ALMA & ACA Subarraying – Scientific Considerations

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Since the introduction of the four 12-m and twelve 7-m antennas of the Atacama Compact Array into the bilateral ALMA Array the ability to cross-correlate signals from this array with the 12-m antennas of the bilateral ALMA telescope has been required. The purpose of this document is to describe the scientific requirements for subarrays within the ALMA Array. The baseline technical implementation for (1) the LO distribution scheme, and (2) the data transmission system have been discussed in a companion document, ALMA & ACA Subarraying – Technical Considerations by W. Shillue, C. Janes, T. Beasley.

Development of Subarray Scientific Requirements

Scientifically speaking, a subarray is defined as any set of antennas observing the same astronomical source with similar FE/BE setups. At the 29 February 2000 Sytem Review, some confusion arose concerning the definition of a subarray. Under one definition, the number of subarrays is the number of discrete subsections into which the baseline correlator could be divided. In another definition, the number of subarrays is the number of discrete frequencies at which a collection of ALMA antennas may be deployed. The latter definition has been adopted in the technical definition of ALMA; these subarrays have in common the use of a particular LO reference signal. This signal is developed by the laser synthesizers, so that the number of these laser synthesizers sets the number of frequency subarrays. At the 29 February 2000 Sytem Review, the Science IPT developed a discussion of scientific requirements which drove the number of subarrays, with a recommendation that eight subarrays be deployed for ALMA. These subarray scientific requirements were originally presented in the white paper "Astronomical Requirements for the Millimeter Array Correlator" by Rupen, Shepherd and Wright (1998). The Science IPT document was presented to the ASAC at their 7 March 2000 meeting in Leiden, with the result that the ASAC recommended that ALMA should provide: "*a number of 4 to 6 sub-arrays, but the number of frequencies operating simultaneously will not exceed 3 or 4. At present we could envision 4+1 subarrays*". This recommendation was adopted by the project, refined, and incorporated into the ALMA Science Requirements [SCI-90.00.00.00-0390-00] and into the ALMA System Requirements as SCI-420.

1. From the ALMA Science Requirements: [SCI-90.00.00.00-0390-00]. It shall be possible to have at least four subarrays where the observing frequency and antenna control in each is completely independent of the others.

2. From the ALMA System Requirements: [SCI-420] Independently tunable subarrays=4

Subsequently, a need, partly driven by the selection of the ALMA site and by the scientific drive to use all frequencies available on that site, was envisioned for an array of antennas devoted to collection of short spacing information. This became the Atacama Compact Array, or ACA, which became a Japanese deliverable upon that country's entry into the ALMA Project. During the discussions leading to this, as early as the June 2002 Calibration Review, a mode was described in which elements of the ACA would be incorporated into the main array for calibration purposes:

1. To ensure that the absolute calibration of the two arrays was commensurate, and
2. To allow as many baselines as possible to the smaller elements of the ACA to ensure the most accurate calibration of those antennas.

Subsequently, as it became clear that ALMA resources might not support construction of the entire 64 element array, putting several science goals at risk, another situation in which elements of the ACA would be incorporated into the main array was described:

3. To bring extra sensitivity to the main array to allow it to more sensitively address Level One ALMA science goals.

The ACA project book (Feb 17 2004 version) indicates that the ACA will be operated as two subarrays – one containing the four 12-m antennas, the other the twelve 7-m antennas. The ACA correlator treats all 16 ACA antennas equally, i.e. cross correlates all of them, according to ALMA-J documentation.

Discussion—Calibration

Absolute amplitude calibration of the array (1 above), will occur by observing calibrators of known, stable brightness at standard intervals. 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. The steps involved, listed in the ALMA Calibration Plan [SCID-90.03.00.00-007-A-PLA], are:

I. 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''.
II. 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''.
III. Observe the same bright quasar, now of known flux, with all antennas in interferometric mode to set the interferometric flux scale.
IV. Correct these observations for elevation-dependent antenna and atmospheric effects such as the gain curves and time dependent atmospheric attenuation.

