Atacama
Large
Millimeter
Array

ACA/ALMA Calibration Coordination

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Specification Document

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Contents

1 Introduction

There the three instruments in the ALMA project. The ALMA 12-m array consisting of 50 twelve-meter diameter telescopes; the ACA 7-m array consisting of 12 seven-meter diameter telescopes; and the ACA TP array, consisting of 4 twelve-meter diameter telescopes that will be used mainly in a total-power mode of operation. These three arrays can be combined in a variety of ways. At one extreme, all 66 telescopes can be used as a single array to image a target region. At the other extreme, the three instruments can be used independently to image the target region at different times, and then the data can be combined to form the final image. Most of the time, however, observations will use a suitable mixture of the three instruments in order to best meet the needs of the science goal.

2 Coordination Goals

We will mainly concentrate on the ACA 7-m array and the ALMA 12-m array since these two instruments have similar calibrations and reductions although they are of different antenna diameter, array size and number of elements. The additional calibration problems posed by the ALMA TP array are briefly discussed at the end of this memo.

The general concerns described in this memo are given below.

1. Infrastructure: The ACA and ALMA array infra-structures (receivers, frequency coverage, correlators) should be sufficiently similar in order to produce consistent correlated data that can be easily combined and analyzed.
2. Meta-data: The on-line corrections and supporting meta-data needed for additional off-line corrections are consistent and complete. This includes meteorological and water vapor meta data and also included various system and sky temperature measurement switching methods.
3. Data Archival and Pipeline input: The archival data repository and pipeline reductions are coordinated between the ACA and ALMA to enable similar calibrations and reductions to be done on each array separately, or on combined data from both arrays.
4. Semi-stable array calibrations: The primary beam mapping, antenna locations, pointing models, frequency characteristics, system delays are examples of calibrations that are obtained from interferometric observations. They should be coordinated for maximum overlap and sensitivity. Many of these calibration can be obtained for the ACA-TP array used in interferometric mode with the other telescopes.
5. Calibrator Monitoring: Coordinated ACA and ALMA observation and scheduling are needed to monitor the variable flux density and polarization of primary and secondary calibrations. Accurate positions and structure will also be determined.
6. Combined ACA and ALMA Science Operations: Develop guidelines for determining when combined ACA/ALMA observations are needed. For non-simultaneous ACA/ALMA observations, explore methods to determine the flux scaling and position registration of the two data sets. A proposed method for high frequency imaging is to use the ACA for the target observations, but the ACA/ALMA array for some of the calibrator observations in order to increase the SNR for the phase calibration, the reference pointing and accurate bandpass determinations..
7. Heterogeneous array imaging: Develop software for the combining/deconvolving/self-calibration of data made with the heterogeneous array of the ACA and ALMA instruments.

8. Combining ACA TP data: Develop total-power calibrations for the ACA TP (both internal switching and with some interferometric observations) and how to incorporated total power data into the interferometric data.

3 Coordination Details

In this section we elaborate on the points listed above. Much of the detailed calibration procedures are written in the other calibration memos and will not be repeated here. However, the different sensitivity, resolutions and u-v coverage of the ACA-array and ALMA-array were designed to be complementary to reach the science goals, so calibration differences between the arrays must be done consistently..

3.1 Infrastructure

The coordination of the delivery and testing of the telescope mechanical systems will be done somewhat independently by the Japanese, European and North American Groups. However, the expected performances are well developed and are consistent among the three ALMA instruments. The receiver systems are virtually identical for all three instruments. The ACA TP array will have additional switching flexibility for accurate single-dish imaging. The ALMA telescopes will be able to switch between a calibrator and target more quickly than that by the ACA, and may effect the strategies of the interaction of the water vapor radiometry viz-a-viz fast-switching. Additional details in the infrastructure differences are beyond the scope of this memo.

The ALMA and ACA correlators have a significantly different design, but the output correlated data will have nearly the same characteristics (see memo xx). The specific use of the two correlators will depend on the mix of the ACA and ALMA arrays for the science programs. Correlating the same experiment through both correlators will be an important test of each correlator during debugging.

