Evolution of the Combined Array Operation Concept for ALMA

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Draft 2006-10-10, Version 1.1

This document is a historical summary of the evolution that the concept of wide-field imaging with ALMA has undergone in the last few years. In particular, the role of the short-spacing data in the quality of the restored images is addressed. The recent developments relating to the "combined" array are also presented.

1. Mosaicing Issues

Synthesis imaging in the mm and sub-mm regimes always faces the conflicting requirements of high sensitivity per baseline (i.e., larger and better-surface dishes) and source size. By selecting larger dishes, the primary beams end up being smaller than a significant fraction of possible targets, and therefore, synthesis at several pointings (mosaicing) becomes necessary.

A second major concern is the so-called "zero spacing" issue. Most arrays cover baselines from a minimum length as close as possible to a single-element diameter. Therefore, the shorter spacing information needs to be supplemented somehow for observations of targets of sizes comparable or larger than the main beam of an element at the observing frequency.

Two possible approaches have been proposed/used in the literature so far:

a) "homogeneous" array: The same antennas are used both for interferometric and single-dish observations (Cornwell et al. 1993).

b) "heterogeneous" array: Antennas of different diameters are used in the same array (i.e., all possible cross-correlations are taken). The difference in sizes allows closer packing of the smaller dishes that can thus recover shorter-spacing information. Single-dish data, either from a separate instrument or from the same array also is used for the "zero" spacing (Wright 1999).

2. ALMA Evolution: Homogeneous to Heterogeneous Array Models

The initial thinking for ALMA was that the "homogeneous" array approach would be used, either by having some dishes dedicated solely to single-dish observations or by switching the observing modes for all the elements (Cornwell et al. 1993).

This method has the appealing features of not requiring any extra hardware (except nutators for some), the calibration and data reduction are simpler (only one type of antenna involved) and that in principle the single-dish and interferometric data can be taken (almost) simultaneously, increasing calibration reliability.

It was soon realized, however, that several factors can severely affect the performance of a homogeneous array. Among this:

a) Phase (pointing, etc) and amplitude errors (Welch 2000,Pety et al 2001a)

b) Source Structure Issues (Pety et al 2001b,Tsutsumi et al 2004)

c) Deconvolution Algorithms (Yun 2001, Morita 2001)

Pointing errors tend to introduce phase shifts that result in poor uv-plane fidelity at short spacings. Since the single-dish data added to supply the zero-spacing is also affected in a similar fashion, the overall imaging performance for sources with most of the power there is conspicuously degraded.

Simulations also showed that, even in an error-free case, homogeneous array imaging performance depended significantly on the deconvolution algorithms used. Finally, simulations also demonstrated the fact that, for some model sources, homogeneous array observing never recovers enough of the flux at short spacings to reach an acceptable fidelity.

3. The ACA: Definition and Role

As a remedy to this situation, a "heterogeneous" ALMA was proposed (Wright 1999). The initial design concept was to create an array of small-sized antennas that would have some overlapping baselines with the compact 12m array configuration (for cross-calibration purposes). Smaller dishes would allow to map more efficiently the baseline region between 4-16m and would also possibly be more stable to some of the pointing errors (Baars 2000). As before, dedicated 12m antennas would still provide the "zero-spacing" data.

It was agreed by the ALMA project that this additional array, called the Atacama Compact Array (hereafter ACA), would be one of the contributions that Japan would provide as a tri-partite project.

Considerable simulation effort has been devoted to specifying the ACA, i.e., the number of antennas, their size and distribution(s) (Welch 2000, Morita 2001, Yun 2001, Wright 2003, Morita and Holdaway 2005).

Initial simulations based on a BIMA array compact configuration suggested a number ~10 and two configurations (NS extension to cover extreme declination targets). Additional simulations on several basic array concepts suggested that the diameters should be below 8m. These studies have culminated in the ACA Array Design Concept Memo by Morita and Holdaway (2005).

In parallel with the simulation work on the ACA array properties, several authors have also carried out simulations on the impact of imaging with and without the ACA using standard model sources and realistic errors (thermal, pointing, antenna calibration, gain variations, etc.) (Yun 2001,Pety et al. 2001,Tsutsumi et al 2004). These simulations cover a wide range of possible array configurations, use several different packages (SDE, AIPS, Miriad, GILDAS), different deconvolution algorithms (MEM, "maximum emptiness", CLEAN and hybrid), and a wide range of model targets. The methods used for the "comparison" between the "homogeneous" and "heterogeneous" cases vary among authors. In particular, the different use of the single-dish data at the deconvolution stage of a homogeneous and heterogeneous simulation in the GILDAS package has raised some concerns (Holdaway 2004). At the other end, some works have produced clearly conflicting results, which possibly reflect the excessive reliance of those on a single source model.

