ALMA Science Advisory Committee

Report from Meeting of February 24-25, 2005

European Southern Observatory, Garching, Germany

ALMA Scientific Advisory Committee

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Ex-officio

R. Kawabe (Japan), T. Wilson (Germany), A. Wootten (USA)

Other participants

A. Beasley (JAO), D. Emerson (NRAO), R. Murowinski (JAO), M. Tarenghi (JAO), M. Holdaway (NRAO), D. Silva (ESO)

1 Executive Summary and Recommendations

The ALMA Scientific Advisory Committee (ASAC) met in Garching in February, 2005. The Committee heard presentations from members of the Joint ALMA Office (JAO) and the European, Japanese, and North American partners. The ASAC is gratified to see the progress in the ALMA project, including the staffing of the JAO office in Santiago, the work on the operations plan, and the massive effort of the rebaselining project, which is nearing completion. The ASAC looks forward to the early placement of antenna contracts that would lead to early science in late 2007 or 2008.

The ASAC considered two charges from the ALMA Board. As part of the first charge, the Committee discussed possible rescope options that would have minimal effects or delay to the science while achieving cost-savings to the Project. The Committee identified a number of possible options in this category, including postponement of the implementation of two of four planned subarrays, reduction in the number of pads through a reoptimized configuration design, and delay in the implemention of the largest, Y+ array. Options presented by the Project that were deemed unacceptable in terms of the serious impact on early science were the delays the implementation of one polarization, one IF, or three of the four sub-arrays.

The issue of the scientific impacts of a smaller number of antennas, either 40 or 50, is a more complex issue. This portion of Charge 1 was discussed extensively by the Committee in Garching. The ASAC has previously stated, in its report of November 2004, that a 10% change in the number of antennas from the original 64 would have minimal impact on the science, and would not rule out any of the Level 1 science goals. The Committee believes that a submillimeter array with either 40 or 50 antennas would be a superb instrument that would surpass all existing arrays by a wide margin. The scientific capabilities of such a powerful continuum and line instrument at the high and dry Atacama site will be remarkable and unique. ALMA will be a spectacular complement to concurrent efforts such as Herschel, James Webb Space Telescope, and SOFIA.

On the other hand, the specification of a 64-antenna array was driven by the need to do groundbreaking submillimeter science at the highest resolutions. Studying galaxies in the early universe requires the highest sensitivity and resolution. Equally strong requirements are placed on resolution and sensitivity by the imaging of structure and kinematics in the gas and dust of nearby protoplanetary disks on sizescales comparable to the gaps between planets. The imaging of line emission from protoplanetary disks at such high resolution requires the full sensitivity of the 64 12-meter antennas; however the ability to study the internal kinematics of disks would be unequalled by any other instrument. The third Level 1 science requirement is to achieve the highest quality imaging in the millimeter and submillimeter bands, to match the quality of images from HST and ground-based adaptive optics. This too is highly sensitive to the number of antennas. It is already difficult to achieve the Level 1 science goals with 64 12-meter antennas. These goals are seriously compromised by a smaller number of antennas. The ASAC strongly urges the ALMA Project to consider any methods possible to eventually attain the goal of the original 64 antennas to achieve these important science goals.

The second charge to the ASAC concerned the issue of how to encourage collaboration through the individual partners of the ALMA project, and the scheduling of large programs in a way that would maximize the scientific productivity of the ALMA instrument given the requirement that the individual partners will have separate Program Review Committees (PRCs). There is a consensus within the Committee that there is some requirement for an international Program Review Committee to consider joint proposals, and particularly very large proposals. However there is not complete agreement on the scope of an IPRC. The Committee feels that further consideration of this issue is warranted.

2 Introduction

The ALMA Science Advisory Committee (ASAC) met on February 24 and 25, at ESO Headquarters in Garching. The meeting coincided with the coldest weather that Munich has seen in 30 years. In addition to the members in attendance in Garching, Diego Mardones participated by videocon from the Joint ALMA office from Santiago. The ASAC was joined by members of the Joint ALMA office (JAO) from Santiago, and by members of the individual executives, from North America, Europe, and Japan, for discussions and presentations.

