Atacama
Large
Millimeter
Array

Calibration Plan

SCID-90.03.00.00-007-A-PLA
Version: A
Status: (*Draft*)
2004-02-27

Prepared By:		
Name(s) and Signature(s)	**Organization**	**Date**
Bryan Butler, M. Holdaway, Al Wootten R. Lucas J. G. Mangum	National Radio Astronomy Observatory Institut de RadioAstronomie Millimétrique National Radio Astronomy Observatory	2004-02-12
Approved By:		
Name and Signature	**Organization**	**Date**
Released By:		
Name and Signature	**Organization**	**Date**

Change Record

Version	**Date**	**Affected Section(s)**	**Change Request #**	**Reason/Initiation/Remarks**
A	2004-02-12	All	ALMA-00.00.00.00-000-A-CRE	Initial Version
A	2004-02-27	Chap 4		Added this section

Table of Contents

1 INTRODUCTION

1.1 Purpose

This document provides techniques which are planned in order to allow ALMA to reach the calibration requirements detailed in ALMA-90.03.00.00-001-A-SPE. For each type of calibration, this document describes the technique suggested, with references to more detailed treatments if available and some detail if not. For each technique, the required hardware is described with reference to the specifications for that hardware if they exist or to the requirements for that hardware if not. For each calibration type there are different requirements as to frequency of performance and to the frequency at which it is performed. This document makes recommendations for these to the best current knowledge. Each calibration will take some time. This, too, will vary with frequency for some types of calibration. Calibration quantities may need to be archived at some particular frequency, with recommendations in this document for that frequency.

1.2 Scope

1 Related Documents and Drawings

1.1 References

Applicable documents

The following documents are included as part of this document to the extent specified herein. If not explicitly stated differently, the latest issue of the document is valid.

Reference	*Document title*	*Date*	*Document ID*
[AD1]	ALMA Product Tree	2002-11-01	SYSE-80.03.00.00-001L-LIS
[AD2]	ALMA Project Plan v1.0	2003-07-29	ALMA-10.04.00.00-001-A-PLA
[AD3]	System Design Description	2004-02-20	SYSE-80.04.00.00-002-D

Reference documents

The following documents contain additional information and are referenced in this document.

Reference	*Document title*	*Date*	*Document ID*
[RD1]	List of acronyms and glossary for the ALMA project	2003-04-23	ALMA-80.02.00.00-004-B-LIS
[RD2]	ALMA Project Book	2002-02-20	Version 5.5

[RD3]	Water Vapour Radiometer Technical Specifications	2003-09-21	FEND-40.07.00.00-001-A-SPE
[RD4]	VLA Computing Memo 154	1979	F. Schwab, author.
[RD5]	VLA Scientific Memo 163	1992	M. Holdaway, C. Carilli and F. Owen, authors
[RD6]	MMA Memo 208	1998	W. Cotton, author.
[RD7]	Hamaker, Bregman and Sault	1996	A & AS 117, 137
[RD8]	Hamaker, Bregman and Sault	1996	A & AS 117, 149

1.2 Abbreviations and Acronyms

xxx

1.3 Glossary

xxx

1.4 Related Interface Control Drawings

Xxx

2 ALMA Amplitude and Flux Calibration[1]

2.1 Introduction

The goal of amplitude and flux calibration is to convert the output voltage or counts from the correlator into brightness temperature or flux density by carefully tracking instrumental and atmospheric variations and determining accurate conversion factors. Because the adverse effects of instrumental and atmospheric variations grow rapidly with frequency, standard calibration procedures will not work well at submillimeter wavelengths.

The design specifications of ALMA demand a much higher calibration accuracy than achieved by the conventional techniques used at the existing millimeter arrays, which is typically no better than 10%. Producing high dynamic range ($>10^3$) images, for example, requires better than a few percent accuracy in amplitude calibration, and there are many scientific demands for achieving similarly high accuracy in flux calibration as well.

---

[1] Original contribution by B. Butler, M. Carter, J. Gibson, M. Holdaway, J. Mangum, J. Martin-Pintado, W. J. Welch

Absolute amplitude calibration for ALMA requires standard radio sources whose fluxes are known to 1% accuracy. Because the bright compact radio sources which are potentially useful for calibration at millimeter and submillimeter wavelengths are generally time variable, the calibration process must be something that can be repeated as often as needed. Special equipment will be needed as part of the ALMA system to provide this capability. This equipment will enable accurate antenna gain measurements followed by accurate radio source flux measurements.

In the following, several methods for amplitude and flux calibration are described. Achieving 1% accuracy in absolute amplitude and flux calibration has been shown to be attainable. We should point out, though, that the viability of the amplitude and flux calibration system is critically dependant upon the quality of the pointing accuracy of the ALMA antennas and our ability to correct for amplitude decorrelation.

2.2 Amplitude and Flux Calibration

There are two parts to the standard amplitude and flux calibration system:

- Amplitude Calibration (``Chopper Wheel" Calibration)
- Antenna Gain Measurement (Radio Source Flux Measurement)

After describing these standard amplitude calibration steps, we describe an alternate system which bypasses many of the difficulties encountered with the standard calibration system.

2.2.1 Amplitude Calibration

Variants of the standard ``chopper wheel" amplitude calibration technique have been evaluated and tested. ALMA Memos 461, 442, 434, 423, 422, 372, 371, and 318 have addressed a variety of issues related to the chopper wheel technique. A design which incorporates several calibrated loads, one or more of which is a semi-transparent vane, have been shown both by design and experiment to allow for 1% amplitude calibration precision.

The ALMA prototype development plan for this amplitude calibration system has three phases:

- Semi-Transparent Vane System. The tests of the first prototype of a semi-transparent vane (STV) calibration system have been made at the IRAM 30m telescope, with encouraging results. Further tests with this system are required to confirm that the STV concept can work at the 3% level. The test that needs to be made is to check that the losses in the vane are due to absorption to within 3%. This test will require a measurement of the transmission of the vane on an astronomical source with very good weather conditions. Unfortunately, the 30m telescope is unavailable for further tests; the feasibility of some astronomical tests at the ATF with evaluation front ends is being investigated. Tests are needed at frequencies for which both ALMA and the ATF operate, with 1.3mm and 3mm most critical.

- Wire Grid Amplitude Calibration System. Design and construction of a test prototype for a more advanced device containing a polarization grid has been stalled. This second prototype will allow us to study the anticipated advantages of using a grid, which are anticipated to allow calibration accuracy of 1%. In fact, in the previous observing tests made with Prototype1 at the IRAM 30m telescope, some preliminary measurements with the grids of the 30m receivers have been made. These tests were quite encourageing, and we are confident that tests could be made which would allow for a precision of about 1%. These tests will be pursued at (insert name of lab at Madrid) at a maximum frequency of 60 GHz. Tests are needed at frequencies for which ALMA operates, with 1.3mm and 3mm most critical. These tests might be pursued at the ATF.
- Multi-Load Amplitude Calibration System. This more advanced design would incorporate the concepts detailed in ALMA Memo 461. Three types of couplers will be tested and compared: semi-transparent vane; wire grid; dielectric film. An ALMA design will be developed, and testing will be performed at the ATF telescopes with ALMA prototype front ends, currently planned to be available for Q3 2005. Tests are needed at frequencies for which both ALMA and the ATF operate, with 1.3mm and 3mm most critical.

2.2.2 Amplitude Calibration

A good flux calibrator has the following properties: (1) unresolved size; (2) constant or theoretically predictable flux; and (3) bright. At millimeter and submillimeter wavelengths, few if any sources meet all of these criteria. The current generation millimeter interferometers calibrate flux using variants of the following procedure:

- Observe a planet with some or all antennas in total power mode to set the total power flux scale. The planet is the ``primary flux calibrator''.
- Observe a bright quasar with some or all antennas in total power mode to determine the quasar flux. The quasar is the ``secondary flux calibrator''.
- Observe the same bright quasar, now of known flux, with all antennas in interferometric mode to set the interferometric flux scale.
- Correct these observations for elevation-dependent antenna and atmospheric effects such as the gain curves and time dependent atmospheric attenuation.

This calibration system is just an extension of the flux calibration system used with millimeter and submillimeter single dishes. The key step in this calibration scheme is the determination of the flux of the primary calibrator (the planets in the above). Unfortunately, determination of the flux of a planet is not straight forward. Many planets are resolved in interferometer measurements. Most of the measured planetary fluxes are derived by referencing to flux measurements of Mars, whose flux can be model-predicted to about the 10\% level. Some effects which limit the reliability of a Mars-determined flux calibration, and which are not taken account of in models which predict the Martian flux, are dust storms, illumination phase effects, and the influence of the polar caps.

Asteroids are also compact and bright blackbody emitters that may be used as primary flux calibrators. The bolometer observations at 250 GHz of 15 nearby asteroids (heliocentric distance $r = 2.0$-3.5 au, geocentric distances $\Delta = 1$-5 au) by Altenhoff et al. (1994) found strong continuum emission (50-1200 mJy; $T_B = 150$-200 K), which agrees with the blackbody model within the uncertainty of calibration on Mars. They are compact, $\Theta_D('')=0.28\sim[D/(200\mathrm{km})][r(\mathrm{pc})]^{-1}$ -- an order of magnitude smaller than Uranus or Neptune. Their flux density changes significantly due to their and Earth's orbital motion around the Sun, but the changes are highly predictable. Because they are not perfectly round, small oscillation in observed flux is also expected from rotation, which is about 4% peak to peak over 9 hour period in the case of the largest asteroid Ceres (Altenhoff et al. 1996). Ultracompact H~II regions may also be useful at low frequencies, but extended dust distribution is a serious problem at high frequencies.

As is the case for the VLBA, the high spatial resolution achievable with ALMA presents a fundamental problem in that most of these possible primary flux calibrators are highly resolved at the maximum resolution of the array -- for example, the 3 km baseline corresponds to $8.5 \times 10^6\ \lambda$ at 850 GHz or an angular resolution of 24 mas. Even most quasars show structures at these scales and are highly variable.

An alternate primary flux calibrator for ALMA might be main sequence stars. Many nearby main sequence stars should have detectable millimeter and submillimeter continuum emission. For example, the Sun at a distance of 10 pc is about 1 mas in diameter and will have about 1.3 mJy of flux at 650 GHz. Active regions on the Sun will cause some flux variations, perhaps at the few percent level or less. The zodiacal dust in the solar system may be at the level of ~1 percent or more, depending on how much cool dust resides in the outer parts of the solar system. Predicting the precise flux (likely to be somewhat higher because of the higher effective temperature at mm wavelengths) will require fairly detailed models of stellar atmospheres.

By searching the HIPPARCOS data set, Richard Simon has found that there are ~250 stars which will be brighter than 2 mJy at 650 GHz. Of these, he finds that the number of non-variable, non-binary, main-sequence stars visible from Chajnantor is much smaller -- ~22 stars, listed in Table 1. There are probably other suitable stars which are not listed as main sequence. The integration times needed to achieve SNR=20 are computed assuming an rms noise of $0.50 \times t_{min}^{-1/2}$ mJy, which is the sensitivity for a 40 × 10-m array (corrected for the collecting area from the sensitivity calculation for a 40 × 8-m array by Holdaway 1997a).

A serious concern for accurate flux calibration of ALMA is bootstrapping of the flux measurement from the primary calibrator to the secondary or gain calibrators observed hours ahead or later in time because temporal variation in amplitude gain is expected to be significant ($\geq$10%), particularly at high frequencies. An accurate accounting of the amplitude gain variation has to be applied first before any flux scale factors are applied. For many tracks covering only a small range of hour angle (e.g. shadowing, transit at low elevations, snapshot imaging), observing a primary flux calibrator at the same elevation range as the gain calibrator and the program sources may not be possible.

Table 1: Candidate main sequence stars for primary flux calibration.

