Atacama
Large
Millimeter
Array

Optics Calibration Steps

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Specification Document

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1 Goals

Misalignment of optical components at each of the ALMA telescopes, such as, primary dish surface, subreflector, mirrors, and receiver feeds will result in loss of sensitivity and image quality degradation. This is due to overall gain loss, beam-shape distorsion, excess pickup noise from spillover, and polarization property changes caused by the misalignments.In this document we describe the observational steps required to optimize the positioning of the following optical components of each antenna:

- Surface Setting: Significant deviation of the main reflector shape from an ideal parabolic surface will result in severe loss of collective power/gain of an antenna (Ruze 1966). The main dish surface of the antennas will be segmented into multiple movable panels whose shape w.r.t. that of an ideal parabola can be adjusted. The goal is to set the panels as close to the ideal main dish shape as possible.
- Subreflector Positioning: The subreflector of each antenna will be movable along 3 axes (i.e.,optical axis of main reflector and in a plane perpendicular to it). The optimum position of the focus along any of these axes is a function of elevation and enviromental parameters. The goal is to position the subreflector so that there is a maximum transfer of the power collected by the main dish into the off-axis ALMA receiver system.
- RX Feed Setting: The ALMA Receivers will be placed off-axis w.r.t. the main dish. If the plane of the aperture of the feeds is inclined w.r.t. the focal plane (defined by the optimized subreflector position defined above), the shape of the beam will become elongated (i.e., coma aberration). Furthermore, some of the ALMA Receivers will observe simulataneously two orthogonal polarizations through re-direction of the signal from the subreflector using various beam-splitting mechanisms/devices. The goal of the feed setting is therefore to set the planes of the feed apertures as close as possible to being perpendicular to the optical axis of the subreflector and to match the orientation of both polarization channels on the sky (i.e., beam-squint correction). The feeds should also illuminate the subreflector adequately to avoid excess pick-up noise from the side-lobes.

2 Calibration Steps

2.1 Surface Setting

2.1.1 General Description

The method used for measuring the shape of the main reflector will be radio holography (Baars et al 2006 and references therein). Several techniques have been proposed in the literature (Butler 1998), that can be broadly classified based on the existence or lack of phase information in the data. All holographic techniques are based on the Fourier Transform equivalence that exists between the far-field radiation pattern of an antenna and its surface current distribution (Rahmat-Samii 1984). At the OSF, holography will be done on each antenna individually using a transmitter located near the pads (near-field) and with a dual-channel receiver that provides phase information (Perfetto and Emerson 2000). Phase-retrieval techniques (see below) may also be used on a few celestial sources. Both these techniques have already been used during the AEG phase of the ALMA antennas at the ATF (Mangum et al 2006). At the AOS, since no trasmitters will be available, interferometric holography (phase-referenced) and phase-retrieval (also called ”Out-of-Focus” or OOF) techniques (autocorrelation information only) could be used on selected celestial sources. Both techniques will not usually provide enough SNR for a full mapping of the surface innacuracies, but can be used as a check of the overall surface error distribution (specially as a function of elevation).

A brief breakdown of what is involved in the surface-setting process would be as follows:

1) Measure radiation pattern of antenna(s)
2) If necessary, perform near-field to far-field correction to data
3) Derive aperture current distribution via 2-D Fourier transform (or midified transform if required)
4) Use phase information of step 3 to derive surface errors, correct for rigging angle optimization if required
5) Adjust panels of main dish to compensate for surface errors
6) Repeat whole process from step 1 until desired surface accuracy is achieved

Steps 2-5 can be done offline with adequate software (several observatories in the world have also developed their own, like HOLIS for the SMA, CLIC in the GILDAS package, etc)(Kenball 1999,Zhang 1997).The main issue is therefore step 1,that is, the accurate measurement of the radiation pattern, which will be affected by environmental, structural and receiving system stability issues.

The current thinking in terms of the *frequency* of the holography measurements is that transmitter holography (and possibly OOF on some of the antennas) will be initially carried out at the OSF for all the antennas and then again once every 5 years when each antenna is brought back down for maintenance (or in the event that some major structural problem is detected). Celestial holography (interferometric or phase-retrieval) will be carried out at the AOS for testing purposes.