From the presentations of the Director Tarenghi, and Project Manager Beasley, the ASAC learned of the progress in the ALMA construction in Chile, in the staffing of the Santiago office, and the overall progress in the project, including the rebaselining effort. The ASAC eagerly looks forward to placement of the antenna contracts. If the contracts are placed soon, early science will be possible by late 2007 or 2008. It is most gratifying to the Committee to see real progress toward this remarkable instrument.

The Committee heard a presentation from the ALMA-J project, given by Deputy-Director and Project Scientist for ALMA-J, R. Kawabe. The Committee was gratified to see the progress made in ALMA-J, including the first antenna contract for 3 12-meter antennas that was placed in early 2005, and for a schedule for future antenna contracts for the 7-meter antennas of the Atacama Compact Array (ACA) that will result in delivery in 2007. Also reported were preliminary results of simulations to study the effects of systematic amplitude offsets when combining the data from the 64-antenna array with the ACA; amplitude offsets appear to significantly affect image fidelity when these data are combined. The ASAC feels strongly that cross-calibration between the arrays will be very important for maintaining image quality when ACA and ALMA-B data are combined, and urges the Project to make this a priority.

Two presentations were made to the committee on issues specific to the Charges. The first was a presentation by Project Manager Tony Beasley on the rebaselining project and options for rescope. The second was a presentation via video conferencing by Mark Holdaway on imaging simulations for arrays with different numbers of antennas, including noise.

3 ALMA's Science and Re-baselining

The first charge to the ASAC was:

Charge 1: Examine the status of ALMA re-baselining, including rescope options identified to date, and comment on the impacts that the proposed changes will have on ALMA's scientific capability. The ASAC is invited to comment on the scientific capability of a smaller number of antennas operating simultaneously, specifically 40 or 50.

The ASAC decided that this Charge consisted of two distinct parts, the first being consideration of the scientific impact of various options for delaying portions of the project, or other cost-saving measures that have been identified as part of the rebaselining. The second question is the issue of the effects on the science of a smaller number of antennas. The two issues are discussed separately in the following sections of the report.

As a part of Charge 1, the ASAC heard a detailed presentation from ALMA Project Manager Tony Beasley. Because the rebaselining process is in its final stages, the Committee did not receive any written materials from the Project on this Charge, instead receiving this information through the oral presentation. Beasley explained the process of rebaselining that the project is undergoing since 2004. His presentation included a description of the rebaselining procedure and timescales, the move to the PMCS system for scheduling and budget, the search for hidden scope in the project, the identification and mitigation of risk, revised timescales and budget. Beasley also presented the Committee with possible rescope options for the baseline project, or items that might be deferred, to be considered for Charge 1. The ASAC was impressed by the rebaselining effort and by the management plan. The Committee found Beasley's presentation extremely informative and useful for the consideration of Charge 1.

3.1 "Rescope options identified to date"

During the ASAC meeting, Project Manager Beasley presented seven specific rescope options as well as list of other possible items. One of these options is related to the extra savings that occur for each antenna that is not built, which we will not discuss further in this section of our report. Of the rescope options that were presented to us, the ASAC felt that the following items would be acceptable areas for rescope (in priority order):

1. **postponing two sub-arrays out of a total of four sub-arrays planned.** The ASAC felt that ALMA operations can function well with just two subarrays, one for the science observations and one for technical work (measuring baselines for recently moved antennas, etc.). However, this would preclude simultaneous science observations of more than two frequencies, which may affect observations of objects with rapid variability, including perhaps Solar flares.

2. **reducing the number of pads that are needed through a new configuration design optimized for the new number of antennas in ALMA.** We understand that the project is looking at new configurations in light of the possibility that ALMA will not initially build 64 antennas.

3. **delaying the implementation of the longest baselines (the Y+ array).** These baselines are the most difficult and expensive to implement, both technically and scientifically. The ASAC notes that this option would delay part of a Level 1 science goal (for goal 2, imaging of gaps in proto-planetary disks requires the longest baselines).