Catalog	Name	RA	Dec	Parallax	V	Spec	T_{eff}	Diam.	S_{650}	$t_{Int}^{\dagger ½}$
No.		(B1950)	(B1950)	(")	(mag)	Type	(K)	(mas)	(mJy)	(min)
113368	24Alp PsA	343.73	-29.89	0.130	1.17	A3	8720	2.24	11.8	0.7
7588	Alp Eri	23.97	-57.49	0.023	0.45	B3	18700	1.53	7.9	1.6
8102	52Tau Cet	25.42	-16.19	0.274	3.49	G8	5570	2.09	5.1	3.8
49669	32Alp Leo	151.43	12.21	0.042	1.36	B7	13000	1.36	5.0	4.0
108870	Epslnd	329.97	-57.02	0.276	4.69	K5	4350	2.29	4.9	4.2
66459		203.81	35.97	0.092	9.06	M9	2500	5.28	4.3	5.4
22449	1Pi 30ri	71. 79	6.88	0.125	3.19	F6	6360	1.64	4.2	5.7
9236	Alp Hyi	29.31	-61.81	0.046	2.86	FO	7200	1.45	4.0	6.3
54872	68Del Leo	167.87	20.80	0.057	2.56	A4	8460	1.25	3.5	8.2
8903	6Bet Ari	27.97	20.56	0.055	2.64	A5	8200	1.27	3.5	8.2
57757	5Bet Vir	177.03	2.05	0.092	3.59	F8	6200	1.45	3.2	9.8
71908	Alp Cir	219.60	-64.76	0.061	3.18	F1	7045	1.32	3.1	10.4
84143	Eta Sea	257.14	-43.18	0.046	3.32	F3	6740	1.36	3.1	10.4
19849	400mi2Eri	63.22	-7.77	0.198	4.43	K1	5080	1.61	3.1	10.4
27072	13Gam Lep	85.59	-22.47	0.111	3.59	F7	6280	1.40	3.0	11.1
65109	lot Cen	199.44	-36.45	0.056	2.75	A2	8970	1.04	2.6	14.8
15510		49.53	-43.25	0.165	4.26	G8	5570	1.47	2.5	16.0
109176	24lot Peg	331.18	25.10	0.085	3.77	F5	6440	1.22	2.4	17.4
78072	41Gam Ser	238.54	15.81	0.090	3.85	F6	6360	1.21	2.3	18.9
69701	99lot Vir	213.35	-5.77	0.047	4.07	F7	6280	1.13	2.0	25.0
64394	43Bet Com	197.38	28.14	0.109	4.23	GO	6030	1.15	1.9	27.7
28103	16Eta Lep	88.53	-14.17	0.066	3.71	F1	7045	1.03	1.9	27.7

Table 1 A list of 22 bright main sequence stars visible from Chajnantor that are non-variable and non-binary with expected 650 GHz flux get 2 mJy. They are unresolved by the 3 km baseline of ALMA, and

---

[2] Required integration time to achieve SNR=20 assuming rms sensivity of $0.50 \times t_{min}^{-1/2}$ mJy

the thermal blackbody emission from the 5 brightest stars can be detectable with SNR=20 in 5 minutes of integration.

2.2.3 Required Special Hardware

The STV device described in §3.2.1 is required special hardware.

2.2.4 Frequency of Calibration

Measurement should be made with each Schedule Block.

2.2.5 Time Required for Amplitude Calibration Measurements

Several minutes will be required, depending upon calibrator strength and sensitivity.

2.2.6 Archiving Needs

All of the gains and fluxes measured should be archived.

2.2.7 Further tests

For amplitude calibration, the development plan is described in 3.2.1. Accurate measurement of standard flux calibrators is a research project which should be carried out during the commissioning and verification phase of ALMA, continuing into the Early Science phase.

2.3 Direct Antenna Gain Measurements

2.3.1 Overview of the Technique

2.3.1.1 Amplitude and Flux Calibration

The strategy for calibration of the ALMA system at the 1% level is based on an experiment in which the gain of one of the BIMA antennas was determined to an accuracy of about 1% at 28.5 GHz (Gibson & Welch 2003). The gain calibration is to be established on the ACA antennas by an interferometric comparison process using all of the ACA antennas. The standard for the measurement is a small pyramidal horn of accurately known gain, about 40 dB less than that of an ACA antenna, on a separate mount with its own receiver. The horn gain can be calculated with an accuracy of better than 1%. The horn will be of simple and rugged design and will remain gain-stable over time. A bright planet is observed with the ACA plus horn, with fringes observed between the standard horn and the other ACA antennas, The ratio of the correlations with and with out the horn gives the voltage gain ratio of each antenna to that of the horn. The system temperature of the horn and its receiver system must be established, and a closure amplitude calibration must be made between the horn and the other antennas. The system temperature of the horn and its receiver can be established by loads of two temperatures that can be coupled to the horn.

This scheme with the horn on a separate mount and with closure amplitudes measured is a suggestion of Stephane Guilloteau and differs a little from the actual experiment of Gibson and Welch. In the latter experiment, the horn was mounted at the edge of one of the BIMA antennas, and its receiver was alternately switched between the horn and the main feed using waveguide components. The waveguide losses were measured by standard techniques. Standard waveguide components are not readily available above about 240GHz, and the use of the closure amplitude calibration is probably the only way that the standard horn comparison technique can be readily extended to frequencies above 240 GHz. A further experiment is planned at the BIMA array at about 110GHz which will use both the previous technique of Gibson and Welch and also the closure amplitude suggestion of Guilloteau to study their relative ease of execution and accuracy.

This interferometer measurement has a number of important advantages over the usual total power comparison. The cross-correlation of the standard horn with a dish is 1% (20 dB voltage ratio) of that between two dishes, rather than the total power ratio which is 10^{-4}. This is readily measured to 1% accuracy on a strong planet. Furthermore, since only the correlated signal contributes in the measurement, side-lobe response and multipath echoes, the bane of all antenna calibrations, are completely eliminated. Also, the atmospheric extinction is common in the ratio and cancels out.

2.3.1.2 Radio Source Flux Measurement

The second part of the calibration is the use of the antennas with known gain to measure the flux of candidate calibration radio sources. This requires accurate knowledge of the system temperature(s) of the calibration antenna(s). In the Gibson and Welch (2003) experiment, waveguide loads at known temperatures (70K and 300K) could be switched into the receiver of one antenna to establish the system temperature.

As part of the flux measurement, an accurate atmospheric extinction measurement must be made. In the 28.5 GHz experiment, tipping curves for the BIMA antenna were used and calculation from meteorological variables (radiosonde) was used. They agreed, and, in any case, the total correction was only 3\%, so there was confidence in the result. It will be more difficult at higher frequencies, and one of the goals of the 110GHz experiment is to study how best to make this correction. Probably the best way to do the extinction correction is to use the standard gain horn with a backing shield to make the tipping measurement. This is the scheme adopted by ground based measurements of the

CMB in the past, and good accuracies were obtained. Precise patterns can be calculated for the horn so that correction for the effect of the finite beam size can be readily made. The other advantage of doing the tipping with the standard horn is that its system temperature will be accurately known.

There remains the problem of getting an accurate system temperature for one of the ACA antennas so that it can measure an accurate flux from the Planet. It may be possible to transfer the system temperature from the horn to one of the ACA antennas. If this cannot be done, it may require building both a hot and a cold load that can be put in front of the ACA antenna to calibrate it. Once this is done, the flux of the planet can be measured.

2.3.1.3. Flux Calibration Transfer

The next step is to transfer the measured flux of the planet to the whole ACA. At this point there is no clear plan of how to get accurate system temperature measurements for any of the antennas. Suppose that they are all equipped with an ambient flap at the vertex that would permit the usual chopper wheel calibration. Experience shows that this gives a system temperature calibrated flux with built in extinction correction with an accuracy of 5-10%. If all the antennas are identical including their flaps, they should all have the same amplitude error. A map made of a source should be correct except for its amplitude. Making an image with the ACA of the planet used in the above measurement would then provide an overall calibration of the ACA, since the planet's flux is known accurately. This step would require an atmospheric extinction correction, and that can be supplied by the horn.

Other source fluxes could then be measured accurately by the calibrated ACA, including extinction corrections. This work would have to be done in good weather for the extinction corrections to be reliable. The compactness of the ACA insures that atmospheric phase fluctuations are largely not a problem. In particular, the fluxes of compact sources planned for phase calibration of the large array could be accurately determined in advance. If the large array is then equipped with chopper wheel absorbing flaps that produce identical although uncertain scalings of all the system gains, then an observation will produce a map which is only incorrect in its overall scale. The phase calibrator which is nearby with its known flux then permits a rescaling of the mapped source. To the extent that the phase calibrator is only a few degrees away, only a small extinction correction will be needed in the rescaling.

2.3.2 Required Special Hardware

The main special equipment is the calibration horn on a separate mount with its receiver similar to the other receivers. In fact, there must be a horn and receiver for every band. The mount could be simpler than the ACA mount, but it might be easiest to just copy the

ACA mount. There must be dual loads that can be carefully coupled to each horn for the basic horn system calibration. Such loads have been successfully built for early CMB experiments. Except for possibly one pair of calibration loads for one ACA antenna (for each band), the only requirement for all the other antennas is the standard "chopper wheel" flap, which can be located at the vertex window, so that it works for all bands. The mount with the horns is a separate piece of equipment which could be added to the ALMA system at any time. It should be located very close to (perhaps in the middle of) the ACA. There probably is no money budgeted for this item. On the other hand, if the standard flap calibrator is all that is needed on all of the other antennas, the calibration expenses are quite small for the other antennas.

2.3.3 Frequency of Calibration

The antenna gain calibration need not be done very often, perhaps only when the antennas are serviced and receivers are changed out. Experience will be the judge here. Source flux calibration will need to be carried out more often. Some of the planets may be sufficiently stable in some bands that they need not be re measured frequently. The phase calibrators are quite variable and will need to be done frequently. However, they are bright and the ACA is very sensitive, and only a small amount of time will be needed for their calibration, perhaps a few percent.

2.3.4 Time Required for Amplitude Calibration Measurements

An antenna gain measurement should take about an hour for good statistics. Since the phase calibrators will be mostly 300mJy or more, an observation of 1000 seconds (15 minutes) with another 15 minutes for the tipping curve should be adequate. Altogether very little time from the ACA will be required.

2.3.5 Archiving Needs

All of the gains and fluxes should be archived; these will constitute a compact dataset. The phase calibrators can change more than a percent in a day, so they will need to be monitored. This material should be online. ALMA personnel, probably at the ARCs, will be assigned to track calibrator fluxes for the ALMA Calibrator Database.

2.3.6 Further Tests

As noted above, further tests of the technique are planned to be carried out at BIMA in May of 2004. This will be a calibration of a BIMA antenna at 110GHz (possibly also 90 GHz) of both the waveguide method and the closure amplitude method. Based on the results from the 28.5 GHz experiment, 1% accuracy is reasonable accuracy goal.

2.4 Amplitude Decorrelation Correction

Decorrelation, a reduction in the amplitude of an averaged complex visibility by phase cancellation over the course of an integration, is half the reason for the battle for accurate compensation for the atmospheric and electronic phase fluctuations. If our integration times are very short, each visibility will not suffer much from decorrelation, but the phase of each visibility will be incorrect, resulting in imaging errors. It is possible to correct these phases after the fact (self-calibration, fast switching, WVR), but if they are not corrected, we will end up gridding several visibilities onto the same (u,v) cell in imaging, effectively averaging them, resulting in decorrelation in spite of the short integrations.

To put the magnitude of the problem of decorrelation into perspective, the median phase from the 11.2 GHz phase monitoring interferometer with a 300 m baseline is 3.3 degrees rms. Scaled to 230 GHz, this results in 103 degrees rms, which will result in a coherence of only 0.50 if we do nothing to compensate for the atmospheric phase fluctuations. Of course, things are worse at higher frequencies and on longer baselines. Obviously, we need some sort of active phase correction.

With a cycle time of 20s, fast switching phase calibration will effectively remove atmospheric phase fluctuations on time scales of about 10~s or greater (interpolation effectively moves us below the cycle time). However, decorrelation will be a problem, even on these short time scales. Holdaway (ALMA Memo 403, 2001) finds that after fast switching, the residual phase errors will typically result in a coherence of 0.90, though low elevation observations will do worse. The real problem comes from the fact that the atmosphere's phase fluctuations are not statistically stationary. Over some integrations the coherence will be high, around 0.95. However, there will sometimes be extreme phase events which occur on some integrations on some baselines, reducing the coherence to 0.8 or 0.7 for short periods of time.

If the atmospheric phase errors were statistically better behaved, we could perform a very simple correction for decorrelation. Total power observations will not suffer from decorrelation, and we could observe a compact source, such as a bright quasar, with both total power continuum and with the interferometer (with integration times typical of the target source observation, which are subject to decorrelation, rather than with short integration times which seek to beat the decorrelation). By requiring the interferometric observation to have the same flux as the total power observation, in one step we correct for the decorrelation and set the flux scale of the interferometric observations to that of the total power observations.

A similar strategy can improve the decorrelation for the non-stationary atmospheric statistics we must live with, where the decorrelation varies with baseline and time. Since we are observing a compact calibrator source every 20 s with enough SNR to adequately solve for the antenna-based phases, we can construct the baseline-based phases as the difference of the antenna phases (there would not be enough SNR to just take the raw baseline- based phases), and we can infer the approximate decorrelation experienced by the target source data from the statistics of the baseline-based calibrator phases over a moving boxcar interval covering 4-6 fast switching cycles. The rms phase for each baseline is calculated for all calibrator observations within the window, the decorrelation factor of *e-(J~/2* is calculated for each baseline, and the target visibilities at the center of the boxcar interval are amplitude corrected by dividing by the decorrelation factor. The full rms phase over the 4-6 switching cycles needs to be reduced to account for the fact that we ware just asking about the decorrelation on a single target source integration (ie, 17 s).

