Evolution of the Capabilities of the ALMA Array

This note provides an outline of how we plan to build up the scientific capabilities of the array from the start of Early Science through to Full Operations. For reference the existing definitions of the capabilities for the current major milestones are given in the appendix. There is of course a huge jump between what we have defined as the minimum capability for the start of Early Science and the final performance of the full ALMA system. It would make no sense to keep what is on offer to the user community to the minimum level right through the remainder of the construction period. On the other hand, running a meaningful proposal and time allocation process requires that the users know what capability is expected to be available at which stage, so that they can tailor their applications accordingly: we can't just tell them that, "New features will be added when they have been commissioned".

The process of adding capability is more or less continuous in some areas (e.g. the number of antennas at the high site) but goes in discrete steps in other areas (e.g. the quadrants of the correlator). In order to provide both clear milestones for use within the Project and a description of the evolution that it will be practical to use in the time application process, it is proposed that we define a set of distinct phases and identify the capabilities that will be available for each of these. Clearly the important parameters for the users are things like sensitivity, angular resolution, imaging quality and polarization capabilities, but here we will work at the more practical level and consider the numbers of antennas, the lengths of the baselines, etc. It is relatively straight-forward to derive the scientific performance parameters once we have defined a set of technical capabilities.

These are the parameters that need to be considered:

1) Number of Antennas: this drives the sensitivity and, especially in the early stages, the imaging quality. We have to take account of the number in 12-m array, the number in ACA and the number of "zero-spacing" (single-dish) antennas.
2) Configuration: the arrangement of the antennas sets the range of angular scales that the telescope is sensitive to (for a given frequency). The most important parameters are the maximum baseline length and the number of different configurations that will be available in a given period. (These will be converted into sets of specific configurations when we have established the framework.)
3) Observing modes available: single field interferometry, single field plus "zero-spacing", and mosaics (described by the maximum number of pointings).
4) Frequency bands: we cannot install the new bands in all the antennas at once, so there will be a subset that has the additional bands and the relevant parameter is the number of antennas with a given band[1].
5) Spectral capabilities: this is means the range of spectral resolution available and the amount of flexibility in defining sub-bands, etc.
6) Polarization capabilities: none, full-Stokes on axis, full-Stokes extended sources. In fact the main issue here is how accurately the polarization can be measured, so the uncertainty in the Stokes parameters is the quantity quoted.
7) Multiple arrays. The system needs to support simultaneous operation the 12m array, the ACA and the zero-spacing antennas as they come on line. The full capability includes using "sub-arrays" – sub-sets of the 12m array doing separate observations in parallel

[1] It will unfortunately be almost impossible to arrange that the selection of antennas that contain the additional bands will be arranged in such a way that they form good configurations, so the imaging properties of the array using the new bands will be less than optimal during this period.

from within the same scheduling block. For simplicity we just give the total number of separate arrays here.

8) Calibration techniques: there are too many aspects to cover this fully here. Amplitude, phase, band-pass and polarization are all of direct interest to the users and further development of other important technical aspects, like antenna pointing, delay calibration and baseline measurements, will also be taking place. As indicated in the appendix, the general plan is that the Early Science data should be calibrated to about the level achieved on existing millimetre-wave arrays and that ALMA more ambitious goals will come in later phases. Three specific (and difficult) steps in phase calibration are however listed here. (“Slow” phase cal, including transfer between bands, is included from the start.)
9) “Special” observations: solar observing, astrometry, rapid spectral survey. We do of course hope to add things like VLBI here but that is clearly outside the current scope.

It is most convenient to present the evolution of capabilities in a table:

		Phase A	Phase B	Phase C	Phase D	Final
Number of Antennas	12m Array	16	25	30	40	50
	Single		1	1	2	4
	ACA			6	8	12
Configur-ation	Max length	250m	750m	2km	5km	15km
	Number	2	4	6	10	16?
Observing modes	Single field	√	√	√	√	√
	Single dish		√	√	√	√
	Mosaics		30	100	200	~1000?
Receiver Bands	3,6,7 & 9	All antennas				
	4 & 8		8	20	36	All
	10				16	All
	5			6	6	6
Spectral Modes		“ASAC[2]”	ASAC+8[3]	All except highly specialized		All
Polarization calibration		On-axis 1%		On-axis 0.3%, Off 1%		0.1% ?
Multiple arrays		1	2	3	4	6 ?
Phase Calibration	WVR	√	√	√	√	√
	Fast-switch		√	√	√	√
	Fast Φ-trans			√	√	√
Special Observations	Solar			√	√	√
	Astrometry				√	√
	Spectral Scan				√	√

[2] This is a basic set of correlator modes chosen by the ASAC which will provide a reasonable range of scientific applications for Early Science. The details are given in this table.

Mode	Total Bandwidth	Effective Bandwidth	Number of Spectral Points	Spectral Resolution	Polarization
7	2 GHz	1.875 GHz	3840	488 kHz	Dual
9	500 MHz	469 MHz	3840	122 kHz	Dual
12	62.5 MHz	58.6 MHz	3840	15 kHz	Dual
18	62.5 MHz	58.6 MHz	1920	30 kHz	Full
70	2 GHz	2 GHz	64	31.25 MHz	Full

[3] A set of additional modes available for Phase B will be proposed to the ASAC on 13/14th Oct.