3.2 Meta-Data

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Several calibrations associated with specific telescope hardware are being coordinated among all of the telescopes. For example, see the memo on the Amplitude Calibration for the techniques that are proposed for determining the system and the sky temperature. Some of the calibrations and flagging will be done on-line and some will be associated with the meta data for later application in the pipeline or subsequent programs. There should be minimal differences between the ACA and ALMA arrays.

The use of weather stations located in and near the telescopes, and the use of satellite and balloon data should be coordinated for the ACA and ALMA arrays. The number of stations has not yet been determined. Has there been a decision whether the meteorological instruments for the ACA and ALMA will be supplied by the same vendor?

The WVR measurement to remove the quickly-changing tropospheric phase fluctuations and the variable atmospheric opacity will be one of the important calibrations for ALMA and the ACA. These instruments offer the best method to remove short-term phase fluctuations between 1-second and 60-second time scales. The density of WVR receivers needed in the ALMA array is still under consideration. It seems likely that most ALMA telescope will have a WVR system, but the ACA array will have about four to five WVR systems surrounding the ACA 16 telescopes to determine an instantaneous phase wedge over the array. It may take a year or more of experience in using the WVR system over a variety of weather conditions and array sizes to determine the optimum number of WVR receivers and its coordination with fast phase switching. All such research must be coordinated between the two arrays.

3.3 Data Archival

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It is presumed that all correlated data will be read into the same archive, regardless of whether there are ACA-ALMA correlated baselines, or independent ACA and ALMA experiments, or the data were correlated on the ACA or ALMA correlator. Thus, the fundamental data from each array must be essentially identical. It is likely that some of the meta-data and flagging algorithms may be somewhat different between the ACA and ALMA systems, but such differences must be documented, and have little impact on the data calibration. The data from the ACA-TP array, however, is of a different character. It should be stored in the same archive, but no details are yet available about the coordination of the total power and correlated data for an experiment.

3.4 Semi-Stable Array Calibrations:

There are a large number of calibrations which are relatively stable with time. Fixed properties of each telescopes, such as the full-Stokes primary beam pattern, antenna efficiency, elevation dependencies, and internal pointing characteristics for each telescope, will be determined during the commissioning of the telescopes as they come on line. These antenna properties will ultimately have to measured sufficiently accurate so that they can be used for high-dynamic range imaging.

Array parameters that change when an antenna is moved are the precise location of each antenna, pointing collimation, and peculiar delay. Receiver changes will also change the receiver-based delay, on-axis cross-polarization terms, and nominal bandpass over the frequency range of each band.

The above ACA and ALMA array parameters will be made by the commissioning teams during construction and the operation teams when debugging and scientific operations begin. Because many calibrations require relatively high snr, and are more efficiently done with many telescopes at once, coordination between the necessary observing of the ACA and ALMA arrays is useful. Clearly, bringing a new telescope on-line will probably be handled by the ACA and ALMA separately, but serious calibrations should be done in concert as much as possible.

Two operational concerns should be address: First, nearly all of the above calibrations requires the development of robust software to analyze the appropriate data in order to obtain the array and telescope parameters. Some of the software can function on-line as the data are transferred to the archive, with results obtained nearly instantaneously. Some calibration parameters require hours of data that must be first stored in the archive and then subsequently analyzed in the software package. Many of these software packages will be useful for off-line reductions; for example, the determination of more accurate antenna locations. At present, these necessary software packages have not been fully designed, let alone implemented.

Secondly, the results from the calibrations must also be accessible to the archive data. The calibration parameters should be referred to the relevant observations so they can be redone if necessary, with better algorithms or better edited data. Also, the calibration parameters will be applied to many experiments within the period of time applicable to the calibration type. The methods and accounting of the parameters and their applications have not been formulated in any detail.