A preliminary version of this decorrelation correction algorithm, applied to simulated data, was very effective in fixing the average decorrelation: instead of 0.90 coherence, the flux scale was returned to 1.00 (ie, less than 1% error in the flux scale due to decorrelation). While this technique does the right thing on average, using a 80-120 s boxcar window to adjust for phase flucuations occuring on a 17 s integration in the middle of that window will obviously not be right in detail, and at times will overcorrect and at other times undercorrect for the decorrelation. The effect of making these errors in the details is to scatter flux about the image (ie, the visibilities aren't agreeing with each other: some say the flux is higher, some say it is lower, and the result is that the imaging gets it right on average at the position of the source, and the disagreements get splattered across the image at a lower level like the point spread function). This error process ends up decreasing the dynamic range to only a few hundred to one.

We obviously need to come up with a better approach to the decorrelation correction, as we do not want to have to degrade the dynamic range to achieve the correct flux scale.

One great hope for improving the decorrelation is water vapor radiometry (WVR). WVR will work on time scales of 1 s (it has enough sensitivity in 1 s to result in 25 microns of path length error). However, at 950 GHz, 25 microns per antenna of path length error results in a coherence of only 0.78. (During the best conditions, fast switching will do better than WVR because there is no noise floor as with WVR.) Unlike the atmospheric phase fluctuations, the noiselike phase fluctuations introduced by the WVR will be pretty random, and should have similar statistical properties for a long time. Hence, phase errors on longer time scales will be corrected for while the decorrelation from the short time scale noise-like phase errors can be simply corrected by observing a compact source in both total power and interferometrically.

For most observing frequencies and atmospheric conditions, WVR does hold the prospect of substantially reducing the decorrelation, but WVR is somewhat unstable on the longer time scales. We need to understand how to tie together the short time scale corrections of WVR and the longer time scale corrections of fast switching. If we can effectively do this, then decorrelation can be taken care of reasonably well.

2.4.1 Required Special Hardware

The Water Vapour Radiometers (WVRs) are required for the decorrelation correction.

2.4.2 Frequency of Calibration

Correction for amplitude decorrelation will need to be made on time scales from 1 to 20 seconds.

2.4.3 Time Required for Amplitude Calibration Measurements

The decorrelation correction will not take any additional calibration time, but will use data already being taken for fast switching, flux scale calibration, or WVR.

2.4.4 Archiving Needs

All the raw data which will be useful for making the decorrelation correction will automatically be archived: the data taken on the fast switching calibrator, data taken on a flux scale calibrator, and WVR data. If we are applying a decorrelation correction to each visibility, we probably what to note that correction in a table associated with the visibility data so it can either be corrected on the fly, or if it is used to alter the visibility data, permit the correction to be undone.

2.4.5 Further Tests

The big hope for dealing with decorrelation is to make WVR work well in conjunction with fast switching, which is mainly in the scope of phase calibration.

3 Phase Calibration[3]

The goal of phase calibration is to measure atmospheric and instrumental delays which corrupt the incoming wave front from a celestial source in order to form the best possible image of that source. Quickly varying (compared to the timescale of one integration or calibration cycle) phase causes a loss of signal usually called ‘incoherence’. Instrumental phase should be stable on timescales of many minutes; if uncorrected systematic errors will arise in the determination of the absolute visibility. Therefore calibration to measure slowly varying phase components may be achieved by periodic observation of astronomical point sources. Contributions to slowly varying phase include changes in the distance between the subreflector and the feed, and the stability of the LO and other

---

[3] Original contributions by Hills, Holdaway, Wootten.

electronics. A goal of the ALMA design is that its contributions to systematic error and to shorter term error, incoherence, should be well below those of the atmosphere under good observing conditions and after all available corrections have been applied ([AD3], §3.1.1.2). This section therefore focuses first on determination of correction for atmospheric delay.

At millimeter wavelengths, the main atmospheric constituent which causes phase errors is inhomogeneously distributed water vapor. The water vapor varies on all scales but is effectively smoothed to the timescale of a crossing time of an antenna diameter, or a second or so. Measuring and removing atmospheric phase errors constitute one of the major challenges to ALMA calibration. As the ASAC stated in its September 2002 report, 'most of the exciting science cannot be done without the successful functioning of the phase correction scheme. Making this scheme work will also make the periods of good transmission but poor phase noise usable.'

Most of the time at Chajnantor, phase stable observations are possible only for long wavelengths or short baselines. To achieve the ALMA performance goals, compensation for atmospheric phase fluctuations will be necessary much of the time for millimeter wavelengths and modest baselines and most of the time for submillimeter wavelengths and long baselines.

In [AD3], it is noted that soundings with water vapor radiometers suggests that a reasonable goal for defining atmospheric contributions under good observing conditions can be established at the 95% level[4] in the joint distribution of phase stability and water vapor content. This distribution is fairly well established from many years of site characterization data; analyses may be found in ALMA Memo No. 471 and LAMA Memo No. 801. As discussed in [AD3], adjustment of zenithal values to 45° elevation yields 0.96mm of precipitable water vapor and 143 fsec rms delay fluctuations within ten minutes on a 300m baseline as the atmospheric conditions appropriate to defining the best 5% conditions.

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. In section 3.1, fast switching is described. This technique can remove

---

[4] In Memo 471, *stringency* is defined as $S = t_a/t_p$, where t_a is the total available time and t_p is the total time during which the conditions for the observations are met; for a project needing 5th percentile weather, the stringency S~20.

residual short-term (tens of seconds) fluctuations. In section 3.2, the technique of water vapor radiometry, which particularly targets fluctuations down to scales of 1 second, will be described. Optimal incorporation of both strategies into actual observations will be a feature of the ultimate phase calibration strategy; a preliminary discussion may be found in the final section 3.3.

3.1 Description of Fast Switching Phase Calibration

Fast switching phase calibration is a technique which tracks atmospheric phase fluctuations as quickly as is reasonable by slewing the antennas to a nearby suitable calibrator source, detecting it with sufficient SNR, and then slewing back to the traget source. It is planned that the calibrator will be observed at ~90GHz where the quasars are still fairly bright, and the detected phases will be scaled to the target frequency. The details of the length of integration are determined by the brightness of the calibrator and the ratio of the target frequency to the calibration frequency. The overall cycle time is determined by an optimization between minimizing the time lost due to calibrator observations (*i.e.*, maximizing the time on source with long cycle times) and minimizing the decorrelation due to residual phase errors (*i.e.*, pushing towards more frequent calibrations and shorter cycle times).

In addition to the frequent fast switching phase calibration observations, we must perform a less frequent cross-band phase calibration if the target source observing frequency and the calibrator source observing frequency are not the same. We would like for the phase of the electronics and the physical structure of the antenna to be stable enough of to require this cross-band calibration only once every 5-20 minutes.

3.1.1 Extra Hardware for Fast Switching

Fast switching requires no extra hardware at this point. Fast switching was the main motivator for the antenna specification that the antennas be able to move 1.5 deg and settle down to 3 arcsec pointing in 1.5 seconds. Fast switching also requires fast switching between observing bands, and the requirement that 90 GHz always be available. Stability across bands from the target frequency to the calibration frequency (90GHz) is required. Also, the online system needs to be able to handle the data coming in, with calibration observations of less than a second and target source observation of 20 seconds, or potentially much longer if WVR is used in conjunction with fast switching.

3.1.2 How Often Will Fast Switching Be Performed?

ALMA Memo 403 (Holdaway, 2002) presents the latest results of numerical simulations on fast switching phase calibrations. These simulations have been updated in LAMA Memo 803 (Holdaway, 2004). The switching cycles were optimized to maximize sensitivity (including time losses due to calibration and decorrelation from the residual phase errors). The optimal cycle time is a strong function of the atmospheric conditions and the observing frequency. However, if we match the high frequency observations to the best atmospheric conditions, then the cycle time comes out to be typically 20 seconds for all frequency bands. At times, cycle times as short as 15 seconds or as long as 30 seconds may be optimal.

It is hoped that WVR will extend the time between fast switching calibrations to something more like 60-300~seconds, but this has not been studied enough to say how well that will work.

3.1.3 How Often Will Cross Calibration Be Performed?

We hope that we do not need to perform the cross band phase calibration any more than once every 20 minutes. At the higher frequencies, it is quite possible that the electronics will require more frequent cross-band calibration. Of course, at the highest frequencies, suitable cross-band calibrators are rare and weak at the target frequency, so we will need to observe them both more often and longer. We need to perform calculations to ensure that we are not in a situation where we have to spend 100% of the time performing the cross-band phase calibration.

3.1.4 How Long Will Fast Switching Calibration Take?

As a general rule, antenna motion for fast switching will take between 1 and 1.5 seconds, one way. I report some specifiics for 60 degrees elevation angle. At 37 GHz, bright calibrators (0.06 Jy) are always close by (0.65 deg), and it typically takes about 1.1 s to reach the calibrator according to the antenna slewing model in Holdaway 2002a. The calibrator will be detected with sufficient SNR in about 0.02 s! At 650 GHz, the typical calibrators (at 90 GHz) are 0.23 Jy, about 1.5 degrees away, the antennas reach the calibrator in 1.5 seconds, and the desired sensitivity is reached in 0.38 seconds.

Freq (GHz)	T_{slew}	T_{cal}	$2*T_{slew}+T_{cal}$
37	1.7	0.018	2.16
81	1.19	0.047	2.43
113	1.19	0.062	2.44
157	1.26	0.095	2.62
209	1.32	0.118	2.76
271	1.34	0.167	2.85
355	1.40	0.218	3.02
415	1.45	0.266	3.17
650	1.54	0.376	3.46

Even though there is a huge difference in the time it takes to observe the calibrator with sufficient SNR as you increase in frequency, there is only a mild increase in the fast switching time with frequency because the time is dominated by the slew time, which varies mildly with frequency.

3.1.5 How Long Will the Cross-calibration Observation Take?

This is a matter to investigate once we know more about the source counts at the higher frequencies. We can probably make an estimate of this now.

3.1.6 What Needs to be Archived?

Fast switching requires that a good database of calibrators exist. We will need to archive the fluxes of any potential calibrators that we do a quick observation of to test if they are suitable for fast switching calibration or cross-band phase calibration.

The calibration and imaging pipeline will perform phase solutions with the calibrators. We will need to share these solutions with the dynamic scheduling algorithm so that an accurate assessment of the atmospheric phase stability can be made.

3.1.7 Further Work for Fast Switching:

There is actually enough further work required to make fast switching work well on ALMA that there should be a single person appointed to be the FAST SWITCHING CZAR. Fast switching will not be their only job, and other people will contribute to the fast switching effort, but having a single person coordinate the fast switching work and keep abrest of all fast switching tests and developments would be important for success of fast switching.

* Testing the ALMA prototype antennas to ensure that they meet the fast switching spec (1.5 deg in 1.5 seconds, with 3 arcsec residual pointing error). Also, derive a model for the switching time as a function of switching distance and permitted residual pointing error, in az or in el. And last, when the test interferometer is running, verify that the antenna phase does not bounce when the antennas switch.

* Compilation of calibrator source databases. We are aiming to have a calibrator within a degree (or less) of the target source. Hence, we expect the fast switching calibrator database to contain on the order of 100,000 sources. A first stab at this list could be made by selecting all compact sources brighter than 25 mJy at L Band from the NVSS database, and searching all large databases at higher frequencies (5 GHz for example) to get spectral index information to reject steep spectrum sources. Any source which survives this technique is a potential fast switching calibration source, but interferometric

observations at 90 GHz would be required to confirm a source from this list to be a viable calibrator. The confirmation process will be performed by ALMA, probably just in advance of the target source observations.

* Calculations to determine the highest frequency that will permit fast switching calibration at the target frequency. A first guess can be made now, but we probably need to study the spectral steepening of quasars at high frequencies to determine this with any accuracy.

* Writing observing scripts which search the database for potential nearby calibrator sources and do a quick check on them to determine which cal source is optimal for the target source. We could also perform quick observations at the higher frequencies to determine what frequency is optimal for calibration. The optimal calibrator will minimize the residual phase errors. We currently have simple algorithms for selecting the optimal calibrator, ie, minimizing v_{atmos} * t_{cycle} + d. Usually, the ``d'' parameter is unimportant compared to the vt term (in part because the cycle time depends upon d indirectly -- sources further away will require longer slew times to reach). A more complicated algorithm for selecting the optimal calibrator could be generated which included the source brightness, the source compactness, the accuracy of the knowledge of the position of the source, the proximity to the target source, the elevation angle of the cal source, the orientation of the cal source and the target source to the wind direction, the atmospheric velocity magnitude, the antenna switching rate, and the ALMA sensitivity. A detailed software model of the time it takes the antenna to slew a given distance in (az, el), including settle down time and on-line system latency must be generated.