Notwithstanding, the general picture that emerges from these works can be summarized as follows:

1) The inclusion of the ACA observations improves significantly the fidelity of mosaicing for some objects (specially those with power at a wide range of spatial frequencies) under expected observing conditions (errors included) (Tsutsumi et al. 2004).
2) The final fidelity (after deconvolution) is, in many cases, more a function of the actual object structure than the deconvolution algorithm used (Pety et al 2001a).
3) Simulations using a single target are not enough to judge the capabilities of the heterogeneous ACA and 12m Array (Baseline ALMA). An average of several targets covering different declination ranges is required (Pety et al 2001b).

4. Operation of the Heterogeneous Array: the Pre- ACA System PDR Scenario

A latent issue in most of these simulations has been the fact that observation times for the ACA were always scaled by a factor of 4 to those of the 12m array to match uv point-source sensitivity in the overlapping baseline regions (including the assumption of mosaicing observations). This came both from common practice among array designers, and the fact that the only simulation so far including the ACA and covering a range of observing time ratios indicated that x4 gives the best average imaging performance.

The obvious outcome of this paradigm was an operation scenario for the enhanced ALMA (ACA+12m Array) that envisioned the ACA operating separately from the main array(i.e., coordinated observations), and being able to only cover ~25% of the main array projects.

5. Combined Observations (I): The ACA System PDR

At the time of the ACA system PDR (Nov 2005), the need for a "combined" mode of observation (i.e., cross-correlations between the ACA and 12m antennas also taken) started emerging.

The main reason that led ALMA-J to propose this mode was calibration accuracy (Iono 2005). It was realized at the time that some of the most stringent calibration specifications (very high quality bandpass, sideband gain calibration, etc) would require a long integration time for a standalone ACA. Furthermore, cross-calibration is also an issue when the data sets obtained by the ACA and the 12m array are widely separated in time (Mangum 2005). This is due to the fact that most secondary calibrators are variable to some degree, thus limiting the accuracy of any relative and absolute calibration of the data.

Simple computations showed that including the 12m Array in the calibration of these high quality observations would reduce considerably the time required for them by the ACA, which would increase the time available for actual target observations.

A further appeal of the "combined" mode observations was that it could also be used to increase the overall sensitivity of the ALMA observations by 15-20% (higher at the high frequency ALMA bands because of the better surface RMS of the ACA 7m) for ~10% of the DRSP project proposals. This statement was supplemented with simulations of the synthesized beams for different declinations and the ACA+compact 12m Array configurations. The simulations demonstrated that in spite of the non-optimal relative location of the ACA site and the main array, the beam quality would not be appreciably degraded in a "combined" mode (Iono 2005).

For the first time, it was also pointed out that the "canonical" observing time ratio x4 factor would actually be smaller because of relative antenna performances of the ACA 7m and the 12m (better surfaces improve sensitivity and imaging quality).

It is important to note that at the time of the PDR, the "combined" mode was NOT considered the major mode of operation, just a necessity for specific projects.

The technical feasibility of the "combined" mode proposal was studied into the early months of 2006, concluding that the technical impact would be minimal, but that some software development effort would be required in the offline reduction.

6.Combined Modes(II): Ed Fomalont's Proposal

The core idea of the "combined" array was further extended by Ed Fomalont (NRAO) (February 2006). Based on the expected source characteristics, he concludes that BOTH weak/small source and extended source observations would benefit from a "normal" operation closer to the "combined" mode (still stand-alone modes would be required for some specific projects) than to the "coordinated" mode that had been proposed so far. Weak/small source observations would gain in sensitivity while extended/mosaicked images would benefit from simultaneous cross-calibrations, higher calibration accuracies and higher scheduling efficiencies. He also pointed out the obvious ease of operation that would result from upgrading the "combined" mode from minor to major, and the fact that the expected reduction in number of antennas from 64 to 50 (at least for some initial period of the life of ALMA) in the 12m Array will allow the cross-correlation of the ACA antennas with the BLC. Finally, he also suggested that the "canonical" observing time x4 ratio that had been used did not adequately cope with the properties of a large fraction of sky sources, which have more power at short spacings.

7.What is the optimum observing time ratio?

It has been known for a while (see also previous section), that many celestial objects have a steep increase in power at short uv distances. Therefore, several authors have pointed out that pure uv sensitivity scaling at the central uv hole of the 12m array will, in fact, result in higher relative SNR for the short spacings. This would in fact suggest that a smaller factor might still produce comparable fidelities in deconvolved mosaics.
This is clearly in contrast with the "canonical" factor x4 used in the simulations so far, which would imply that a "coordinated" operation was unavoidable.
To settle this issue, the ALMA-J Science Team decided to start an extensive simulation project that would use several model images, at different SNR levels, and cover a wide range of observing time ratios. The ultimate goal was to find the optimum average observing time ratio for a "heterogeneous" array (Takakuwa et al. 2006).
To be consistent, all the simulations have been carried out with the same package, i.e, GILDAS and using the same deconvolution algorithms (Pety et al. 2001c). To also check the effects of declination, the sources were re-centered adequately to include targets with significant shadowing of the ACA antennas. All simulations included thermal and pointing errors, but for simplicity, the phase screens were not used. To model the border-line between mm and sub-mm, the frequency of the observations was set to 345GHz. The observations have used the most up-to-date array configurations for the ACA (Morita 2006, private communication).