All radio holography methods listed above obtain some form of raster map of the target.Although the specific parameters of the raster maps will vary with the technique (as discussed below), the parameters involved are common:

a) Precision of Measurements: The precision of the measurements is usually set to *half* the required surface RMS setting.

b) Map Dimensions: Maps are usually square, with axial lenght decided based on the requirement of enough sampling. Maps should have *at least* 3 samples per smallest significant surface panel dimension (James et al. 1993) to allow sampling all the relevant spatial frequencies. Beam maps should also be oversampled to avoid aliasing. Most reduction algorithms use the FFT, and thus some internal regridding and padding with zeros is required at that stage to reach a multiple of 2 in the number of pixels.

c) Time per Sample: Long maps are not desirable because of variable thermal and gravitational deformations (in the case of tracking a celestial source) of the dish surface. Common practice is to set a reasonable upper time length limit per map and then calculate the time per sample based on the dimensions in b).Several maps should be taken in succession, and once reduced, can be compared directly or averaged offline (initial results at the ATF seem to suggest that averaging may be counterproductive).

d) Gain Corrections, etc: Any receiving system is subject to gain variations with time. Periodic observations at boresight are included in the maps to track/correct them (usually at start/end of rows). Pointing observations may also be required.

Since wind loads,high humidities and temperature gradients over the main dish may severely affect the precision of the measurements, holography should be carried out at night and in good weather conditions (possibly with an inversion layer present). We now outline the steps required for the measurement of the radiation pattern of the antennas for the three possible (i.e., transmitter and 2 celestial holography) methods listed above.

2.1.2 Transmitter Holography

This method involves a single antenna and a beacon/transmitter signal usually installed in the near-field (Baars et al 2006). The signal of the transmitter (usually fairly narrow-band) is scanned by the antenna in a 2-D raster-map extending enough beamwidths at the frequency of observation to sample small-scale structures on the surface (a map of size Nθ_A samples structures on the main dish at scales D/N, where θ_A is the **amplitude** main beam FWHM and D the antenna diameter). Given that the transmitter power output is high, very good SNR can be achieved with relatively short integration times per point. It is therefore the preferred method for setting the surface panels on the main dish. The planned ALMA holography receiver used in the observations has two channels (Perfetto and Emerson 2000), one, with well known beam-pattern, for phase reference looking at the transmitter and the other receiving the signals reflected from the main dish.Since the beacon is usually located at low apparent elevations (i.e., $\sim 10^o$), and the antennas are expected to operate at higher elevations, the optimum surface shape will be set to an average “operation angle” (the so-called “rigging angle”) based on models of the expected gravitational deformation of the antennas.

a1) Required Precision of Measurements: The current specification for the surface RMS of the ALMA antennas is 25μm (Wootten 2005) with a goal of 20μm.This implies that the measurements will have to be as precise as $\leq$10μm.For observations at 104.2GHz (currently used at the ATF), and the map size mentioned in b1) (i.e., 128x128) this implies a required SNR per point at boresight of SNR$\geq$2800 (see Appendix).

b1) Size of Map: For the prototype antennas at the ATF the smallest dimension of the surface panels is $\sim$0.5m. For a 4 sample per dimension scenario, this implies 0.125m or (at least) 96x96 point maps. The maps taken at the ATF during the AEG phase were usually 128x128 points to provide some additional sampling and additional ease of computation.

c1) Time per sample: For a total map length of 1 hour, the integration time per point for the beam map in b1) will be $\sim$0.1-0.2sec (when boresight observations are considered).

d1) Dual Frequency transmitter: To cope with ground scattering and EM clutter, the transmitter/receiver system can be set up to measure raster maps at two frequencies.The maps thus obtained can be compared and spurious effects removed.

e1) Signal Feed Phase Pattern: The feed that points directly to the main dish (i.e., ”signal” feed) can introduce significant distorsions in the maps due to its phase response characteristics. Its phase response should therefore be measured carefully (usually in a lab) and the response pattern corrected offline in the reduction stage.