* Fast switching with the cal and target source at different frequencies has never been tested. This technique could be tested right now on the VLA, calibrating at K band and observing at Q band.

* Compilation of a shorter list of sources suitable for cross-band calibration. These sources must be bright enough at the target frequency to permit detection at both the target frequency and the cal frequency in a time short compared to the atmospheric coherence time.

An estimate of the number of appropriate cross-band calibrators for each band could be made by searching the literature for the high frequency spectral index of flat spectrum quasars, and the application of this spectral index distribution to the 90~GHz source counts. Knowledge of the number of suitable cross-band calibrator sources would help in setting specs for how far on the sky the antenna must remain phase stable.

Even if only WVR is used for phase correction (and not fast switching), we will still need these sources for the calibration of the electronic phases.

* Study of optimal interpolation. Interpolation can reduce the residual phase errors substantially for fast switching. For example, if the phase errors occur largely in a thin phase screen, then selecting a calibrator which is either upwind or downwind of the target source, and performing a delayed or advanced interpolation, will decrease the residual errors or permit a longer cycle time. With a more realistic 3-D distribution of turbulent water vapor, this will still work, but not as well. In order to perform the delayed or advanced interpolation, we need to have an estimate of the height of the turbulent layer and the velocity of that layer, or at least the ratio of these, h/v. The optimal delay, along with a measure of the improvement that can expected, can be measured by performing fast switching between two calibrators and determining the delay that minimizes the residual phase errors. It is unclear at this time if this delayed/advanced interpolation technique will improve fast switching enough to justify spending time doing the short observation to calculate the optimal delay.

Study of optimal interpolation could proceed on the VLA.

* It is not clear how fast switching and Water Vapor Radiometry (WVR) will be used together. The general idea is that WVR does not measure the absolute phase, but can track the relative phase. If we are able to reset the absolute phase to something close to zero at the start of each fast switching calibration cycle by observing the calibrator, we should be able to track the relative phase via WVR. As time passes, the accuracy of the relative WVR phase will decay, and we'll need to go back and do another fast switching calibration cycle. This joint calibration technique should reduce the residual phase errors and extend the cycle time, both of which will result in higher sensitivity observations on the target source. The biggest problem in this joint technique is that the phase calibrator will be at a different elevation angle than the target source, so resetting the WVR phase at the start of the calibration cycle will be problematic, and we will need to compensate for the jump in WVR signal at the target source elevation. Obviously, selecting a cal source at the same elevation as the target source will reduce this effect. A bias towards cal sources at a similar elevation to the target source at the cal source selection phase should improve this situation.

* We need to do some phase measurements towards the edges of the 650 and 850 GHz windows to determine if the ATM atmospheric propagation model's prediction of dispersive phase is correct or not. Both fast switching and WVR will depend upon the accuracy of the dispersive phase predictions from a propagation model such as ATM.

This work will probably need to wait until ALMA is built.

3.2 Water Vapor Radiometry

Fast switching, operating over finite time periods, will not remove short term fluctuations imparted by the atmosphere. Water Vapor Radiometry determines the amount of water vapor above each antenna radiometrically, in our case at frequencies bracketing an atmospheric water line, and calculates the phase by dead reckoning. A water vapor radiometer located at each antenna focus must be able to provide sufficient information to give a reliable estimate of the phase delay suffered by the astronomical signal arriving at the antenna. The Owens Valley Radio Observatory (OVRO) millimeter-wave interferometer is investigating one method to correct for rapid phase fluctuations by monitoring the 22.2 GHz atmospheric water vapor line along the line of sight of each telescope. By calibrating the fluctuations in the amount of water vapor to the corresponding change in astronomical phase, the astronomical phases can in principle be corrected on time scales of seconds. Experiment showed that phase-corrected images could be obtained, with residual path delay of ~100 μm achieved. Recently, the Very Large Array began installation of the first of a series of 22.2 GHz radiometers for this purpose. At high dry sites, the low opacity of the 22.2 GHz water line offers insufficient leverage for correction to low levels of path delay. Better correction might be achieved by using the atsmopheric water line at 183 GHz. Furthermore, the high frequency ALMA optics could not easily accommodate the beam for a 22.2 GHz radiometer. The JCMT-CSO single-baseline interferometer was the first to demonstrate phase correction using the 183 GHz line, using equipment built by Martina Wiedner, Richard Hills and colleagues. Only a limited quantity of data were gathered but the results (ALMA memo 252) were encouraging and suggested that even an uncooled system could provide effective phase calibration at submillimetre wavelengths.

The WVR system will provide a measurement allowing correction of the atmospheric path, but some residual errors will remain. A major portion of this is the uncorrected error of 10(1 + wv) microns of path, rms, (where wv is the precipitable water vapour along the line of sight measured in millimeters) given as a specification in the WVR contract, as discussed in ALMA memo 303. This should be achieved (FEND-40.07.00.00-001-A-SPE) with a time resolution of 1 second and be maintained over time periods of up to 1 minute and for changes in zenith angle of up to 1 degree[5]. For the 5th percentile conditions this specification equals 19.6microns (65.3fs) for the 5th percentile conditions adopted in the System Design Description. The WVR beam on the sky will be aligned with that of the observing receiver to within 10 arcmin.

---

[5] These latter numbers are related to the need to make observations of reference sources from time to time. Note that it is actually the change in air mass that is likely to be important rather than just the change in zenith angle so perhaps a 3% change in secant z would be more sensible.)

The residual errors will include a term proportional to the uncorrected path fluctuation, to allow for the uncertainties in the atmospheric conditions and modelling and the errors in the calibration of the radiometers; this term has been set at 2% of the uncorrected path fluctuation, to allow for the uncertainties in the atmospheric conditions and modeling and the errors in the calibration of the radiometers.

Lastly, of course, the residual errors will include a term due to phase fluctuations not measured by the radiometer at all—'dry' air fluctuations originating in thermal variations along the path. This component is expected to show a diurnal component as convection is driven by solar heating during the afternoons. During the best conditions at night some information on the size of these fluctuations may be obtained from optical interferometer measurements. A first examination of a small set of data suggests a value of 10microns (33fsec) is not unreasonable for this component. Adding these terms in quadrature provides the 75 fsec short term residual adopted in [AD3].

3.2.1 Additional Hardware

ALMA Memo No. 352 describes the plans for the development of the prototype 183 GHz radiometers for ALMA. One radiometer will be mounted on each of the antennas and will provide real-time measurements of the brightness temperature of the atmosphere at frequencies near the 183 GHz emission line of water. Water vapor radiometry includes an element of atmospheric modeling. The Atmospheric Transmission at Microwaves software provides the most accurate modeling available for the conditions of interest; this software is currently available to ALMA and in use by members of the Science IPT. Other codes exist, such as the SAO Submillimeter Receiver Laboratory's *am* code. Ancillary instrumentation is needed to provide input for modeling. A description of this instrumentation (SCID-90.05.13.00-001-A-SPE) is available; the draft ICD between these instruments and the Site is also available (SCID-90.05.13.00-001-A-SPE).

3.2.2 Frequency of Calibration

Water vapor radiometer measurements will be obtained every second. Within the Correlator software system, current plans envision the Correlator Data Processor using WVR data to remove atmospheric phase fluctuations from the data on .5s timescales.

3.2.3 Time Required for Calibration

The sensitivity of the WVR system is such that sufficient sensitivity is attained in 1s for the WVR correction. Observation of a bright source for instrumental calibration occurs on several minutes timescales.

3.2.4 Archiving Needs

This needs to be addressed.

3.2.5 Further Tests

Tests are planned for the prototype systems at the ATF. The selected WVR device will be deployed at the ATF as soon as the test interferometer is phase stable in early 2005. Operation at this site is viable only during the driest winter months when precipitible water vapor falls below 2-3mm (VLA Memo 232). The evaluation receivers have been demonstrated at frequencies as high as 265 GHz but the available baseline is only 35m. Tests at the ATF would demonstrate integration of the WVRs into the system.

3.3 IRMA

An Infrared Radiometer for Millimeter Astronomy, IRMA, is being developed at the University of Lethbridge in Canada. Testing at the Submillimeter Array (SMA) will occur soon. At present, IRMA is not part of the ALMA Calibration Plan.

4 Bandpass Calibration[6]

The bandpass calibration is the measurement of the time-independent frequency response of the instrument (in amplitude and phase) including the atmosphere. The bandpass calibration accuracy is limited by the changes with time of this frequency response. While the electronic part can be made stable by proper design and operation (including temperature control), the atmospheric variations can only be modeled. Bandpass accuracy will thus depend on the precision of this modelling. The antenna chromatism must also remain small: standing waves should be minimized by appropriate shaping of the sub-reflector as described in ALMA Memo #457.

In ALMA Memo #XXX (Bandpass calibration for ALMA, draft submitted), Bacmann and Guilloteau show that the best bandpass accuracy is obtained when the amplitude calibration is applied in a single-load scheme. The proposed scheme is a variant of the so-called bandpass normalization technique. It uses normalization by the difference between the sky emission and the load emission, rather than normalization by the auto-correlation spectrum in the usual case. Bandpass calibration should be performed at the observing frequency. It will be limited by the knowledge of the sideband opacity difference. This knowledge can be based on a model, but a direct measurement is also possible, although time consuming.

Whenever the correlator is configured into narrow bands, it can be advantageous to perform the bandpass calibration in two stages, one in broad band, the other in narrow

---

[6] Original contribution made by A. Bacmann.

band, to improve on the accuracy of the atmospheric modelling. The bandpass calibration makes direct use of the known properties of the digital filters. The response (in amplitude and phase) of these filters will have to be calculated (and if possible measured once in the laboratory) to be inserted in the calibration software.

The bandpass calibration must be performed on strong point-like sources, of known spectral index. The knowledge of the spectral indexes will be a limiting factor in the wide band modes. Building up a database of suitable sources will be necessary, since the knowledge of these spectral indexes could be improved by bootstrapping techniques among several sources. Since astronomical sources have to be used, the required integration time varies substantially as a function of frequency. High accuracies can be reached in a minute of time at mm wavelengths, but integration time as large as an hour can be needed at sub-mm wavelengths. Occasional direct measurements of the sideband opacity difference could also be used to improve the accuracy of the atmospheric modeling.

4.1 Ancillary Hardware

No special widget is required (standard dual-load calibration device), however refracting cones on antennas to minimise standing waves are desirable.

4.2 Frequency of Bandpass Calibration

The calibration should be performed once per project for each correlator setup.

4.3 Length of Time Required for Bandpass Calibration

The bandpass calibration will take periods of time from ~10s to 50 min depending on frequency.

4.4 Archiving Requirements

Amplitude and phase response of each channel for each sideband (or a suitable function of the frequency) must be archived whenever the calibration is performed.

4.5 Interaction with Other IPTs

No ICD is required with other IPTs, but the description of the algorithm will be required for implementation by the Computing IPT.

4.6 Further Testing

Tests should be carried out during commissioning and early science. Tests on other telescopes (e.g. IRAM) are possible, but would require specific software development and test time to be funded. Accuracy will be limited also if testing is performed at IRAM. Tests are best performed at the ATF with the prototype correlator on the ALMA prototype antennas with a full set of ALMA hardware.

5 Polarization Calibration[7]

5.1 General Polarization Calibration Issues

ALMA will use linearly polarized feeds because they have a wider usable bandwidth than circularly polarized feeds, and can provide complete coverage of all millimeter wavelength atmospheric windows with a reasonable number of receivers. Cotton (1998) treated the problem of polarization calibration for the MMA in detail. A more recent treatment for ALMA can be found in Appendix C to the Report of the ALMA Science Advisory Committee March 2000 Meeting. The general problem of calibrating polarization in interferometry has been described fully by Hamaker, Bregman and Sault [RD7], [RD8], who develop a Jones matrix approach (for an earlier similar approach, see Schwab [RD4]). The main detail that we must be concerned with here is that the measurement of linear polarization is corrupted by contamination from Stokes I. For linearly polarized feeds, this corruption is in the form of a gain stability term (as opposed to circularly polarized feeds, where the corruption arises from a leakage term). Another point of note is that it is not easy to distinguish circular polarization from the instrumental polarization terms when using linearly polarized feeds. We first consider the dominant on-axis instrumental polarization (e.g. that exhibited in observations of a point source in the center of the field), then generalize to dealing with the instrumental polarization over the entire primary beam (e.g. needed for observations of extended sources and for mosaicing).