3.5 Calibrator Monitoring

The relative amplitude and phase calibration of the ACA and ALMA arrays will be determined from fast switching observations between a calibrator and target source, usually separated by less than a few degrees. This requires a known list of several thousand compact calibrator sources with approximate flux densities (many will be variable) and accurate positions to 1 mas (see Phase Calibration Memo). When ALMA begins operations, a reasonable number of calibrators north of $-30°$ will be available, but with limited knowledge of their high frequency strength. South of this declination, very few calibrators are known, and one of the first early surveys of the ALMA array (say with six or more telescopes) will be to observe several thousands of southern candidate sources from existing catalogs for suitability as ALMA calibrators. During the middle construction period for ALMA and the ACA, such surveys using 6 to 10 telescopes may be available and sufficient for this search.

However, the accurate position of the new calibrators to 1 mas accuracy can only be determined using one of the larger ALMA-12m arrays and a 24-hour observation astrometric quality schedule, similar to those now using VLBI techniques. The use of the group delay (phase slope a wide bandwidth), rather than the phase, may be needed since these observations must cycle around the sky quickly in order to model any residual tropospheric refraction.

The absolute flux density and polarization angle calibrator of ACA and ALMA observations can only be obtained from observations of primary calibrators–those sources with known flux density and polarization properties. Approximately 6 absolute flux density calibrators will be needed to determine the array flux density scale to better than 2% at the lower frequencies and possibly 5% at the higher frequencies. These calibrators need not be point sources, but must be non-variable or predictably variable. The likely candidates are the outer planets and some large asteroids that are relatively small in angular size and dominated by thermal emission. Small-diameter planetary nebulae and other compact galactic objects may also be useful. It is expected that ACA low-resolution observations will be critical in monitoring a list of possible primary calibrators in order to find the most stable sources.

The determination of the accurate flux density of the secondary calibrators (a large majority will be very variable quasars) used in an ALMA or ACA observation must be bootstrapped from at least one observation of a primary flux density calibrator during the experiment, or determined in other observations within a few days of the experiment. For example, it may be feasible to use the ACA-alone, with its relatively low resolution, to observe the primary calibrators mixed in with the secondary calibrators that will be used/were used for scientific experiments. Such exploratory observations may also be useful to determine if a tentative calibrator to be used in an up-coming experiment has become too weak.

3.6 Combined ACA/ALMA Science Operation:

The coordination of use of the ALMA 12-m array, ACA 7-m array and ACA TP array for scientific observations, including calibrations, is unclear at the present time. In fact, the optimum observation strategy will depend on the two angular-scale properties of the target region. The minimum angular scale (ie, what are the longest ALMA spacings that are needed?) and the largest angular scale (ie, is the ACA-7m array needed or is mosaicing needed?). For some targets, this angular information is already known. For other targets it may be unknown, especially imaging of a rare chemical species.

We conclude that short, exploratory observations of a relatively unknown target source may be needed in order to schedule optimally the target. A short period of observations with the ACA-TP plus ACA-7m observations, for about 10 minutes, would probably give sufficient information to schedule the bulk of the observations properly. If the target is relatively weak and with an unknown extent, then short observations beforehand will be of little use. The exploratory observations could be merged with the calibrator bootstrapping ACA observations, suggested above.

For observations of extended sources which are known to be larger than the primary beam size, then all three arrays will be need, and mosaic observations (several pointing locations) will be common. There are clear advantages to combining the ACA and ALMA arrays into one array of 62 elements: Lower detection level for a point source, compared with separate array observations; fullest u-v coverage; more uniform snr over baseline length since the less sensitivity ACA baselines will have significantly more correlated flux density than the longer ALMA baselines; and possibly the most important, the identical amplitude and positional calibration for the ACA and ALMA telescopes. The addition of the ACA-TP single-dish data to include the extended emission in the final image will probably be required. In this case, some interferometric observations of the 4 ACA-TP antennas individually with the ACA-ALMA array may be needed to obtain a consistent single-dish amplitude scale with the array data. However, conversion of the ACA-TP antenna 'interferometric' gain to that appropriate to its total-power mode may depend on several properties used for the total-power switching.