4. **possible additional cost savings from construction of infrastructure such as the AOS, OSF, and Santiago buildings.**

5. **adopting the semi-transparent vane instead of a more complicated calibration system, if it can be shown to meet specifications.** The ASAC notes that relaxing the calibration specifications further would have a serious impact on image fidelity. However, the semi-transparent vane would clearly be a viable option if it can be proved to deliver the required accuracy.

6. **implementing the amplitude modulated LO scheme, if required to have an LO solution for ALMA.** The ASAC notes that this option will probably cause higher phase noise, which will have a negative impact on high frequency and long baseline observations. Under the current specifications, the electronics are already the limiting factor in the best 5% of the weather.

The ASAC felt that the following items are not acceptable for rescope (in order of scientific impact):

1. **delaying the implementation of one polarization from one or more of the front-end cartridges.** This option would have a major scientific impact in that the sensitivity of each affected band would be reduced by a factor of $\sqrt{2}$, which is equivalent to a reduction in the number of antennas from 64 to 45. In addition, polarization observations would not be possible for each affected band.

2. **delaying three of the four total sub-arrays.** Having only a single sub-array with ALMA would lead to large inefficiencies in determining baselines for recently moved antennas. Either the whole array would have to be used for baseline determination or the baseline observations would have to be done at whatever frequency was being used by the current science program.

3. **delaying the implementation of one IF in the system.** The ASAC had considerable discussion of this issue, as the scientific impact depends on how it is implemented. If the implementation meant the loss of one polarization for all bands, it is subject to all the problems described in the discussion of front-end cartridges (see first item in this list). If the implementation allowed a tradeoff between sidebands and polarization, then continuum and polarization observations would suffer a reduction in sensitivity by a factor of $\sqrt{2}$, while spectral line observing be affected because of needing longer integration times on continuum observations of calibrators.

> Continuum programs make up xx % of the total time in the DRSP. In either of these implementations, the scientific impact would be serious, equivalent to reducing the number of antennas in the array from 64 to 45.

The possibility of saving costs in the area of computing was also raised. The ASAC feels that cuts in computing may have a large impact on the science community for ALMA and would make ALMA more of an expert instrument. Thus, the ASAC would prefer to be consulted if cuts become necessary in this area.

3.2 ALMA with "a smaller number of antennas... specifically 40 or 50 operating simultaneously"

ALMA will be a revolutionary instrument. The combination of the extraordinary site, the excellent technical developments made during ALMA's development phase, and its large collecting area enable to open new areas of scientific research and provide definitive studies which will solidify our understanding of star and galaxy formation. Regardless of whether the final ALMA has 40, 50 or 64 antennas, ALMA alone has the capability to achieve the cutting edge science outined in its science justification. Even at 40 or 50 operating antennas ALMA will make fundamental scientific break-throughs in areas ranging from local star and planet formation to first galaxy formation and cosmology. ALMA will be a qualitatively different instrument from existing millimeter arrays.

It is also true that the full scientific capability of ALMA will *strongly* depend on the number of antennas. In the following sections we discuss the scientific impact of decreasing the number of antennas, including impact on the sensitivity, the imaging quality, the level 1 science goals, and the science as represented by the DSRP.

3.2.1 General issues: Imaging Quality and Sensitivity

The scientific specifications of the array were established based on the idea that the Level 1 science programs could be accomplished with relatively routine integration times (12 to 24 hours). This would also allow for the study of representative samples of objects rather than single objects. Increasing the required integration times by a factor 1.6 to 2.6 (50 or 40 antennas, respectively), would decrease the sample sizes that can be studied, and increase the risk to successfully completing the program, by introducing potential systematic errors, due to changing arrays and weather.

The original number of elements in ALMA was defined in order to achieve relatively uniform coverage of the visibility plane in a single track. This allows for high fidelity imaging for reasonable integration times with a given configuration. The uv coverage goes as the square of the number of elements, and going down to 40 antennas changes qualitatively the nature of the array, in that multiple configurations will be required to obtain adequate uv coverage to perform high fidelity imaging. Hence, many programs will require multiple configuration data, thereby extending over a longer time, increasing both the operational cost, and increasing the risk of systematic errors (eg. calibration difference between arrays). For transient objects, e.g. comets, where multiple configurations are not an option, the image quality would suffer irrecoverably.