For linearly polarized feeds, two (presumably) orthogonal polarizations X and Y are measured, with X and Y oriented at some angle in the focal plane of the telescope (e.g. with X aligned with the elevation axis). After correlation, four products are available: XX, YY, XY, YX. To linear order in the instrumental polarization terms, these products relate to the Stokes parameters by the relation:

(1) XX = 0.5*g_X1*g_X2*[I + Q*cos(2*chi) + U*sin(2*chi)]
YY = 0.5*g_Y1*g_Y2*[I - Q*cos(2*chi) - U*sin(2*chi)]
XY = 0.5*g_X1*g_Y2*[(d_1X-d_2Y*)*I - Q*sin(2*chi) + U*cos(2*chi) + i*V]
YX = 0.5*g_Y1*g_X2*[(d_2X*-d_1Y)*I - Q*sin(2*chi) + U*cos(2*chi) - i*V]

---

[7] Original contributions by M. Holdaway and S. Myers.

where the g are the instrumental gains and d are the polarization leakages, and chi is the parallactic angle (this assumes all feed have the same focal plane orientation). Note that if the gains are known accurately, then the intensity I can be recovered by observing the two parallel hands,

(2) $XX + YY = I$

with the error proportional to the linear polarization and the gain errors. In the absence of any source linear polarization Q,U it is even simpler as either of the parallel hands is a proxy for I. Note that unless the observations are made over a range of parallactic angles chi, one cannot separate Q and U with only parallel hands (chi=0 only gives Q), with

(3) $XX - YY = Q*cos(2*chi) + U*sin(2*chi)$

for a gain-stable system. Circular polarization is obtained by differencing the cross-hands,

(4) $XY - YX = d*I + i*V \qquad d = 0.5*(d_1X - d_2Y^* - d_2X^* + d_1Y)$

again assuming stable gains. Note that a fraction of I given by the polarization leakage shows up as an error in V, so to meet the 0.1% spec one needs d-term calibration stability upon calibration transfer of 0.1% (this does not imply the magnitude of the d-terms need to be 0.1%). In both cases, differential gain instability shows up directly as a limitation on the polarization determination (e.g. the spec of 0.01% on gain fluctuations and 0.05% on the difference between polarizations on a given antenna).
In the absence of gain errors,

(5) $XY + YX = e*I - Q*sin(2*chi) + U*cos(2*chi)$
$e = 0.5*(d_1X - d_2Y^* + d_2X^* - d_1Y)$

and thus if the leakage is calibrated (and I known), then for a single parallactic angle chi the system of equations given by XX-YY and XY+YX can be solved for Q and U. Obviously, for a calibrated system, with g's and d's known, then the system XX,YY,XY,YX can be solved for I,Q,U,V.

For the calibration stages, the matrix form of the full (not linearized) equations are used (see the Hamaker et al. papers) which are solved iteratively using the difference between observed and model visibilities. This is the implementation in the ALMA Offline AIPS++ software. The quantities that must be solved for in the equivalent of eq.(1) are the antenna gains G (two complex matrix elements per antenna) and the leakages D (two complex matrix elements per antenna).

Thus, because the linear polarization is entangled with the total intensity, and in general many sources exhibit linear polarization at the percent level, there are many times when all four cross correlations per baseline will need to be performed, which will reduce the available bandwidth by a factor of two and the sensitivity by root two. We consider several ALMA use cases which 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.

Case 1: Amplitude calibration is performed by knowing precisely the gains and system temperatures of the antennas (not by looking at an astronomical source), and phase (delay) calibration is performed on a quasar (or a combination of radiometric [WVR] 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 linear polarization of the calibrator will not affect the phase, only the amplitude.
Note here that we are only concerned with imaging, as the calibration is known.

We further consider the subcases:

Case 1.1: 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 (see above).

Case 1.2: 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.

Case 1.3: 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.

Case 2: Amplitude calibration is performed by assuming the flux density of some astronomical sources is known precisely, and using measurements of that source to set the voltage to flux density conversion scaling. If the source of flux density 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. In this case, we are dealing with imaging of the calibration sources in order to arrive at a calibration solution.

There are several options:

Case 2.1: 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.

Case 2.2: 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 on the quasar, even if there is no interest in polarization. Full polarization observations of the source are only needed if desired. 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, 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 (it does not calibrate the portion of the offset which occurs before the IF). 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 density 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 density 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 general 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 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 ALMA, time constant instrumental polarization is certainly an important design goal. An analysis of the cause of the VLA unstability would also be useful.

One way around the complication of good parallactic angle coverage is to use sources of known polarization (one special case of which is totally unpolarized sources). Holdaway, Carilli, and Owen (1992) have demonstrated that it is possible to solve for the instrumental polarization for a singlesnapshot, (i.e., 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. Unfortunately, such sources are currently completely unknown at millimeter wavelengths - all quasars have variable polarization angle. Perhaps sources with emission dominated by dust (which is polarized) or planetary observations will suffice, and should be investigated as part of the commissioning or verification phase (or earlier on existing millimeter arrays). Some study of what level of polarization is acceptable as "unpolarized" is also warranted, as the symptom of source polarization in d-terms is an offset (which may be easily calibratable later in the processing).

5.2 Description of Polarization Beam Calibration

Because the polarization response of the telescope varies across the primary beam, there is an "off-axis" leakage pattern that must be dealt with in addition to the "on-axis" leakage described previously. As in the on-axis case, this manifests as a corrupting leakage of total intensity flux into the cross hand visibilities. For "classic" synthesis observations of small sources near the beam center, the polarization primary beam is not an issue. However, as many as 50\% of ALMA's observations may require mosaicing ie., the source fills the primary beam), so there must be a strategy for dealing with the effects of the polarization beam for ALMA's polarization observations.

As an example of the magnitude of the effect, for the VLA the polarization beam (ie., the apparent fractional polarization which an unpolarized source observed off-axis would show) is about 5\% in amplitude at the primary beam half power point. In a linear mosaic constructed by summing dirty images apodized by the primary beams, an unpolarized source which sat at the half power point of one pointing would be near the center of an adjacent pointing (where the polarization beam is essentially zero if the on-axis polarization calibration has been done correctly). So, the first pointing's image, after multiplying by the primary beam, would show an apparent polarization in that source of 2.5\%, and the second pointing would show no polarization. After adding the images together and normalizing, the apparent polarization of that source would be about 1.25\%. However, other factors will reduce this spurious polarization signal more: if we observe for more than just a snapshot, the polarization beam will rotate on the sky, and the source of interest will sample the beam at a different level. For the VLA, the spurious polarization can be reduced by another factor of 2 this way, to approximately the 0.5\% level. For many polarization projects, observations with 0.5\% rms errors in fractional polarization will be acceptable. The VLA can often achieve this level of error without doing anything beyond on-axis polarization calibration (Dubner et al.\ 1996, AJ, 111, 304).

In general, if the polarization beam magnitude is ϵ at the half-power point, it is reasonable to expect the errors in polarization at the half power point (in the absence of very bright sources) to be of order $\epsilon / 8$. If there are bright sources of flux $I_{\circ}$, one can expect polarized flux to be scattered from this source at an rms level of about $I_{\circ}\sigma_{PSF} \epsilon / 8$, where σ_{PSF} is the rms sidelobe level in the PSF. So, for a 100 mJy source, 0.03 rms sidelobes, and polarization beam of about 0.05 fractional polarization at the half power point, one will be left with confusing polarization error emission of order 0.02 mJy rms scattered across the image. More problem sources will increase this confusing polarization error like $\sqrt{N}$.

There is also an important subtlety: if there is a very bright source out in the beam, not only will there be an error in the polarization at that point, but because the spurious polarization signal at that point changes as the beam rotates with parallactic angle, that error will scatter like the sidelobes of the point spread function. However, this effect can be be dealt with using self-calibration and/or the determination of direction-dependent gains. For example, when Carilli and Holdaway made a polarization mosaic of NGC 253, they were limited by the spurious polarization error scattered from the 1~Jy starburst core of the galaxy. They got around this problem by imaging the polarized emission for each pointing on a snapshot-by-snapshot basis. For each snapshot, the spurious polarization at the starburst core was constant because the polarization beam was being sampled by the core at only a small range of parallactic angles. Also, as a single polarization beam was sufficient to describe the patterns of all antennas, no flux was scattered for a given snapshot. While they made an error in the polarization at the location of the core (which they were not interested in), they did not scatter spurious polarized flux across the image. They could then add the snapshots together to form a superior polarization mosaic which was not limited by the scattered flux from the bright core (Carilli & Holdaway, VLA Test Memo 163). In the regions of interest (ie., not the core), the error level was still around 0.5\%, the error level you'd get if you "did nothing", and if there were no bright core to appear as a source with fluctuating spurious polarization, scattering flux around the place.

One drawback to this method is that imaging in snapshots deprives the image of the non-linear advantage of deconvolving with more data. But in this modern day, we can have our cake and eat it too: using a direction-dependent gain solver in an advanced imaging package such as AIPS++, one can solve for ``time variable" polarization leakage terms at the location of problem sources. Given the time dependent (actually, parallactic angle dependent) polarization leakage terms at the locations of the problem sources and a model for the total intensity emission, the spurious polarization contribution from each problem source to the visibilities can be calculated and subtracted from the data, and the residual polarization visibility data can be inverted to achieve an image which is not adversely affected by scattered polarization errors.

However, ALMA has a very demanding polarization spec of 0.1\% (meaning one should be able to detect polarization flux which is 0.1\% of the total intensity emission, providing it is above thermal noise). In the two cases handled above, one is still left with a basic background error of about 0.5\%. The 3 sigma level is then about 1.5\%, so there is still an order of magnitude of improvement to make. Thus, the polarization primary beam must be fully incorporated into the imaging in order to meet this specification.

The VLA's polarization beam has been found to be moderately stable with time, and it has been found that a single beam can be used to describe all antennas. Bill Cotton has measured the polarization beam at 1.4 GHz and used that to correct snapshot observations in the Northern VLA Sky Survey, rotating the beam to the parallactic angle of the snapshot observation (Condon et al. 1998, AJ 115, 1693). For longer observations, it is proposed that the polarization beam be incorporated directly in the imaging and deconvolution steps. For example, given a model of the total intensity source distribution, for each interval of parallactic angle one could rotate the polarization beam, multiply the rotated beam by the total intensity distribution to get an estimate for that snapshots' contribution to the spurious polarization emission in the image plane, inverse Fourier transform, subtract the spurious signal from the polarization visibilities, and finally image the residual polarization visibilities. This sort of algorithm is being implemented in AIPS++, and should allow the spec of 0.1\% to be reached for ALMA.

5.3 Impact of Polarization Beam Calibration

The polarization beam calibration requires no extra hardware.

The full beam correction will require a battery of test observations during ALMA commissioning and then fewer test observations intermittently to monitor the polarization beams. A set of ``standard'' polarization beams will be measured and made available to the users and to the science pipeline. These will have to be monitored (in case of time variability) and updated when necessary (e.g. when an optics change is made).

Occasionally, a demanding polarization observation may not be supported by the standard polarization beams determined by the ALMA staff, and the observer will need to determine polarization beams which are unique to their observing setup (or one will have to be measured and provided by the ALMA staff). At this time it is unknown how often this will occur. It should be the goal that the set of standard beams cover at least 75\% of projects.

Determination of the polarization primary beam is equivalent to a standard holography run, but would not require a raster out into the far sidelobes as in a holography observation. The time required to perform this observation will be frequency dependent: at low frequencies where good sources are available and the noise is low, the observation could be carried out in a few to 10 minutes. At higher frequencies, it is estimated that an hour will be required. [NOTE: do we have any real estimates of the time to raster?]

Open questions are whether a single polarization beam can be used for all antennas or if each antenna needs its own beam, whether a parameterized model is sufficient or a stored beam image is necessary, whether the polarization beam changes with elevation, across the frequency band, or with other variables. The issues will impact how often beam measurement must be done, and how many instances of the beam must be archived. This will impact the required use of ALMA test time, and use of the archive.

5.4 Further Work for Polarization Beam Calibration:

The most important work for polarization beam calibration is the measurement of the polarization beam. This could be performed on the ALMA prototype antennas to give us an idea of what it will look like for the final ALMA antennas, but as the feeds are evaluation feeds and not production feeds, we expect the final ALMA polarization beams to be different. In any event, such measurements will establish the magnitude of the problem.

In the meantime, optics modeling should be used to estimate the polarization effects, and to provide a baseline to compare with the data.

Furthermore, implementation of advanced imaging algorithms incorporating the full polarization primary beam will be necessary, as argued above, to meeting the ALMA specification of 0.1\%. There are ALMA software requirements to this effect, and these are part of the scope of the software being developed in AIPS++ for the ALMA project. The ALMA Imaging and Calibration Group should review the progress of the development of this software, and to participate in the testing, and to monitor that the algorithm and software will reach the required level of accuracy.