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 (≥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. For the ACA, steps I-III. above are the critical steps for observations including ACA and Main Array antennas. Step I is executed about once per day, ideally under excellent weather conditions. On the ALMA site, phase stability shows diurnal variations; to measure the calibrator fluxes most accurately one will perform the calibration under night or early morning conditions, under which decorrelation (affecting step III) can be expected to be least severe.

Fast switching phase compensation alone results in significant residual phase fluctuations which lead to variable decorrelation. This variable decorrelation must be accounted for both to maintain an accurate flux scale and to make high quality images. However, there is strong indication that a phase compensation scheme using both fast switching and water vapor radiometry will be able to reduce these residual phase errors to the point that they will not result in significant decorrelation. Additionally, the residual phase errors of a combined FS/WVR scheme will probably be dominated by Gaussian noise from the WVR, so if a decorrelation correction is required to achieve an accurate flux scale (*i.e.*, at the highest frequencies), that correction may be nearly independent of time and baseline. Thus a simple scaling of the interferometric data which can be accomplished with an interferometric/total power cross calibration or by dead reckoning based on the known noise properties of the WVR units may provide a useful decorrelation correction.

In (2) above, all 12m antennas are cross-correlated with the ACA 7m antennas to improve the accuracy of the cross-correlation normally employed only between ACA 12m and 7m antennas. This is important only in the event that the ACA antennas are oversubscribed and calibrations involving them need to be shortened to accommodate program observations. This may occur; a separate study of tradeoffs (time lost in the main array, etc) should be performed.

In conclusion, combined observations of the ACA and Main Array to determine primary flux calibration will occur about once per day, in early morning. One question presented by the proposal for array-wide subarraying (AWS) is can the switching to include the ACA antennas in the array be performed manually.

Discussion—Sensitivity

In (3) above, the incorporation of ACA antennas into the main array is contemplated to increase sensitivity so that ALMA may more effectively reach its science goals. This use of the ACA directly competes with its primary goal, to supply short spacing information to the main array. Therefore it should only be supported when strong argument could be made for the increase in sensitivity. Substantial increase in sensitivity can be obtained when ALMA contains many fewer antennas than the planned 64. During early stages of ALMA implementation—Commissioning, Demonstration Science or Early Science, for instance—much of the collecting area of ALMA will reside in the ACA 12m antennas under current delivery schedules. Later, as (or if) the ALMA main array complement exceeds 40 antennas, the sensitivity increase becomes lessened, and arguments for inclusion of ACA 12m antennas in the main array should be compelling indeed. We expect this to occur mostly at the highest frequencies. Owing to the deployment of the

ACA 12m antennas in a definite compact configuration, the baselines to these antennas will be most useful in imaging when the main array is in its most compact configuration. We believe that inclusion of the ACA 12m antennas is unlikely to improve imaging performance (unless the antennas are transported to pads in the main array, which we consider unlikely in nearly all circumstances). Brightness temperature sensitivity is highest in the compact configurations; it may be expected that demand is highest at high frequencies for inclusion of the ACA antennas in the compact array for this reason also. However, some of the Level 1 science requirements which require sensitivity also require high resolution (imaging protostellar and protoplanetary disks).

Consider DRSPs?

Science Advantages of AWS Plan vs. Baseline Plan

For both arrays the returning astronomical data terminates at the combined patch panel, and therefore implementing AWS would usually involve fiber reconfiguration of the returning data stream (specifically, connecting the bilateral correlator inputs to the ACA antennas and/or vice versa). This could either be done manually, or electronically. During normal operations, personnel are only present at the AOS building which contains the fibers during daylight working hours, so that reconfiguration could only occur on this schedule. An electronic option should allow reconfiguration to occur at any time of day, an advantage which must be considered in relation to the cost of this option.

In the baseline plan, the ACA and Main Array are independent. Short or long term phase drifts between subarrays driven by different laser synthesizers may become an issue in this scheme. ALMA requirements are stringent enough that this is not thought to be an important consideration.

We conclude that the flexibility allowed by the AWS Plan makes it worthy of consideration on scientific grounds. We find no clear science driver which would require automatic remote switching of LO distribution and signal paths, though the costs and benefits should be assessed—automatic switching clearly enhances flexibility and thus enhances ALMA’s scientific abilities.