This will shift ALMA from being predominantly a one-configuration array to a multi-configuration array. One of the consequences will be that projects take much longer to complete, since the the cycling of the array through the necessary configuration is likely to take of order a year. High stringency projects needing exceptional weather and good uv coverage could become extremely difficult to complete due to the limited cross section for outstanding weather in multiple configurations. The long time between proposal and project completion would also lessen the appeal of ALMA to a wider community, which expects a fast return.

The shift to longer integration times, multiple configurations and longer project completion times also threatens one of the top level goals of ALMA: to enable millimeter wave interferometric imaging as a scientific tool for the broad astronomical community. The road to a smaller number of antenna will likely lead to more complicated operation and higher barriers to broadening the user base.

In addition, given that sensitivity goes linearly with area but as square root of integration time, decreasing the number of antennas is an inefficient way of descoping an array, when one also considers the long term operating costs. For example, going from 64 to 40 antennas means that ALMA will be 2.6 times slower, with a commensurate increase in operations costs per project. This measure is relevant for ALMA; despite its tremendous stride forward in sensitivity, many of the key science goals are already ambitious, requiring 8 to 24 hour integrations (with the 64-element array). Hence, the science throughput of the array will be significantly impacted by decreases in antennas.

To summarize, even 50 or 40 operating antennas, ALMA would be a superb instrument which would surpass all existing arrays by a wide margin. It will enable cutting edge observations and science which cannot be done on any other instrument. In particular, ALMA's high frequency capability and long baselines make it a unique scientific instrument for the forseeable future. However, ALMA's capabilities would be noticeably eroded compared to the baseline ALMA with 64 antennas. It would become less agile, and less capable of doing larger samples of objects. The impact would be heaviest on projects requiring high sensitivity and/or high image fidelity.

3.3 Level 1 Science Requirements

3.3.1 Proto-planetary disks

The Level 1 science goal to image and trace the kinematics of gas and dust in circumstellar disks is challenging for the 64 antenna ALMA. While lesser numbers of antennas can achieve major advances toward the Level 1 goal, full achievement of this goal is at risk if the number of antennas drops to 40 or below.

The key scientific elements of this Level 1 science goal are: (1) to image the continuum emission from disks with sufficient resolution and sensitivity to find gaps and holes in disks caused by planet formation, (2) to image the molecular emission from disks with sufficient resolution and sensitivity to trace gas loss and the evolving chemistry of the disk, and (3) to image the gas kinematics with sufficient spatial and spectral resolution to learn about the thermal structure of the disk and the physical processes that are shaping the disk.

Science element 1 requires excellent imaging quality, excellent sensitivity and the highest resolution possible with ALMA. It is expected that gaps within disks will be typically less than 1 AU wide.

Inner holes in disks are likely to be from a few AU to tens of AU in size. The disks will be complex structures which will require multiple configurations to properly image. Decreasing the number of antennas in the array increases the time requirements and increases the number of configurations needed to get high quality images.

Science element 2 requires imaging of the emission from a variety of molecules to study the gas content of disks and how that content evolves from protostellar to transition to debris disks. This is of paramount importance to understanding planet formation and the end-game of early evolution of other planetary systems. Such studies will be high-profile signature science for ALMA. No other instrument existing or planned has the resolution and sensitivity to challenge the definitive work that ALMA can accomplish. Sensitivity is the driving factor for this science.

Science element 3 requires excellent imaging quality and excellent sensitivity. The sensitivity of ALMA is challenged by the requirement for both 0.1" spatial and 0.1 km/sec velocity resolution. The latter is needed to untangle the thermal, turbulent, and orbital contributions to the kinematics and to potentially explore the vertical structure of the disk. Such information is vital to understanding the role of turbulence in the disk, the physical mechanisms enabling angular moment transport in the disk, and the physical processes limiting/enabling planet formation in disks.

