Joint ALMA/ACA Calibrations, Reductions and Observations

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1. Motivation

A memo (Kawabe, Takakuwa & Vila Vilaro, dated 2005/09/05) described the scientific and calibration benefits of combined ALMA/ACA correlations. The combined array produces a modest increase in the signal-to-noise (SNR) for most observations and calibrations, but a few critical calibrations, especially at high frequencies for ACA observations alone, need the combined array. These gains should be balanced against the cost and effort needed to produce crossed-array correlations with the ALMA correlator.

The joint ALMA/ACA correlation of data has recently become more technically feasible for several reasons: 1) The total number of operating antennas is unlikely to exceed 64 antennas, the limiting number of antennas that can be simultaneously processed by the ALMA correlator; 2) The various combinations of ALMA and ACA antennas can be switched under computer control; 3) The basic characteristics of the ALMA and ACA antenna data streams are similar.

This correlation capability suggests that combined ALMA and ACA interferometric observations, calibrations and reductions could become the normal operation of the arrays. The separate observations of the ALMA and ACA arrays may still be common but more arbitrary subarraying (egs. ACA array plus nearly ALMA telescopes) may be useful, especially at the higher frequencies. This memo discusses the impact of a closer collaboration between the arrays.

2. Description of the Arrays

It is possible to view the ALMA/ACA as three different instruments: a high resolution array with 50-12m antennas (ALMA array); a low resolution array with 12-7m antennas (ACA array), and a total-power system composed of 4-12m antennas (TP array). These systems were designed to be compatible in the sense that together they cover a range of angular structure from many degrees down to $0.1''$ in some cases. Stand-alone scheduling, calibration and imaging of the three instruments is possible and with the use of two separate correlators—the ALMA 64-element correlator and the ACA 16(?)-element correlator—mainly stand-alone usage was originally envisioned. For those scientific programs for which all three array resolution coverages are needed (perhaps $> 50\%$ of the programs), the combination of the three images at different resolutions, observed at independent times, can be made with feathering or other techniques to obtain one image covering the entire resolution range. Some problems concerning the accurate calibration and precise combination of these images are discussed below.

A suggestion in this memo is that the ALMA 50-element array, the 4-element TP array, and the ACA 12-element array, should be considered as one hybrid array 66-element array. The 4-12m TP array will also be specially equipped to determine the accurate 'single-dish' images of large regions of sky, but it should to be correlated with all other antennas in the ALMA array and ACA arrays with no additional complications.

3. Anticipated Use of the ALMA/ACA Arrays

The mix of the probable scientific use of the ALMA arrays should be the prime driver to the calibration and reduction schemes that are being developed. The major types of observations are:

- **Weak and small sources**: Observations of either continuum or line emission regions, that are smaller than the 12-m primary beam (and with no other confusing emission present) require the maximum collecting area. Thus, ALMA/ACA observations using all antennas, correlated together, will give the best signal to noise. All baselines can be used in the imaging and calibrated together without regard to the different primary beam of the antennas (to zeroth order). The slight degradation of optimum (u-v) coverage because of the high density of ACA/ALMA baselines at ~ 1 km baselines, is relatively unimportant for these projects. However, the slight increase in SNR for these noise-limited projects may be an inefficient use of ACA-array time if there are significant ACA-stand alone programs with high scientific priority.

- **Extended sources:** The imaging of source emission which extends more than about the half-power size of the 12-m primary beam, may or may not need mozaicking, but will need observations of the entire ALMA/ACA arrays for accurate image reconstruction over the large range of angular scale. Although the observations can be made independently at different times uses the ALMA, ACA and TP arrays, simultaneous observations have the following advantages: 1) Better SNR for the calibrations and for the source image when we understand how to incorporate the 7m x 12m baselines; 2) Consistent relative gain and registration between the ALMA, ACA and TP amplitude using one calibrator; 3) The efficiency of scheduling and reducing the combined data.