The typical steps involved in a transmitter holography map are as follows:

- Transmitter Initialization
- Receiver Set-up (tuning, etc)
- Antenna pointing and focusing on transmitter (locating maximum power on boresight direction). Setting up level so that system is in linear regime.
- Taking map by repeating sequences of one or more rows and a boresight measurement
- Take several maps per run

2.1.3 Celestial Holography

Two celestial holography techniques can be used for ALMA, ie. phase-retrieval (OOF) and interferometric. As will be shown below, the former will only be possible on a very limited number of sources because of more stringent SNR requirements. Neither of these two techniques will provide enough sensitivity for panel setting, but can be used to check overall surface shape and its elevation variations.The main differences with transmitter holography are:

- Maps will include **both** the main reflector and the subreflector illumination (tapering, etc).
- Sources are quite weaker than transmitter signal.
- Most usable sources will have a broad-band continuum spectrum, but strong SiO masers are also a possibility.
- Sources at different elevations can be used.
- Sources need to be tracked on sky.
- No near-field correction needed.
- No specific holography receiver used. ALMA receivers at any band can be used, but low frequencies are preferable (i.e., Band 3). Bandpass calibrator observations are advisable to take advantage of the wide ALMA bandwidths.

Interferometric Holography

A celestial source is observed by two or more antennas at the same time in interferometric mode. One (or more) of the antennas is always tracking the source while the rest scan the source in a raster pattern.Using N antennas as reference will improve the SNR by sqrt(N). The role of “reference” antenna(s) can be assigned to any antenna in the array and can be changed at any time. However, because of the problems (see below) associated with long baselines, it is expected that this will be carried out with a small group of nearby antennas.

Since the SNR requirements per baseline follow the same formulae as for the transmitter holography case (see appendix),to reach ALMA antenna surface RMS precision, a SNR> 3300 at boresight would be required at 90GHz and a 128x128 map. Using median weather conditions on site, ALMA specifications for T_{RX}, ELV=60 deg and an 8GHz bandwidth, this implies source fluxes of $S_\nu > 190$Jy for a 0.2sec/point integration time.This problem is *not* alleviated by going to higher frequencies, because the decrease in required SNR with frequency is compensated by the system temperature increase. For continuum observations, only Solar System planets have 90GHz fluxes >190Jy, and the brightest tend also to be the largest in apparent size. For the 86GHz SiO masers, the brightness of the lines can reach a few 1000Jy, but the bandwidths will have to be reduced to a few 100kHz. This implies a SNR that is 20 times worse than in the case of continuum sources for the same integration times per point. Therefore, to increase sensitivity, the use of several ”reference” antennas, larger subarrays and smaller map sizes is required. For instance, for a 64x64 map with 0.8sec/point, the required continuum source fluxes become $S_\nu > 48$Jy per baseline. Smaller maps can still be very valuable in troubleshooting antenna problems at the AOS and for long term studies of the behavious of antennas with elevation and environmental conditions.

Additional complications for this method are:

- Pointing Errors: For two identical ALMA antennas with the current 0.6arcsec pointing specification, 6μm of error will be added to the maps. Pointing jitter (scintillation) due to the atmosphere will also be present (see appendix).
- Source Resolution: If the sources are resolved by the baselines, their brightness structure must be known. Any assumptions on them will result in decrease of accuracy of the holography.
- Elevation Tracking: Structural changes due to elevation changes during the mapping need to be either taken into account at the reduction stage or minimized by doing fast maps.
- Atmospheric fluctuations: uncorrected PWV fluctuations will cause decorrelation, which will increase with the lenght of the baselines.