The intention here is that Phase A marks the start of Early Science and the subsequent phases are steps that are sufficiently significant to the users that they will want to take them into account. By reference to the appendix it will be seen that Phase A corresponds to the "minimum requirements for Early Science" with the addition of a basic polarization capability. It also proposes that all four of the day-one bands are available, instead of the minimum of three. Phase B is close to the Early Science definition with "Goals". Phases C and D are a natural progression to the specified final capability based on the expectations for the delivery of the equipment and additional functionality, together with a reasonable phasing of the work needed to commissioning the new features and techniques. Phase D is corresponds pretty closely to the Inauguration capabilities as presently defined.

Schedule

In choosing the definitions in the table above, the intention was to have each phase last about 6 months. The details now need to be worked through to make sure that this is indeed consistent with the present forecast schedule. In general the rule should be that the equipment, software and infrastructure needed for each operational phase should be in place 6 months before the start of that phase. This is <u>not</u> intended as a margin to allow for slippage but rather it is there to provide an adequate period for carrying out commissioning and scientific verification, so that we can offer these capabilities with a reasonable level of confidence.

Relationship to Calls for Proposals

From the technical point of view it would be best to have a separate call for each Phase since that would enable us to make the best informed judgements on what should be offered at each stage. It is however felt that this would lead to a lot of wasted effort in writing and reviewing proposals. The suggestion therefore is that the Early Science Call should cover phases A and B and that there would then be a second call for phases C and D. With the above definitions, this means that the tools for proposal preparation and handling for the Early Science Call need to include, e.g., single-dish and pointed mosaics, but they will not need to cover the ACA and "special" observations until the second call.

Status of this Document

Note that this is very much a working document and that the details of how these proposals mesh with the schedule and other constraints all need to be looked at much more closely before finalising it. We do however need have a rather firm plan within the next few weeks.

Richard Hills 30th Sept 2010 (minor edits 5th Oct)

Appendix – Definitions and Requirements for Scientific Milestones

1) Start of Early Science[4]

A) Minimum Requirements

- At least sixteen 12m antennas fully commissioned with at least 3 receiver bands available on all antennas.
- Synthesis mapping of single fields.
- Sufficient antenna stations to provide a range of configurations covering the shortest spacings and out to at least 250 m.
- A basic set of spectral modes as previously selected by ASAC.
- Calibration of all the above to a level comparable with existing millimetre-wave arrays – requires hot/ambient loads and WVRs.
- Software to support users' applications, the preparation and execution of observations and off-line data reduction.
- After taking account of the time lost due to bad weather, power outages, equipment failures and the time needed for engineering work, at least 33% of the remaining time should be available for the Early Science observations.

The following criteria are to be considered as goals. The project will endeavour to achieve them, but Early Science can start without this. A readiness review will decide which of these capabilities should be announced as being available in the Call for Early Science Proposals.

B) Goals

- Receiver bands 3, 6, 7, and 9 available on all antennas plus bands 4 and 8 on as many antennas as we can manage.
- Synthesis mapping of extended fields using pointed mosaic mode.
- Configurations extending to baselines of 1km
- Linear and circular polarization of compact sources.
- Single-dish mapping of extended objects in both continuum and spectral line modes including on-the-fly observing.
- Calibration better than existing mm-wave arrays

2) Inauguration

This will mark the point at which ALMA has qualitatively reached its full capabilities, although not all of the antennas will be completely kitted-out by this stage. We expect that the facility will be scheduled for scientific observations for about 75% of the time at this point.

Requirements

- Regular operation with ≥ 50 fully-equipped[5] antennas. (This includes both 12m and 7m antennas.)

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[4] Commission activities continue after the start of Early Science, which requires simultaneous operation with at least 2 sub-arrays.

[5] Fully-equipped means a minimum of four receiver bands – typically bands 3, 6, 7, and 9 plus some of 4, 8 and 10, plus a full set of electronics, radiometers and calibration devices.

- All antenna stations complete, providing synthesis mapping with high fidelity using the full set of array configurations.
- Simultaneous operation of ≥ 4 subarrays possible.
- Capability for combining data from the12m array with data from the ACA including "zero-spacing" data, and multi-configuration images
- Linear and circular polarization, including mosaicing of sources that are larger than the primary beam.
- High time resolution observations, e.g. of solar flares.
- All major software systems available and working in a way that allows astronomers who are not synthesis experts to use ALMA[6]1.
- Accurate calibration of all the above.

The goals set for the calibration of ALMA data are very stringent and we may not achieve all of them by this point, but we must be doing a lot better than is currently achieved at these wavelengths.

Some capabilities will still be under development at this stage – e.g. on-the-fly aperture-synthesis mosaics, high-precision polarization maps of extended sources, and some of the less popular correlator modes .

3) 66 Antennas in Service

Although this will of course be an key moment for everyone involved, this point does not mark a qualitative change in ALMA's scientific capabilities. The main reason for including it is to maintain continuity with the previous schedule.

This occurs when we have commissioned all 66 antennas with full sets of electronics and FE's with at least bands 3,6,7 and 9.

4) End of Construction

- By definition this occurs when all the items defined in the current baseline have been delivered and accepted.
- This should clearly include a full set of spare components and resolution of substantial non-conformities in the performance of all major components and sub-systems.

For practical reasons it may be necessary to exclude some items from this so that the construction effort can be wound up at an appropriate time. The most obvious case is the final deliveries of the band 10 cartridges, which were only recently given approval.

[6] At this stage ALMA staff will still be performing a lot of the data verification but the users will receive the images ready for analysis and interpretation.