6 Pointing Calibration[8]

---

[8] Original contribution by R. Lucas and J. Mangum

6.1 Introduction

The ALMA antenna pointing specifications of 0."6 reference and 2" all-sky places strict requirements on the ALMA pointing model formalism. In ALMA Memos 366 (Mangum), 189 (Lucas), and 372 (Moreno and Guilloteau), analysis of the requirements and performance capabilities of single antenna and interferometric pointing procedures have been investigated. The conclusions of these analyzes were:

- The pointing model formalism described in ALMA Memos 366 and 189 coupled with the refraction calculation described in ALMA Memo 366, which relies upon the weather instrumentation described in ALMA Memo 366 will allow a characterization of the ALMA antenna pointing behavior with a basic uncertainty of at most 0."3 under most meteorological conditions.
- A full atmospheric model, such as that given by Liebe (1993) and Pardo should be used to calculate the refractivity at the antenna, N&ad. This will insure a more accurate calculation of the refraction at the antenna.
- The suggested structure for the pointing coefficient information described in ALMA Memo 366 will allow for a great deal of flexibility in implementation of the ALMA pointing model. Ultimately, these data should be incorporated into a general observatory database to allow detailed tracking of the pointing characteristics of the ALMA antennas.
- Short-term (hourly) time variations of antenna pointing properties can be accurately calibrated by reference pointing, while losing an affordable fraction of the available observing time (1-4 minutes per hour).

Initial pointing studies will be done with optical pointing telescopes (OPT). The OPT systems used on the ALMA prototype antennas have proven to be invaluable to the characterization of the pointing performance of these antennas.

6.2 Description of the Techniques

6.2.1 Single Radio Pointing Measurement

All radio pointing calibrations here are made of combinations of individual radio pointing measurements. A single measurement determines the collimations $\mathcal{CA}$ and $\mathcal{IE}$ (see memo 366) in the observed direction at the measurement time. Quasars are the best sources, and given the spectral index distribution, 90 GHz is the best observing frequency (while the loss of sensitivity in the lower 2mm band is affordable if one wishes to avoid shifting receiver bands for pointing only; see memo 372).

Traditional five point maps can be made (to optimize sensitivity several antennas are observing on-source at any given time). Sources of flux S~100mJy are usable at 90 GHz for the 64 antenna array, in order to get the desired measurement accuracy (0.3", so that the measurement error is not significantly contributing to the pointing accuracy budget). If less than 64 antennas are used (e.g. only a few antennas $\mathcal{N}$ need to be calibrated), the on-source integration time scales like 64/$\mathcal{N}$, and the minimum flux for a given integration time scales like (64/$\mathcal{N}$). However for sources stronger than flux S~500mJy, the slewing time dominates the required integration times.

6.2.2 Global Pointing Model

A global pointing model is derived by observing approximately 100 (or more) radio point sources. The individual pointing results are used, after eliminating possible erroneous measurements, by a linear least square fitting program such as TPOINT (see memo 366).

6.2.3 Reference Pointing

The simple (and commonly used) reference pointing scheme was described in ALMA Memo 189. At regular intervals, a point source is observed in interferometry mode. The measured collimations ($\mathcal{CA}$, $\mathcal{IE}$) are used to observe the target source until a new pointing measurement is done.

An improvement of this scheme is described in Memo 372. Single-source pointing measurements are replaced by local pointing model determinations, using a few (~5) pointing sources, typically 4-7 degrees from the target source. The local pointing model should guarantee more accurate pointing as the changes in azimuth and elevation of the target source between two successive pointing calibrations is appreciable (several degrees). To the two local coefficients ($\mathcal{CA}$, $\mathcal{IE}$), one would add for instance the local partial derivatives of the collimations with respect to Azimuth and Elevation (4 additional terms).

6.2.4 Relative Pointing Calibration of the Receiver Bands

This needs to be mentioned here. The same technique is used for individual measurements, but the results should be stable unless a receiver dewar is taken off the antenna and/or taken apart. Measurements are thus considerably less frequent (several months?) for each given antenna. The accuracy should be better than 0.3", using much stronger sources (~10 Jy).

6.3 Description of Required Hardware and Software

Accurate pointing requires atmospheric refraction to be taken out; its computation relies on accurate atmospheric monitoring devices (pressure, temperature, relative humidity). See "Working Draft Ancillary Devices" document (Hills and Richer) for details.

There are software needs, but nothing really difficult. The needed development is currently budgeted. The local and global pointing model scheme may need more software development, both in the measurement and in the implementation in Control Software (more terms to be included).

6.4 How Often ?

The global pointing determination is needed (conservatively) for each antenna after it has been relocated. A sufficient number of antennas should be measured simultaneously to improve sensitivity. If some additional antennas are included only for this purpose, they do not need to be scanned.
One should also make a global pointing determination at regular intervals (monthly?) to check the global pointing performance and monitor the pointing model coefficients.

We basically do not know how often the reference pointing will be needed. If the antennas are stable enough (i.e. as specified) once every 15 min. should be enough (memo 189). If the pointing requirements are relaxed (this depends on the observing projects, which will have to require a pointing accuracy as one of the stringency factors involved in dynamic scheduling) then the time between measurements can be increased, and observing time saved.

In the local pointing model scheme, one could use less frequent pointing measurements to obtain the same operational pointing accuracy.

6.5 How long ?

The global pointing model determination needs to observe approximately 100 sources well distributed in the observable sky. The typical distance between sources is then 16 degrees, and their typical flux is 0.5 Jy. Each pointing measurement needs 10s (mostly switching between half-power points). Slewing between sources adds 5 s per source. The total time is then about 1500s. For e.g. 4 antennas only, the duration of each measurement goes up to 45s. The total time to get a full model is then 5000s. Determining the pointing parameters after a move should however require many fewer sources as measuring only a few parameters (AZ offset and axes inclination) should be needed.

For reference pointing, in order to get the best accuracy, the observing time per individual measurement on 100mJy sources is about 90s (see memo 189). If the pointing accuracy is relaxed, e.g. according to the needs of long wavelength programmes, or if low dynamic range programmes, then shorted measurements can be used; this is also possible if a nearby or internal strong calibrator is available.

The integration time is not directly a function of frequency, as we should normally use a low frequency for the measurements; however the desired accuracy varies (approximately linearly) with the wavelength of the science programme.

In the local pointing model scheme, the integration times are smaller and the measurement time is dominated by slewing times between the pointing sources. One needs about one minute to observe a local pointing model of 5 sources.

6.6 Archiving Needs

The results of the global pointing model determination, which includes all pointing model term and refraction term coefficients and their uncertainties.

We need to archive for each reference pointing measurement the measured collimations and their associated uncertainties. The total size is 1.26 kB for a 64-antenna measurement. In the local pointing model scheme this is multiplied by 3, but the rate may be smaller if the measurements are less frequent.

The results must be accessed by the Control Subsystem as soon as possible; the Computing IPT has set a requirement of 0.5s on the processing time in order to achieve this.

6.7 Collaboration

There is no specific collaboration with other IPTs (with the exception of the Computing IPT).

6.8 Further Studies

Other measurement techniques can be more time efficient, e.g. if stronger sources and thus shorter integration times (smaller than 2 sec.) are used. Observing a circle at the half-power point avoids the slew time between discrete integrations at half-power points. These refinements will need some tests (e.g. at the ATF) before they are actually implemented.

The local pointing model scheme also would need some validation (also at the ATF). Tests on actual telescopes are quite valuable as the main uncertainties here are the actual telescope thermal and mechanical properties.

7 Antenna Location Calibration[9]

In order to accurately calculate the geometric delay before correlating the voltages from two antennas and to reduce systematic phase errors which will limit image dynamic range antenna locations must be known accurately. The process of locating these antenna positions is often called 'baseline calibration' because it allows for the accurate specification of the baseline as well, but we prefer to simply call it "antenna location calibration" since this more accurately describes what we are measuring/calibrating.

The antenna locations may be measured by determining the phase and delays on each baseline (Wright 2002) for on order of a hundred observations of point sources sampling the whole sky. Individual delays can be fit across the spectrum as in geodetic VLBI. The complete set of phases and delays is used to solve for the three dimensional locations of all antenna relative to a reference antenna (or any reference location). Fomalont and Perley (1999) and Thompson et al (2001) give good general overviews of this measurement. Wright (2002) has given a good description of this process on the BIMA array. Sovers et al (1998) give a description of the technique used in VLBI.

The observing strategy is similar to that for pointing model determination and should take about an hour to complete. As for pointing calibration in order to have a large enough sample of compact calibrators at high enough SNR the frequency of 90GHz is likely to be optimum. Since pointing observations are also done in interferometric mode it may be

---

[9] Contribution taken from Calibration Requirements and Specifications, updated version being written by Conway.

possible to partly combine antenna pointing and antenna position calibration using the on-source pointing data.

Signal to noise is not an issue for 65 micro m accuracy, and the 1 hour timescale is set more by the minimum time to sample many sources around the sky. Atmosphere phase-fluctuations may effect 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 toward a zero mean in differential measurements.

In order to avoid high winds it might be operationally desirable to move antennas starting in the morning and complete movements before afternoon winds pick up. To achieve the required 65 micrometer accuracy yet minimize observing time lost for the moved antennas it might then be necessary to perform position calibration in two parts, once immediately after being moved, and then again after sunset when observing conditions of wind and phase stability are much better. After the first calibration antennas would only be used for lower frequency (345GHz or less) PI observations; this would not be such a loss because presumably most high frequency PI observations would in any case be scheduled for the night when conditions were best. If it turns out that there are no operational constraints on when antennas are moved due to wind or other reasons, then calibration requirements would favor moving antennas in the afternoon so that a single calibration could be done after sunset.

For the largest configurations calibrations longer than 1 hour may be required to reach the outermost scale of the atmosphere and sample several atmospheric screen patterns. Local rotation of the baseline plane is possible otherwise. Experience in the early phases of operations is required.

In order to reduce errors during antenna location determination, only sources with well determined locations should be used (Feissel-Verner 2003; Johnston and de Vegt 1999). In addition, since source structure will introduce further uncertainty in the antenna location determination (Sovers et al 1998), sources with very simple structure should be chosen. Otherwise we must use a more complicated self-calibration procedure, obtaining both the structure and location.

One question is how many antennas will be required to do an antenna location determination? Given the current operational model of frequent antenna moves (Conway 2004) with 4 antennas being moved approximately every 3 days, this question is quite important. After an antenna is moved, it will be required to determine its location (or equivalently its delay), and this will require some number of other antennas to be used for this. In theory, this could be done with a single antenna with accurately known position, but in practice several are always used. Hopefully it should be possible to use 3 or less, but further study is required to decide if this is sufficient. There is a clear tradeoff because we want as many as possible to increase the SNR during the observations, but as few as possible because it takes functional antennas away from normal observing.

Another question yet to be determined is which antennas should be switched out of the array for the calibration. The answer may depend on whether we are in the phase of reconfiguration when we are expanding or contracting. In an expanding array using antennas at the center have the advantage that these antennas that have been on the same pad for the longest time and hence participated in the most calibrations to check and link their absolute positions to the rest of the array. Switching out such antennas will have the least impact on beam shape and overall uv coverage but more impact on short spacing uv coverage. On the other hand if multiple antennas are used then using antennas at the center gives smaller range of baseline lengths and orientations to use in the solutions. Using inner antennas will for the largest configurations also give long baselines which are affected by larger atmospheric phase errors. Because of this using nearby antennas located on the same 'spiral arms' may be better for larger arrays. For a contracting array the outer antennas will have spent longest on the same pad and may be more accurately determined than the inner pads. It is clear that more work is needed to optimize the choice of which antennas are switched in for the calibration observations. It is clear that whatever scheme is chosen occasional calibrations of the whole array should be made to stop antenna position errors propagating and building up (Wright 2002).

Of some concern for antenna position calibration is the timescale over which we expect the antenna positions to remain fixed to 65 micro m. Permafrost has been reported on the ALMA site (see e.g. Snyder et al 2000), which enables an entire class of soil movements. We can probably expect some amount of soil creep, especially after earthquakes (see Otarola et al 2002).

Other possible sources of position change include uneven solar heating of the concrete of pads due to shadowing by the antenna. This belongs to the category of parameters which are difficult to influence, because pad thermal performance will be hard to change without extreme cost. Addition of monitoring equipment might be an option if this is significant effect. Other potential worries are temporary small displacements due to nearby passage of heavy transporters, and settling of a pad after an antenna is placed on top. Its unclear what the magnitudes of these effects are, they maybe can be best assessed by measurements on the APEX antenna on the site.

It is clear that in addition to calibration of each antenna after it is moved there should be periodic position calibration of the whole array. This will allow the monitoring of any changing pad positions, and as mentioned earlier also stop any cumulative pad errors building up. Assessing how often such complete position calibration is needed is hard to do at this stage, perhaps one hour per week or every two weeks. We will gain valuable experience about the required frequency of calibration once ALMA begins to be operational at Chajnantor.