The typical steps involved in interferometric holography mapping are:

- Receiver set-up and tuning for antennas in subarray
- Bandpass Calibration
- Interferometric pointing and focusing on target source
- Raster map on source by keeping one or more "reference" antennas always pointed to boresight. To track gain variations, every one to a few rows do a boresight observation
- Repeat as many maps per run as possible

Phase-Retrieval Holography (OOF)

In this method, only the amplitude of the antenna pattern is measured for each antenna individually. At least two far-field power patterns at different focus settings are mapped. Using any of the variants of the iterative Misell (1973) algorithm (McCormack et al 1990 and references therein), the phase information is recovered during the offline reduction. This method works best when the focus positions are symmetric w.r.t. the nominal focus and the displacement is sufficient to cause at least a full wavelength of curvature across the aperture (Fuhr et al 1993).

As shown in the Appendix, the boresight SNR requirements for this method are 2-3 times higher than for the interferometric case. There are only 3 planets in the Solar System than output fluxes ∼400Jy at 90GHz (128x128 map) (i.e., Venus, Jupiter, and Mars). Halving the map size adds Saturn to the list and reduces the SNR requirements to the levels of interferometric holography. The lack of sources is a limiting factor for this method, but it has already been used on Mars during AEG at the ATF. Experience at the ATF also suggests that the results are improved when a nutator is used. Since nutators will only be installed on the ACA Total Power Array antennas, this suggests that OOF may be best used at the OSF and that celestial holography at the AOS should mainly be interferometric as soon as enough antennas are available.

Additional complications of this method are:

- non-simultaneity: maps for the different offset focuses are *not* taken at the same time. Atmospheric, environmental and structural effects may thus be different between them, limiting the phase recostruction.
- Source brightness distribution: The source intensity distribution must be known or modelled. Any assumptions on it may affect the outcome of this method.
- Bandpass: In single-dish observations, good bandpass calibration will be quite time-consuming. Narrower bandwidths would be a better option, but this will increase the source flux requirements even more.

As in the case of interferometric holography, reducing the map size (compared with ideal sampling) will be the default mode. Some of the planets can be used at higher frequencies (Band 6).

The typical steps involved in phase-retrieval holography mapping are:

- Receiver set-up and tuning for each antenna
- Pointing and focusing on target source
- Raster maps on source for each of several focus settings. To track gain variations, every one to a few rows do a boresight observation.
- Repeat as many sets of maps per run as possible

2.2 Subreflector Positioning

For most telescopes, the average elevation dependence of the optimum focus position can be modelled with a fairly simple function. The fitting of this function can be carried out as a service observation and kept in a database for each antenna. However, due mostly to environmental effects (temperature changes, differential heating of the main dish, windloads, etc.), the actual focus at a given time and elevation will depart from this mean behavior and needs to be measured relatively frequently (every tens of minutes to hours depending on antenna design).

2.2.1 Focus Curves

The standard procedure to measure optimum focus positions in single-dish mode is the so-called “focus curve” approach. The underlying assumption of this method is that the optimum focus for *each* axis of motion of the subreflector can be measured independently. For each axis, the position of the subreflector is changed while looking directly at a celestial source, searching for the position of maximum power transfer to the receivers. The variation of the detected signal with focus displacement can be usually fitted with a simple parabola, whose peak represents the optimum focus position. These measurements are usually done in continuum (sources smaller than the main beam) at the frequency of the observations.

There are two possibilities for the way the positions of the subreflectors are set, i.e. scanning or fixed-length stepping. In “scanning”, the position of the subreflector is scanned continuously along the focus axis being measured. In “fixed-length stepping”, the focus offset is set to integer multiples of some convenient fraction of the observing wavelength, and data are taken for a fixed length of time in each position. In either case, the total length scanned/sampled is $\approx 0.5 - 1.0\lambda$ for the z axis (optical axis of main dish) and twice that much for the x,y axes (perpendicular plane). The positions of the subreflector are set straddling a “reference” point, which is either a previous measurement or the “mean” value for that elevation coming from the elevation variation curves at hand.

As soon as we have an array with a few antennas at the AOS, we will start using interferometric measurements of the focus positions. Small maps (16x16) on bright continuum sources (or masers) can be used, keeping some of the antennas looking directly at the source while the rest execute the maps. Reduction of these maps would give not only the optimum focus position but also the illumination offsets of the feeds (see below). Interferometric maps will also be more sensitive than the single-dish modes.

