scan compensates for this large noise per Nyquist sample.)
- since more time is spent observing the OFF than an individual ON Nyquist sample, the atmosphere is well determined, unlike beam switching where we are differencing two noisy numbers.
- since the OFF's are observed over a range of time, we can remove a second order polynomial trend in the atmospheric emission time series, which greatly reduces the residual sky emission fluctuations.

For sources which are about one beam across, the OTF observing strategy works about as well as beam switching. For larger sources, OTF wins because of the relative increase in the SNR of the atmospheric determination and because multiple throws begin to degrade the beam switching SNR.

Because the entire antenna is moving, many systematic errors which plague beam switching (such as differences in the shapes and gains of the ON and OFF beams) are eliminated. However, it takes much more energy to move the entire antenna, and there is more risk in general with an observing strategy that attempts to move the entire antenna.

3.1.9.1.2.1 Controlling Antenna Movements

OTF will work only if we can slew and reaccelerate the antenna quickly without exciting the lowest resonant frequency of the antennas. An initial analysis of this problem has been performed by Holdaway, Lugten, and Freund (2000). Using a Gaussian acceleration profile and an error function velocity profile, they predict the antennas will be able to turn around from one scan direction to the other in about 0.2 s without appreciably exciting the lowest resonant frequency. This acceleration profile is a good one, but probably not an optimal one, so further work could help optimize the profiles for both OTF antenna motion and fast switching antenna motion.

In order not to excite the antenna motions, the acceleration must be very smoothly varying. This will put strong constraints on both the control system and on the servo system.

3.1.9.1.2.2 Maximum Velocity and Acceleration

OTF simulations of sources of various sizes indicate that the optimal slew velocity varies linearly with source size. For a maximum interesting source size of 1 deg, a maximum slew rate of about 0.5 deg/s is required. This requires a maximum antenna angular acceleration of about 12 deg/s/s. Since the profile is Gaussian, we do not require this maximum acceleration for very long. These maximum velocities and accelerations are for an antenna with lowest resonant frequency of 6 Hz. An antenna which was less stiff could not utilize such large accelerations and velocities in OTF observing. A stiffer antenna would permit faster turnarounds, requiring larger accelerations and velocities. However, the 6 Hz antenna is effectively beating the atmosphere already, so not much is gained from a stiffer antenna.

3.1.9.1.2.3 Reading Out Encoders, Dump Time

OTF requires that we know where the antenna is for each Nyquist beam. At the 0.5 deg/s maximum slew rate, observing at 850 GHz with a half beam size of 0.001 deg will require that we dump the data and know where the antenna is every 2 ms. We don't need to make the antenna go to any precise place at any precise time, we just need to know where the antenna was at a precise time. We may not need to read the encoders every 2 ms; if the antenna position changes smoothly over time scales of 10 ms, we can read out the encoders more coarsely and interpolate. We do not require that the encoders be accurate to within the pointing specification of 0.6 arcsec.

3.1.9.1.2.4 Antenna Motions Don't Need to be Synchronized

Since we are only talking about total power OTF here, we need not synchronize all the antennas in their dance across the sky. The antennas could be staggered to permit a more constant utilization of electrical power.

3.1.9.1.2.5 1/f Noise

In addition to atmospheric brightness fluctuations, beam switching and OTF will remove a portion of the receivers' 1/f noise. From the optimizations we have performed, we can set specifications on the 1/f noise for each observing frequency. Even though the beam switching is performing the switching faster than OTF, the integration time spent on each ON is often larger than the integration time spent per Nyquist sample of an OTF observation, so OTF and beam switching are similar in their ability to switch out 1/f noise. If these specifications cannot be met, we must reoptimize the OTF observing strategy, which would result in moving more quickly to accomplish faster switching and less time or more white noise per Nyquist sample on the source. This would favor both higher maximum accelerations and a stiffer antenna.

Freq	Beam Size Source		0.5 deg Source	
[GHz]	noise	break frequency	noise	break frequency
	[Jy]	[Hz]	[Jy]	[Hz]
90	0.047	1.2	0.081	0.34
230	0.088	1.2	0.25	0.29

345	0.14	1.2	0.47	0.29
650	0.33	1.3	1.6	0.34

Table 1: For continuum (8 GHz bandwidth per polarization) OTF observations, what noise level must the 1/f noise be below, and at what frequency, for 1/f noise to have essentially no effect on OTF observations' sensitivity?

3.1.10.0 Solar Calibration

For solar observing, some type of attenuating "widget" in front of the receiver may be required, to reduce the necessary dynamic range of the receiver and backend electronics. Some special calibration scheme needs to be thought out specifically for calibration of solar observing. This is under study.

3.1.11.0 Editing

Both the on-line and post-processing software should provide for carrying various monitor data through the system and allowing easy editing of astronomical data based on the monitor data, on a per time or per antenna basis.

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