- **High frequency observations:** Observations above 500 GHz will be severely affected by phase and gain fluctuations and may not require the full resolution of ALMA/ACA. In fact, it may be common to use the ACA array plus the TP array plus the a small number of ALMA elements that are within several kilometers of the ACA, for optimum resolution. Even if not all of the ALMA array are needed for the source image (because of over-resolving the source), the necessary sensitivity for calibrations may need the entire ALMA array. The calibrations are: detecting a calibrator that is sufficiently close to the target; the use of reference pointing on the calibrator or another somewhat brighter source not too far from the target; scaling the phase calibration at a lower frequency than the observed frequency, and the determination of accurate time-variable bandpasses.

- **Separate ALMA/ACA Observations:** Stand-alone ALMA or ACA observations will be useful in several other cases: First, those fields that contain only fine-scale structure can be adequately imaged with the ALMA array alone. Secondly, fields which contain only large-scale structure can be imaged with the ACA array and the TP array (inclusion of some ALMA antennas are discussed above). Next, The ACA or ALMA may be better suited for particular kinds of calibrations. For example, the determination and monitoring of the set of primary flux density calibrators and the bootstrapping of the current flux density of variable secondary calibrators that will be used for the scientific observations, may be best obtained using the ACA array because of most of the likely primary flux density calibrators will be too resolved with the ALMA array. However, the determination of the structure and precise position of calibrators will be much better done with the ALMA-array.

The tentative conclusion is that majority of scientific programs may profitably use all of the ALMA/ACA antennas, so that a combined approach to scheduling, calibration and reductions would be much more efficient since all of the data can be correlated together.

4. Calibration Strategies of the ALMA/ACA Arrays:

The antenna and array characteristics will be determined by two general types of calibration techniques: measurements from a variety of electronic supporting devices, and selected astronomical observations of calibrator sources. The electronic support will be similar but not identical for the three different ALMA/ACA arrays, but will provide a consistent basis for good apriori measurements of important array parameters. Many of the calibrations of the TP array will be significantly different than the interferometric arrays, and are not discussed in this memo. Clearly, some of the purely interferometric calibration of the TP antennas with the ALMA and ACA arrays will be useful.

The needed observations of calibrators, on the other hand, will be similar for the ALMA and ACA arrays, and should be integrated into one unified system. The major aspects of the calibrations are:

- **Stable and Semi-Stable Calibrations:** Astronomical calibrations of relatively stable array/antenna parameters can use strong sources which are distributed over the sky, and can be made with a relatively small array of antennas. Some examples are the determination of antenna locations, average pointing parameters, determination of gross delays, focus and sub-reflector settings, many as a function of receiver band. Many of these calibrations will be adhoc, depending on when an antenna joins the array in the early days of development, or when significant changes are made to an antenna or receiver system. Hence, these calibrations can be done at any time by pulling out a relevant small subarray of antennas, performing the calibrations, updating the necessary parameters, and placing this subarray back into the main array. Most of the calibrations will take less than 1 hour of observing time. The impact on the scientific program (if any) by the loss of some antennas must be chosen to not significantly decrease the scientific goals of the program. *The difference between the 12-m antennas and the 7-m antennas will not be a factor in these types calibrations*, so that any convenient sub-array mixing in 7-m and 12-m antennas can be used.

- **High Dynamic Range Calibrations** There are some calibrations of relatively stable antenna parameters that require high signal to noise, and thus need a large part of the collecting area of the ALMA/ACA array. The most obvious calibrations are the determination of the primary beam response in all stokes parameters and the precise bandpass characteristics. These should be done in all of the observing bands. These calibrations require large amounts of scheduled time.

- **Phase Referencing:** A crucial calibration of the ALMA/ACA arrays will be the fast switching between a calibrator and target in order to determine temporal gain and phase calibration over time-scales longer than about one minute. The shorter time-scale fluctuations will be removed using WVR measurements at or near each antenna. The calibration accuracy requires a small angular separation between the calibrator and the target, with a separation of a few degrees as acceptable. At the lower ALMA frequencies, the sky has a sufficient density of bright calibrator sources so the ALMA and ACA arrays (or subarrays) can be calibrated on their own. However, at the higher frequencies, the ACA array-alone may not have the sensitivity to detect an adequately close calibrator to a target, and must use a significant part of the ALMA array to detect a close calibrator with sufficient signal to noise. Thus, the combined ALMA/ACA array may be needed for high frequency imaging even if many of the ALMA array baselines resolve out the emission.