8 Antenna & Electronic Delay Calibration[10]

9 Optics Calibration[11]

9.1 Main Reflector Surface

9.2 Subreflector Positioning

ALMA Memo No. 479 sets requirements on subreflector and feed positioning for the ALMA antennas. In order to keep gain loss at less than 1%, the axial (vertical) positioning error in the subreflector should be less than about 0.09 λ, and in the feed should be less than about 0.9 λ. The lateral positioning error for the subreflector should be less than about 0.45 λ, and for the feed should be less than about 10 λ. The rotational (tilt) error of the subreflector should be less than about 5.5 λ_{mm} arcminutes if the rotation is about the vertex of the subreflector. If the rotation is about the prime focus, then this error can be much larger: about $\surd\, \lambda_{mm}$ degrees.

9.3 Feed Positioning

10 Total Power Calibration[12]

The main use for total power data in ALMA is to add the short spacing data to longer baseline interferometic data for the purpose of making high quality images of large sources that accurately reconstruct all spatial frequencies out to the maximum observed. To this end, the main criterion for total power calibration is to make the total power data accurate and consistent with the interferometer data and to solve for any parameters that will aid in combining the total power and interferometric data. Undoubtedly, there will be some observations that will be made in only total power: for example, a wide field search for emission from some chemical species may determine that there is insufficient signal to perform interferometric imaging in all or part of the region observed first in total power. However, such observations will be the exception.

Unfortunately, the ALMA system design has been moving away from the possibility of simultaneous interferometric and total power observations: using the ACA (ALMA Compact Array) and its four associated total power antennas to measure short spacings, the total power observations could end up being performed at any time, while the interferometric observations will be taken when ALMA is in one of it's compact configurations. Hence, atmospheric or meteorological conditions could be quite different

---

[10] Contribution expected from B. Butler.

[11] See ALMA Memo No. 479 by B. Butler.

[12] Original contribution by M. Holdaway.

for the two observations. Additionally, it would be beneficial to have the sensitivity of the whole array assisting the total power antennas in calibration, but the plan is for the four total power antennas to cross-correlate ONLY with the ACA antennas, resulting in a sensitivity-poor environment for total power calibration. And last, the demands of dynamic scheduling and quick imaging shortly after the observations by the ALMA imaging pipeline will not be well met by the concept of the ACA, which may observe total power data weeks or months after the interferometer data are taken.

When the MMA was proposed in 1991, the {\it homogeneous array} concept, using the same antennas to measure interferometric and total power data, addressed the above issues. However, in the last 5 years, the ACA concept has replaced the homogeneous array concept as the primary method for measuring short spacings. While the four 12~m antennas in the ACA will be the ones optimized for total power, we must accept the fact that some observations may better be served by using some or all of the 12~m antennas in the main ALMA array to take total power data which benefit from simultaneous or contemporaneous observations with the interferometric data to ensure similar atmospheric conditions and to speed up the imaging process, as well as increased sensitivity for superior calibration from correlation with the entire array.

This document will seek to address both of these scenarios: total power data taken with the four antennas in the ACA, and total power data taken with some of the 64 antennas in the main ALMA array.

Several different calibrations need to be performed to make the total power data useful. These include: focus calibration, pointing calibration, flux scale calibration, bandpass calibration, polarization calibration, and beam determination. But before we go off and solve all of these problems, we need to present a bit of background material on ALMA's sensitivity and the millimeter sky.

10.1 ALMA Sensitivity

The sensitivity of the ALMA instrument is modeled in an AIPS++/glish object called ``almasensitivity.g''. This uses a model of the atmospheric opacity called ``almatau.g'' which is derived from Juan Pardo's ATM code. Unless a sort of observation is prohibited by other factors (such as interferometry not working because a large angular object is resolved out), we perform sensitivity calculations for three cases: 64 elements connected interferometrically (64I), four single dishes correlated with each other and with the 12 7~m dishes of the ACA (ACA+4SD), and just a single dish (SD).

- 64I: **If we consider calibrating antennas to be used in single dish mode as part of the entire array of 64 antennas, we can gain significantly through**

calibrating interferometrically. In this case, the noise will go like sqrt(2)/sqrt(64) = 1/5.66

(At this point, the author refrains from using expletives in response to the really stupid project decision to use WORD as the document standard. This is a scientific project, and we need to show equations from time to time. Latex is the standard for good equations in documents, and at least should be permitted.)

- ACA+4SD: **Just as the four 12m single dishes can increase the sensitivity of the calibration of the 12 7m ACA antennas, the ACA can increase the sensitivity of the calibration of the four single dish antennas. The 12 7m ACA dishes have the same collecting area as the four 12m dishes. If we use the ACA just for collecting area, and don't solve for anything on the ACA, then the noise will go like sqrt(2)/4 = 1/2.82. Including the cross correlations among the four 12m dishes improves this noise figure only incrementally.**
- SD: **If we use the total power antennas just as single dishes and calibrate in total power mode only, and use beam switching to remove the effects of the atmosphere, the noise will go like 2, relative to the other numbers above.**
- To recap, the sensitivity ratios for 64I : ACA+SD : SD go like 11.32 : 5.64 : 1. In terms of time, those ratios go like 0.0078 : 0.031 : 1. **In other words, using the ACA to help calibrate the four total power antennas will speed things up by a factor of about 32 over doing the calibration as single dishes, and performing the calibration for an antenna in the 64 element array will speed things up further by a factor of 4. (Also, remember that the ACA is expected to be used for about 25% of the ALMA observations, and observations are expected to time 4 times longer than ALMA main array observations, so if it takes 4 times longer to calibrate the ACA, that is not a huge problem.)**

Depending upon the observational details, not all of the sensitivity gain from the interferometric mode may be useful. For example, if an extended sources becomes resolved out, long baselines will not contribute meaningful sensitivity. On the other hand, for pointing calibration, if the 12 7m ACA antennas are used pointing on the source while the total power antennas are pointed at the half-power point doing a pointing calibration, we could pick up an additional factor of sqrt(2) in sensitivity.

Freq [GHz]	sigma_64 [Jy]	sigma_aca [Jy]	sigma_sd [Jy]
43	0.00013	0.00026	0.00142
80	0.00017	0.00034	0.00189
90	0.00016	0.00032	0.00181
140	0.00023	0.00046	0.00260
170	0.00029	0.00058	0.00329
230	0.00035	0.00070	0.00393
345	0.00065	0.00130	0.00725
490	0.00281	0.00562	0.0313

680	0.00258	0.00516	0.0288
880	0.00285	0.00570	0.0318

10.1.1 Table:

The 60~s integration time 1-sigma noise levels for 8 GHz bandwidth (2 polarizations) for gain solutions using all 64 ALMA main array antennas interferometrically, for gain solutions using the four total power antennas and the collecting area of the 12 7m ACA dishes to help, and for a single dish in total power mode using beam switching. The 225 GHz atmospheric opacity has been assumed to vary with frequency as in LAMA Memo 803.

Freq [GHz]	sigma_64 [Jy]	sigma_aca [Jy]	sigma_sd [Jy]
43	0.00099	0.00198	0.0110
80	0.00131	0.00262	0.0147
90	0.00126	0.00262	0.0141
140	0.00181	0.00362	0.0202
170	0.00229	0.00458	0.0255
230	0.00273	0.00546	0.0304
345	0.00504	0.0108	0.0562
490	0.0218	0.0435	0.242
680	0.0201	0.0401	0.223
880	0.0221	0.0442	0.246

10.1.2 Table:

The 1~s integration time 1-sigma noise levels for 8 GHz bandwidth (2 polarizations) for gain solutions using all 64 ALMA main array antennas interferometrically, for gain solutions using the four total power antennas and the collecting area of the 12 7m ACA dishes to help, and for a single dish in total power mode using beam switching. . The 225 GHz atmospheric opacity has been assumed to vary with frequency as in LAMA Memo 803.

10.1.3 The Quiescent Spectrum of 3C273

One of the brightest point-like sources in the sky at millimeter wavelengths is 3C273. 3C279 is of similar brightness. There will be other bright sources in other parts of the sky, but they will usually not be as bright as 3C273. These quasars, of course, are highly variable, and flares can cause their brightness to increase by a factor of 3 or 4 over weeks or months. While we will take advantage of the bright flares, we can't depend upon it, so we use the quiescent flux of 3C273 as measured by Stevens et al. (ApJ 502, 182, 1998) as a baseline of what is available to us in the way of a bright point source in the sky to use for calibration. The flux of 3C273 has been published for frequencies up to 375~GHz, and the fluxes for higher frequencies are estimates. These fluxes are presented in Table 1. These data correspond to a spectral index of 0.5 (S(freq) ~ freq^{-0.5}) up to 230~GHz and a spectral index of 1.1 above 230~GHz.

Band	Freq	S
[Ghz]	[Jy]	
1	43	20
2	80	16
3	90	15
4	145	11
5	190	10
6	230	9
7	345	5.5
8	500	3.6*
9	680	2.6*
10	880	1.9*

Table 1: Flux of 3C273 with Frequency. As the frequencies associated with the ALMA bands were not measured, interpolation ``by eye'' was sometimes used. Data points with ``*'' are extrapolations based on a steepened spectral index of 1.1, which was determined from measurements at 230 and 375~GHz.

10.1.4 Statistic for Nearby Bright Quasars

We've gone to great lengths to be able to estimate the number of bright quasars at 90~GHz and at higher frequencies. These quasars could be quite useful for ALMA calibration. We've asked the following question of these source count estimates: how bright will the brightest quasar within 15 degrees of your favorite source be? The answer is that there is a distribution. We've taken the median quasar brightness and the tenth-percentile brightness for each ALMA band and tabulated that in Table 2.

Freq [GHz]	10% Flux [Jy]	50% Flux [Jy]
90	1.15	2.35
140	0.79	1.58
170	0.68	1.36
230	0.55	1.10
345	0.41	0.83
490	0.33	0.66
680	0.27	0.55
880	0.24	0.48

Table 2: Expected 10th percentile and 50th percentile maximum fluxes of the brightest quasar within 15 degrees of your favorite source.

10.1.5 Angular Size & Flux of Planets

Planets could be useful for ALMA single dish calibration observations. They have already been rejected for primary flux calibrators because the uncertainties in their fluxes are too large to meet the flux calibration spec. However, it is always nice to have a very bright source.

Tables 2 and 3 indicate the size of the ALMA beam and the minimum and maximum size of the planets as seen from earth. Tables 4 and 5 tabulate the planets' maximum and minimum flux, including beam effects, as a function of frequency. Venus, Jupiet, and Saturn are essentially useless for most ALMA calibrations, as they are just too big. Mars may be useful for low frequencies (ie, below 345 or 230 GHz). Uranus and Neptune will be useful at most frequencies, especially considering that they become very bright (>~100 Jy) in the sub-millimeter. In particular, Uranus and Neptune will be very useful for performing beam maps and other service observations, though the typical observation cannot count on them being above horizon.

Freq [GHz]	Beam_Size [arcsec]
43	119.9
80	64.4
90	57.2

140	36.8
170	30.3
230	22.4
345	14.9
490	10.5
680	7.6
880	5.9

Table 2: Beam size as a function of frequency for ALMA's 12m antennas.

Planet	Min Size [arcsec]	Max Size [arcsec]
Venus	9.6	59
Mars	3.55	5.3
Jupiter	33	49
Saturn	16.35	20.4
Uranus	3.37	3.72
Neptune	2.2	2.3

Table 3: Minimum and maximum angular size of planets for the year 2000 (2001 was included to the full cycle for Venus).

Freq	Venus	Mars	Jupiter	Saturn	Uranus	Neptune
43	-1160	6.3	-410	65.7	1.8	0.7
43	-1	1	-1	0	1	1
80	-3304	23.5	-1236	219.2	5.9	2.1
80	-1	1	-1	0	1	1
90	-3908	30.4	-1491	-274.7	7.6	3.1
90	-1	1	-1	-1	1	1
140	-6237	72.0	-2651	-624.0	18.2	5.9
140	-1	0	-1	-1	0	1
170	-6958	103.9	-3136	-874.3	25.1	9.7
170	-1	0	-1	-1	0	1
230	-7441	188.9	-3614	-1418	47.2	18.2
230	-1	0	-1	-1	0	0
345	-7499	-418.9	-3749	-2358	104.4	41.1
345	-1	-1	-1	-1	0	0
490	-7500	-806.0	-3750	-3011	-207	81.8
490	-1	-1	-1	-1	-1	0
680	-7500	-1435	-3750	-3229	-385	155.4
680	-1	-1	-1	-1	-1	0
880	-7500	-2165	-3750	-3249	-608	-254.2
880	-1	-1	-1	-1	-1	-1

Table 4: Estimated maximum flux (in Jy) of planets at their closest, for each ALMA band, including the effects of the ALMA beam. If the planet is less than 1/10 the beam

size at a particular frequency, it is coded with a "1". If the planet is between 1/10 and 1/3 of the beam size, it is coded with a "0". If the planet is larger than 1/3 of the beam size, it is coded with a "-1", and the flux is coded with a "-". These fluxes are only approximate, and could be off by 25% or more.