Single-Dish Focusing

The observations are done using autocorrelation data only, which will include both the source and atmospheric/system emission. A rough estimate of the required source fluxes can thus be derived as follows:

- T_{sys} as in ALMA Memo 372 (Moreno & Guilloteau 2002).
- Bandwidth: 8GHz
- Integration per sample: 0.1sec
- Detection Level: 5σ
- Level at best focus: $>25\sigma$

This implies source fluxes of S_ν >5Jy at low frequencies (up to Band 6) and S_ν >70Jy at high frequencies (above Band 7).Very few sources on the sky have the fluxes required for the focusing at the high frequency end (i.e, a few planets). For the “fixed-length stepping” method, a total integration per focus position of ∼1-2sec and 5 positions should be enough. The set of measurements should be done at least twice, with a set increasing and a set decreasing the focus settings to eliminate systematic effects.

The typical steps in single-dish focusing would be as follows:

1) Set-up receiver (if needed) and IF attenuator levels
2) Move to calibrator source and point on it
3) T_{sys} measurement (if needed)
4) Do focus curves for 3 axes in the following order: Z, X, Y; measure (fit) and set the focus for each axis
5) Pointing on source
6) Iterate from step 3) if required (i.e., dubious fits, large offsets required, large pointing offsets after focus fit, etc.)

Interferometric Focusing
In this case, several antennas in a subarray can be commanded to do simultaneous maps (16x16) of bright celestial sources, while some act as ”references”. The flux requirements for the sources are thus reduced, compared with the single-dish case, by a factor $\sqrt{(}N-1)$, where N is the number of ”reference” antennas in the subarray.

The gain variations of the system can be measured straddling the focus maps. Real time variations, which will be important for widely spread antenna configuration sub-arrays will depend critically on the WVR phase correction scheme.

The maps can be then reduced offline using software for holography. Since the maps are small, the information in them will not be usable to study any properties of the main reflector, but will be enough to detect the displacements from the optimum focus locations on each of the 3 axes of translation of the subreflectors (Baars et al 2006). This method is currently being used by the IRAM PdB interferometer.

The typical steps in interferometric focusing would be as follows:

1) Set-up receiver(s) (if needed) and IF attenuator levels
2) Move to calibrator source and point on it (interferometrically)
3) Self-Gain Calibration on source
4) Do focus mapping
5) Self-pointing on source, gain calibration and iterate from step 3) if required (i.e., dubious fits, large offsets required, large pointing offsets after focus fit, etc.)

2.3 RX Feed Setting

As in the case of focusing, we have the possibility of using single-dish and interferometric methods of strong continuum sources to measure the illumination offsets of the feeds. Since interferometric methods are quite more sensitive, we will use them as soon as possible at the AOS. The final alignment on the subreflector may require warming the FE dewar if the offsets are deemed unacceptable.

2.3.1 Single-Beam alignment

Single-Dish: OTF/Raster maps in AZ and ELV are required. The maps will *not* need to extend to more than the first null on the main beam, but will need to be sampled at least 3 times per HPBW (convolution of the beam and the source size) along the scanning direction and 2-3 times in the orthogonal direction. The *center* of the map should be located in one of the rows. A simple rule-of-thumb for the number of pixels per map is:

$$N_{AZ} = N_{ELV} = ceil((BWFN + SourceSize)/(HPBW/3)) \tag{1}$$

$$BWFN = 2.44 \times HPBW \tag{2}$$

$$HPBW = 18 \times (345./\nu(GHz))arcsec \tag{3}$$

where BWFN is the beamwidth at first null, *ceil* is the function to round up to the next integer and the calculation has been done for an ideal 12m dish. The outer regions of the maps can be used to subtract the average sky emission from single-dish maps.

A rough estimate of the source fluxes is as follows:

- Detection level: 5σ at -10dB power pattern point of main beam
- Source Size: 20arcsec (real or just region to map)
- T_{sys} as in ALMA memo 372 (Moreno & Guilloteau 2002)
- Bandwidth: 8GHz

For the ALMA antennas, at 90GHz and 650GHz, the map sizes would be (see above) 9x9 and 15x15,respectively. For a scanning speed of ~60"/sec, the integration times per sample would be 0.4sec and 0.05sec, and the required source fluxes S_ν >4Jy and S_ν >150Jy, respectively.