6. Related Topics

This section contains a brief discussion on ALMA/ACA array consideration which may have impact on their combined calibration and observing.

- **7m-12m Baselines:** The simple use of the 7m-12m baselines and the 7m-7m baselines for the combined ALMA/ACA arrays will be problematical except for most calibration observations, for sources much small than the 12-m primary beam, or for very weak sources which are less extended than the 12-m primary beam. In these cases, the imaging effect of the different primary beam areas of the 12m and 7m telescopes can be ignored to first order. The 624 7m-12m baselines has about 25% of the sensitivity of the 1326 12m-12m baselines and improves the image SNR somewhat.

  For accurate imaging of sources which are larger than about the half-power size of the 12-m primary beam, new algorithms must be developed, and may be relatively expensive in computer power, compared with imaging using just the 12m-12m baselines. It is possible that good quality images can be obtained by combining images made from the 12m-12m baselines, 7m-7m baselines, 7m-12m baselines and the TP array. In principle, this combined image would have the same SNR as that from imaging all baselines.

- **Comparative ACA and ALMA Array Sensitivities and Extended Sources:** Because the ACA array is less sensitive than the ALMA array, there has been discussion about the optimum relative observating time needed for both independent array and combined array observations. Most of the conclusions are based in simple SNR considerations that are applicable only for noise limited observations of point sources. Since the most interesting scientific observations may be of moderately strong and extended sources, the main limitation may be residual phase noise, and the correlated signals at the shorter baselines may be significantly larger than the longer baselines. Hence, the appropriate mix of ACA array and ALMA array observations is source structure dependent and depends on the WVR capability in removing phase fluctuations. An analogy is the VLA time needed for extended sources, where the amount of B-configuration time, for example, is considerably less than the A-configuration time for optimum imaging.

7. Recommendations

Three characteristics of the ALMA/ACA arrays drive the recommendations given below: The capacity of the ALMA correlator to process virtually all antennas in the combined array; the likely use of the combined array for a majority of scientific programs; and the similarity of the astronomical calibrations used for the ALMA array and ACA array (although the TP array has additional calibration needs).

- The calibration of ALMA and the ACA array using astronomical sources should be a combined, uniform effort. This effort should include the design of relevant calibration processes, the collection and storage of the data in the archive in the appropriate manner, the development of the necessary software, and the team to analyze, document and apply the results to the arrays. The design and use of this global calibration process should not be significantly impacted by differences in the particular hardware and on-line software among the three arrays. These use of these calibration parameters will have to be coordinated with the on-line quick-look calibrations, the initial pipeline processing, and additional off-line calibrations.

- The ACA correlator is will an important component of the array for the following reasons: Comparison of the ACA and ALMA correlator results will be crucial in determining the accuracy in the correlation process; such as, the proper normalization of the lag data, the accurate incorporation of monitor data, and the main limitations of dynamic range. The ACA correlator has more capabilities than the ALMA correlator for the testing and implementing of better algorithms and array combinations, especially those associated with the TP array for which it will have the major responsibility. The ACA stand-alone observations for array flux density calibrations and some high frequency observations can be processed by the ACA correlator.

- The scheduling of the ALMA/ACA array should be combined as much as practicable. In the early days of development when many calibrations will be adhoc, a realistic scheduling of ALMA and ACA stand-alone calibrations and combined calibrations should be attempted. This will depend on the the construction schedules for each of the two parts of the project. Correlator comparison tests, development of calibration strategies, data archiving and analysis of the results will be an important component of early testing, and these early results must be fed-back into the early scheduling of the arrays, both for initial calibrations and first science.

- The ultimate use of the ALMA arrays and how independently the ALMA array and the ACA array observe will depend on the type of scientific proposals, the nature of mm-radio sources, and the ability to calibrate the arrays accurately. Because of the similarity of the astronomical calibration, the combined effort of the ALMA and ACA groups to determine and implement this part of the calibration process will provide better overall calibration, archiving and documentation. If the calibration and operation of the arrays do diverge, then this calibration process can similarly diverge as needed. However, if the calibration groups and techniques develop independently, then later cohesion if desired would be more difficult.