It is expected that observations at the highest ALMA frequencies may need a more complicated observing/reduction strategy in order to obtain the best scientific images for extended sources. The optimum configuration for many sources may consist of the ACA, the ACA TP arrays and possibly only the inclusion of about 10 ALMA telescopes closest to the ACA. Unless there is very small fine-scale structure, much of the outer ALMA antennas will not be useful (they can be then used at a lower frequency to determine positions and sub-arcsec structure for relatively bright sources).

The ACA may not have sufficient sensitivity to detect within a coherence time of about 5-sec (longer if the WVR corrections are accurate) a calibrator which is only a few degrees from the target. Two methods have been suggested to alleviate this problem. First, the entire ALMA array can participate with the calibrator observations in order to obtain sufficient sensitivity to determine the ACA-telescope calibration values. The necessary signal to noise is even more crucial for an accurate bandpass calibration, even from a stronger calibrator, also requiring ALMA support of ACA observations.

The use of calibrator observations at a low frequency to calibrate a target at higher frequency was described in the Phase Calibration Memo, with a suggested observing scheme. Only the phase connection between the two frequencies is difficult to obtain; transferral of the amplitude calibration should be accurate.

3.7 Heterogeneous Array Imaging:

When the ACA and ALMA arrays are used simultaneously, first pass calibration using a calibrator at the beam center is straight-forward. However, any imaging, except a detection of an object near the phase center, and subsequent self-calibration techniques on strong, large sources, will need more versatile image/calibration software than is now available in an interferometric package. Perhaps, iterative methods will be sufficient to obtains good quality images. For example, after applying the calibration values from the calibrator observations, four undistorted images of the target can be obtained from: ACA-TP observations (if included); 12mx12m baselines; 7mx7m baselines; 7mx12m baselines. Although each image has its own resolution and field of view, they can be combined with feathering techniques in order to obtain an output image consistent with the four input images. Self-calibration of this image with the heterogeneous data sets is now possible, although more complicated.

3.8 Combining ACA TP Data:

The ACA total-power TP (four 12-m antennas) have specially designed hardware and switching modes in order to determine the low resolution image of the target source (if a mosaicing observations) or the zero-spacing flux density (weighted by the 12-m aperture) if a single pointing. The other ALMA and ACA telescopes will also obtain the total-power data (auto-correlation), but with less stability.

The gain calibration of the ACA-TP telescope used in the total power mode is still under investigation and is beyond the scope of this memo. The variable troposphere emission and attenuation can be largely removed with various switching techniques; pointing offset, nutation, and frequency). The system temperature calibration, including the atmospheric attenuation, has been described in the Amplitude calibration memo. These calibrations should be sufficient for the ACA-TP single pointing target observations to be added to the interferometric data of the target source.

However, it is unclear whether the ACA-TP gain derived above from switching observations of the target source alone will consistent with that from the interferometric observations. Additional ACA-TP observations of the interferometric calibrator source, with the same switching mode used for the target, and a few minutes of data in which each ACA-TP telescope is correlated with the ACA-ALMA telescopes, will provide a sufficient gain tie in between the array observations and the TP observations

Multi-pointing (mosaic) interferometric observations and ACA-TP observations will have calibrations that are essentially identical with a single pointing observations. However, the techniques for the combined deconvolution of all of the pointing fields and subsequent self-calibration need more development. For large mosaic regions, it is possible that the ACA-TP array will scan the desired region many times (on-the-fly observations) over the experiment period, in order to decrease the effect of the sky background variations with time and position. More details of the calibrations are beyond the scope of this memo. One additional complexity is that the effective resolution of the on-the-fly image depends on the sky subtraction, switching and convolution methods that are used to produce the image over the region. This resolution must be accurately known before suitable combination can be made with the interferometric data.

Switched polarization TP measurements are possible. Once the gain of the two parallel hand receivers have been obtained using the above strategy, interferometric observations of the TP antennas with some or all of the ACA/ALMA array should determine the on-axis polarization leakage terms. This type of observation has been rarely done, so that more experience is needed to determine the efficacy of TP polarization measurements.