Freq	Venus	Mars	Jupiter	Saturn	Uranus	Neptune
43	35.3	3.6	191.1	41.5	1.8	0.7
43	1	1	0	0	1	1
80	112.1	10.5	-621.0	143.0	4.9	1.8
80	0	1	-1	0	1	1
90	143.7	11.8	-770.1	178.8	5.9	2.4
90	0	1	-1	0	1	1
140	343.9	31.8	-1601	-417.3	15.2	5.9
140	0	1	-1	-1	1	1
170	505.9	47.5	-2099	-593.3	20.6	8.6
170	0	0	-1	-1	0	1
230	-899.7	86.3	-2916	-1004	37.7	16.5
230	-1	0	-1	-1	0	1
345	-1865	190.9	-3623	-1833	87.5	37.3
345	-1	0	-1	-1	0	0
490	-3285	-378.9	-3747	-2641	172.1	74.4
490	-1	-1	-1	-1	0	0
680	-5036	-704.7	-3750	-3121	-321.0	141.8
680	-1	-1	-1	-1	-1	0
880	-6337	-1124	-3750	-3236	-510.7	-233.0
880	-1	-1	-1	-1	-1	-1

Table 5: Estimated minimum flux (in Jy) of planets at their farthest.

10.2 Focus Calibration

The total power focus calibration procedure is essentially the same as that performed for the other ALMA antennas. Primarily, there will be some elevation-dependent focus corrections we will need to make due to gravitational deformation of the ALMA antenna structure. Those corrections will be determined by service observations.

We can perform this in total power mode or interferometrically. The total power calibration is straight forward and is well described elsewhere. If the focus is determined interferometrically, each antennas' subreflector would be shifted in focus position and the on-line system would solve for the antenna-based gain as a function of focus position. The on-line system would then command the antennas' subreflectors to the focus position which optimizes the antenna power. The advantages to performing this calibration interferometrically include improved sensitivity (if the full array can be used) and immunity from variable atmospheric emission, gain fluctuations, and systematic errors such as ground pickup. The main disadvantage is that we need a smaller source -- for example, at low frequencies, we will be able to use a planet to focus on, providing excellent SNR. However, at low SNR, we probably have enough SNR that we don't need a planet. At high frequencies, planets become resolved and we need a small source anyway. Admittedly, we could use a small source which was bigger (and possibly brighter) than 3C273, such as a Compact HII region -- it just needs to be much smaller than the single dish beam in order to perform the focus calibration with a single dish. We posit the existence of such sources without relying upon them right now, and use the 3C273 case as a lower limit for what we should be able to do.

Comment: [HEY HEY HEY: run the sensitivity numbers and figure out how much
time we need to do the focus -- to what acuracy do we need?
IF the focus is inaccurate, it will impact the primary beam]

We hope that during the much of the time (for example, at night, or at low frequencies), standard predetermined focus settings can be applied. For more demanding observations or conditions (such as when the sun is warming up the antenna structure in the morning) we will need to perform focus observations as part of each astronomical Source Block. The exact strategy (ie, when focus observations are required and when standard predetermined focus settings can be used, which source we can observe on, and if we perform it interferometrically or in total power mode) will need to be determined from test observations and through experience as the ALMA array becomes operational.

10.3 Pointing Calibration

ALMA requires excellent pointing -- the spec is at 0.65~arcsecs – in order to make good mosaic images with both total power and interferometric data combined. However, that spec is rooted in pointing error simulation work performed before ALMA became a sub-millimeter wavelength instrument -- any improvement below 0.65~arcseconds would benefit observations at the highest frequencies, especially mosaics.

There are a number of factors that will affect the pointing:

- repeatable mechanical imperfections associated with the foundation, the mount, or the antenna, which can be modeled by observing many pointing sources across the sky.
- non-repeatable mechanical effects associated with thermal distortions
- non-repeatable mechanical effects associated with wind buffetting
- predictable radiometric effects from slowly-varying refraction through the bulk atmosphere
- non-repeatable radiometric effects due to refraction through the varying atmosphere (ie, anomalous refraction)

The first sort of effect can be handled with the ``pointing model", which generally consists of about 10 terms relating to physical offsets and such. Refraction from the bulk atmosphere can be dealt with through atmospheric models. However, there are usually residuals from such pointing models that are coherent over time (perhaps an hour) and space (tens of degrees). The VLA addresses these residuals by performing offset pointing, a single pointing solution on a nearby calibration source, the solutions of which are applied over and above the pointing model. Such offset pointing could address some thermal effects, but would not address wind effects. Refractive pointing jitter probably cannot be corrected for (though there exists a possible fix with the water vapor radiometer).

At 230~GHz and lower, there will be many bright point-like astronomical sources that will serve well as pointing calibrators. Again, if performed interferometrically, the sensitivity is much improved.

Comment: [HEY HEY HEY: mention wind and refractive pointing are not so damaging]

Comment: [HEY HEY HEY: 3 cases: 64 interferometer; ACA+4SD only -- with ACA looking straight ahead; Single Dish make table, vs FREQ -- for brightest sources that are likely to be within 10-15 degrees]

Comment: [HEY HEY HEY: solve for cross-band pointing offsets on a very bright source as service observations, rely upon low freq pointing obs.

Comment: [HEY HEY HEY: pointing self-calibration -- not possible for single dish?? Pointing Cross calibration with interferometer; Many quick scans

10.4 Flux Scale Calibration

Many of the same issues as the interferometer;
BUT:

NO decorrelation

When can we use a planet?

What about HII regions?

Bootstrap to interferometer with a common bright unresolved object
(investigate noise levels for 64I, ACA+4SD, SD)

Variable Opacity & Correction
(time variability & spatial variability)

Gain Curves at highest frequencies

10.5 EXTRA NOISE

Variable Sky Emission

1/f gain fluctuations

10.6 Band Pass Calibration

Investigate noise levels for 64I, ACA+4SD, SD

10.7 Beam Shape Calibration

Usually in single dish observing, the exact shape of the beam is not of great important. At high frequencies where the beam starts to degrade, it is important to know how much power is in the sidelobes, or if the main beam is bifurcated by hideous surface errors. For a mosaicing instrument such as ALMA, detailed knowledge of the beam is essential; we are not just trying to make a single dish map, we are also trying to map the detailed structure on much smaller spatial scales. If the true beam differs from the mathematical model we are using for image reconstruction, this will result in imaging errors.

WHAT LEVEL BEAM?

Model beam out to sidelobes

Average beam

Beam as a function of elevation angle?

2-D beam models?

How to measure beam:

3C273 -- 64I ACA+4SD SD

Strongly recommend being able to move the 4SD's onto regular ALMA pads and connect them with 64I to get beam solution.

It is possible that an observation may be demanding enough to require observational determination of beam during the astronomical observation. We should not make plans for accomplishing this, but should not rule it out.

10.8 Polarization

Polarization leakage and position angle ?????

Beam -- for combination with 64I

Typical Single Dish Observation:

90 GHz

230 GHz

345 GHz

650 GHz

10.9 Service Observations

List all service observations:

10.9.1 Elevation-Dependent Focus Model

Pointing Model

10.9.2 Cross-Band Pointing Offsets

10.9.3 Beam Determinations

10.10 Sideband Gain Ratio

11 Archiving and Accessing Calibration Quantities[13]

11.1 Use of calibrations to control and improve quality of data taking

General science requirements for ALMA Software have been prepared by the SSR group (SSR). Various parts of the documents are concerned by calibration. Here we describe the handling of

---

[13] Original contribution by R. Lucas and B. Butler

calibrations and their interaction with the science operation of the array. It is hoped that this will clarify the picture, and may be used to precise and complete the requirements if needed. Single Antenna Issues

It is very important to use calibrations as a diagnostic tool for controlling the quality of data taking. Using the science data for this purpose would be much more delicate as most project sources will tend to be weak and complex objects for ALMA, while calibration sources are stronger and have simple structure (mostly point like for the baselines in use). We list here the main ways of using calibrations for this purpose:

1. F*ault detection:*

Several hardware problems can be easily detected by looking at the calibrator amplitude and phases. For instance: large antenna pointing errors, poor focus, LO chain problems in one antenna, large delay error, ..., all give weaker or null amplitudes on the faulty antenna. Antenna based amplitudes can be calculated for each observation of phase and amplitude calibrators.

The temperature scale calibration, performed by measuring total power and auto correlations on a specific calibration device in each antenna, gives a test for poorly performing receiver bands (higher system or receiver temperatures will result). This is also valid for the WVRs.

2. Consequences for scheduling, data taking:

A main factor of data quality is quality of calibration. The calibration results calculated in quasi-real time will include system temperatures, precipitable water vapour content, phase rms and seeing parameters. All these parameters can and should be used:

- to improve the observing process: the typical use will be to change the cycle time of phase referencing to adapt to changing atmospheric quality (use slower or faster switching to gain integration time or obtain a better residual phase r.m.s.)
- to improve the scheduling: the scheduler can take into account the actual conditions as measured by the observing system itself to choose the most adapted program.

3. Flux monitoring of strong sources:

Secondary calibrators will be used to obtain the required accuracy of amplitude calibration. Each time they are observed and/or at regular intervals a dedicated procedure should be used to measure their flux; the measured results should be recorded. From these results a data base should be updated so that the fluxes are available to the science pipeline and off-line data reduction (and can be inserted in the exported data from the archive). This data base should also be available to the observing process so that the most suitable secondary calibrator is selected in real time (best elevation, direction similar to that of the source, adequate size and polarization parameters).

4. Data base of all calibrators:

As most calibrators are time variable, to use the best for each project it is important to build and maintain a data base of all calibrators with their properties, including flux, size and polarization parameters. As each of these calibrators will be seldom observed, several may need to be checked when the project is started, but an up-to-date list is important. The data base should be automatically maintained from the science projects themselves.

5. Trend analyses:

On the longer term, trend analyses on the calibration results can be used to monitor array performance (pointing accuracy, receiver performance, beam shape, surface accuracy, ...). It is an operation planning issue to define the extent of these analyses, but the calibrations should provide and properly archive all results that should be used for these purposes.

11.2 Use of calibrations for science projects

Calibration validity:

Passband calibration, sideband ratio calibrations may be valid for a few hours or more. Temperature scale calibration is valid for a few minutes to tens if minutes (as atmospheric attenuation changes). Path length calibration validity can be only a few seconds (when fast switching has to be used). So there is a large range of validity intervals, which can be defaulted for each calibration type, but can be decided in real time depending on the quality of the calibration and on observing conditions. It is thus important that a validity interval be associated to each calibration result.

Calibration scheduling:

In the current plans of ALMA Computing, it is foreseen that calibrations needed by an observing unit of a program are included in its scheduling block(s) and executed only when needed, i.e. if not previously done or if no more valid. This is important to save observing time, as the validity of a calibration can be much longer that the typical time duration of a scheduling block.

Use by other projects:

As a further attempt to save observing time, on may share calibrations between projects. This is generally the case for system calibrations (such as antenna positions, delays, ... etc), but can be also useful e.g. for bandpass calibrations that could be shared between short projects (for instance continuum projects for which the actual frequency can be decided depending on the validity of a passband calibration for that exact frequency). Naturally the stability of the passbands is an issue here.

Results of calibrations performed specifically for a particular project must be applied to that project's science data. If the reduction of the calibration is performed off-line, then it is the user's responsibility to apply it off-line. But if the calibration is automatically reduced on-line (in the calibration or the science pipeline), then the calibration results must be archived so that the calibration need not be re-processed again if needed.

11.3 Consequences for handling of Calibrations

Calibration results must be archived and easily retrieved with adequate metadata, among which are included:

- Date and time
- Unambiguous link to the data used
- Antennas to which the calibration may be applied
- Receiver bands to which the calibration may be applied
- Time interval for which the calibration is valid
- Conditions which will invalidate the result (e.g. antenna displacement, antenna reconnection, change of frequency, receiver exchange, ...)

There is a need for observatory operational software to:

- Maintain the calibration source catalog(s)
- Maintain the calibration data base (e.g. mark some previous calibrations as invalid if a maintenance ever occurs, such as an antenna move or a receiver exchange)
- Extract long term data from the calibration results

12 Examples

12.1 Continuum

12.2 Spectral Line

12.3 Polarization

12.4 Mosaic