7.1 Cautions

Before summarizing the results, here we list some possible issues with the current simulations:

1) Factors that may influence the absolute values of the fidelities:

a) The GILDAS package treats differently the "homogeneous" mosaicking with Single-Dish data and the ACA+Single-Dish+12m Array case.
b) All deconvolutions have been done with a modified Clark CLEAN algorithm in the

hybrid mode (separate deconvolution of ACA+SD and ALMA datasets that are then combined in the uv plane).

c) The observing times of the single-dish data is the same as that of the 7m array

2) "Combined" mode: These simulations do NOT represent a combined mode but a "coordinated" observation.

3) Fixed ALMA observing times: The simulations have all been carried out using the same observing time for the ACA 7m and ACA TP (Single-dish) array. Two different sets of simulations have been carried out, i.e, fixing the 12m Array observing time and varying the ACA's or the opposite.

4) Effect of ACA Antenna Shadowing: The shadowing effect is correctly dealt with by the GILDAS software. However, the ratio of observing times mentioned in the current Memo only uses the actual hour angle coverage. A sensitivity factor will have to be applied in the revisions of the Draft. However, this does not alter the conclusions of the Memo in any way, since this effect would imply that even with less baselines the fidelity effects can be achieved for low elevation targets.

The former issues imply that the absolute values of the fidelities can be different if the same exercise is done with SD integration times different from the ACA 7m Array, a different package, or another deconvolution algorithm. Furthermore, the "relative" fidelities between the ALMA+SD and ALMA+ACA+SD should also be treated with caution due to the different treatment by the software. Simple comparisons with the MIRIAD package (Iono, Private Communication), also suggest that the relative weighting of the ACA and 12m Array data affects the final results significantly. Finally, it should be noted that these simulations are not true "combined" modes, since the ACA-ALMA correlations are not performed by the current GILDAS package. However, if the current simulations suggest that the required observing times for both arrays (ACA and 12m Array) are comparable, they would strongly support a prominent role of "combined" modes of operation.

7.2 Summary of Results

In spite of the cautions in the previous section, it is expected that these set of simulations will be self-consistent and thus be useful to derive, at least, the trends with different observing time ratios.

The main results of these simulations are:

a) No optimum ratio of observing times between the ACA and the 12m Array was found. This statement can be further qualified w.r.t. the brightness of the sources as:

① Bright Source Case: For high SNR cases, the deconvolution algorithms are efficient enough to satisfactorily recover most of the flux even for observing time ratios of 1:1 between both arrays. The final achievable fidelity is mainly controlled by the amount of power in the high spatial frequency components of the target, and thus by the observing time of the 12m Array. The addition of the ACA data is, though, essential to improve the fidelities.

② Weak Source Case: The fidelities follow an increase with observing time ratio that goes approximately as the square-root of the relative observing times. This suggests that, in fact, for the sources used, the ACA data is dominating the fidelities (due to the relatively small amount of power that the model sources have in the high spatial frequency components). For such sources, the use of a subarray of the 12m Array in Total Power mode may improve the fidelities significantly.

③ Source Properties: Although the sources selected for the simulations represent some extreme cases (in Pety et al 2001, "hco43" usually shows a high fidelity improvement if the ACA is added, while "cluster"'s improvement is marginal), there is no difference in overall conclusions between the two models.

7.3 Conclusions

The results above suggest that the "canonical" x4 factor that had been used so far to estimate relative observing times is **not necessary** to achieve the improvement of image fidelity that the ACA provides. For bright sources with extended emission, mosaicing with comparable observing times would be enough to produce a high-fidelity result. In case there is a requirement for high fidelity of the high spatial-frequency components, the 12m Array time should be increased w.r.t. that of the ACA. For weak sources, the ACA dominates the fidelities, and therefore, fidelities will increase as the observing time of the ACA increases. The 12m Array might provide support in terms of improved spatial resolution and additional total power observations. Target sources will usually be somewhere between these two regimes.

Adding these results to the advantages of a "combined" mode of operation already outlined in Section 5 of this memo one must conclude that a more central role of the "combined" array mode for ALMA should be seriously considered. For sources that do not require mosaicking, the advantages would be in terms of calibration and increased sensitivity. For extended sources, significant fidelity improvements can be expected even with a 1:1 observing time ratio.

Studies should therefore be started on the impact that a more important role of the "combined" mode will have to ALMA operations.

7.4 Future work:

Although the current results seem fairly robust, there are several issues that still need to be addressed:

-Increase the number of model sources

-Use other packages to carry out similar simulations

-Tweak the Single-Dish integration times

-Actual “combined array” observation simulations (using also the baselines including different antenna sizes)

-Add additional errors (phase screen, etc).

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