The typical steps for feed alignment will be:

- Tune Rx and IF set-up
- Pointing/focusing on source (1)
- Raster map (gain calibration by boresight observation if needed for interferometric case)
- Repeat from (1) until desired configuration is achieved

Interferometry: For interferometric maps, all the requirements for a single baseline celestial holography apply (see above). The same map sizes as for focusing (i.e., 16x16) can be used in the measurements. The same reduction methods can be used to fit both the focus and the illumination offsets simultaneously.

2.3.2 Beam-Squint

Beam-squints can be easily measured with a pointing run where *both* channels of a given ALMA band observe the same calibrator. The relative orientation of the two channels will be derived from the difference in the pointing offsets. Using several sources distributed in a range of AZ and ELV angles or tracking the same source for a wide hour angle range should show, in case of an offset, that one of the channels is "rotating" on the sky with respect to the other that can be considered the "reference". If the offsets are within the current pointing specification of the antennas, i.e. 0.6",nothing needs to be done, as the pointing model for each channel will absorb the differences. For larger squints, the splitter should be re-aligned if possible.Otherwise, the apparent uv coordinates of each channel will need to be considered during data reduction; also polarization observations will be quite more difficult to calibrate because of the change in relative orientation of the two channels.

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Appendix

The basic formulae for the different types of holography have been presented by several authors in the literature (Butler 1998, Morris 1984). For phase-referenced holography (i.e., either transmitter holography with a dual receiver or celestial interferometric observations), the boresight RMS error due to the SNR of the observations goes as (Butler 1998):

$$\sigma_{SNR}^{ref} \sim \frac{\lambda N}{3\sqrt{2}\pi SNR}$$

where N is the number of samples per map row. This equation can be trivially inverted to obtain the required SNR of a map of given dimensions and for a desired error. As an example, for an N=128 map, and a 10μm RMS, the required SNR=4511 at 90GHz. The SNR requirements for phase-retrieval holography are more stringent, requiring a factor 2-3 higher SNR than the phase-referenced observations (Tarchi and Comoretto 1993):

$$\sigma_{SNR}^{OOF} \sim \sigma_{SNR}^{ref} \frac{Peak_{foc}}{2Peak_{def}}$$

where σ_{SNR}^{ref} is the error in the phase-referenced observations, and $Peak_{foc}$, $Peak_{def}$ the peak values in the defocused maps and focused maps, respectively.For the map parameters above, the required SNR would be in the range 9000-14000, or a source of ~400Jy.

Random pointing errors of the telescope while carrying out the raster maps will result in an overall map error of (Butler 1998):

$$\sigma_{point} \sim \frac{\theta_{rms} D}{8}$$

where D is the antenna diameter and θ_{rms} the RMS pointing fluctuations (in radians). For a 12m dish, transmitter holography with dual receiver and the current ALMA pointing specification of 0.6 arcsecs, this implies an error of 4.4μm. For celestial interferometric holography this number will increase by a factor $\sqrt{(}2)$ for a single baseline.

Atmospheric scintillation will affect both the amplitude and phase of the input signals, causing surface measurement errors for phase-referenced observations of (Butler 1998):

$$\sigma_{amp} \sim \frac{A_{rms}\lambda}{6\pi}$$

and

$$\sigma_{pha} \sim \frac{\lambda \phi_{rms}}{6\pi}$$

where A_{rms}, ϕ_{rms} are the RMS fluctuations in amplitude and phase, respectively.For transmitter holography at the ATF (104 GHz), typical values for these fluctuations were ~0.1% in amplitude and ~0.3deg in phase, which imply errors of 0.1μm and 0.8μm, respectively. At the AOS, and when doing celestial holography, a 1% amplitude and 1deg phase fluctuation (assuming best quartile weather, a 50m baseline and WVR correction working), become 1.8μm and 3.0μm at 90GHz.