Reducing the number of antennas in ALMA increases the risk to full achievement of each of these science elements because it reduces the sensitivity and the imaging quality. These risks can be partially mitigated by observing longer and observing in multiple configurations but these goals already required integrations of 8 to 30 hours in the 64 element array. Increasing integration times and configurations to compensate for loss of antennas puts additional stress on the relative and absolute calibrations requirements across weeks and months, which drive the final image quality.

Finally, a fundamental part of this Level 1 goal is to enable comparative studies by imaging a broad sample of systems covering ages from birth to the age of our Sun and covering a range of stellar masses. Increasing the required integration times to 50+ hours per object essentially precludes study of large, samples of objects.

3.3.2 Molecular gas in high redshift galaxies

The power of ALMA resides in its capacity to reveal dusty, star forming galaxies out to the highest redshifts, by imaging the dust and gas reservoirs of the systems, the fundamental fuel for star formation, by measuring their kinematics, unhindered by extinction, and by probing their physical and chemical properties. These submillimeter data on high redshift galaxies will provide the key complementary information for data gathered on instruments operating at optical, radio, and X-ray wavelengths. The Level 1 science goal has been quantified as the ability to detect molecular line emission from normal galaxies (ie. Milky Way mass) out to the 'era of galaxy formation', or $z \sim 3$. Current arrays are limited to studying either the most massive galaxies (10 times or more the mass of the Milky Way), or strongly gravitationally lensed systems. The ability of ALMA to trace the molecular content of normal galaxies at high redshifts (as well as their main atomic far-infrared cooling lines) and the high sensitivity achieved by ALMA in the continuum, which will allow detection of galaxies a few times less luminous than the Milky Way out to $z \sim 3$, will both have a dramatic impact on our understanding of galaxy formation and its evolution over cosmic time.

The Level 1 science specification is to detect the Milky Way at $z = 3$ in relatively routine integration times of 24 hours or so (including overhead) with a 64 element array. Such science is not precluded by a smaller number of antennas, but obviously programs will require more time, eg. for 40 elements the time increases to 60 hours, which no longer can be considered a ’routine’ observation.

A potential issue is the question of whether systematic errors start limiting the sensitivity such that the noise decreases more slowly than square root time. For example, it may be that the weather and/or array configuration change substantially over the time it takes to complete a project. Adding such data together may not provide optimal sensitivity. In general, completing a program as quickly as possible is the best way to mitigate systematic errors.

Overall, a re-baselined ALMA to 50 antennas would still open a unique window into the study of the gas and dust content of normal galaxies at large look-back times. However, dropping from 64 to 40 antennas would take this program from the regime of relatively ’routine’ observations to being time intensive, and increasing the risk of potential systematic errors.

4 Large Programs, Legacy Programs, and Joint Programs with ALMA

Charge 2: The ASAC is invited to continue its considerations of this September, 2004 charge, which may be combined with the continued development of ideas for implementing demonstration science elaborated at the same meeting.

Following thorough assessment of the procs and cons of policies in use at existing ground- and space-based facilities, including those currently operated by the ALMA Executives, ASAC is invited to consider policy recommendations on:

1. *how to facilitate joint projects between scientists of different partners*
1. *how to handle large proposals with significant scientific duplication*
1. *whether provision needs to be made at this time for legacy projects,*
   and if so, what mechanisms should be used for such projects. These complex, often-contentious issues should be addressed in the spirit of demonstrating how ASAC believes their recommendations, if adopted, would maximize ALMA’s scientific impact.

(To be reworded or expanded?)

The second charge to the ASAC concerned the issue of how to encourage collaboration through the individual partners of the ALMA project, and the scheduling of large programs in a way that would maximize the scientific productivity of the ALMA instrument given the requirement that the individual partners will have separate Program Review Committees (PRCs). There is a consensus within the Committee that there is some requirement for an international Program Review Committee to consider joint proposals, and particularly very large proposals. However there is not complete agreement on the scope of an IPRC. The Committee feels that further consideration of this issue is warranted.

Appendix A: Charge to ASAC Meeting September 2003

To be included

Appendix B: ASAC members and attendees

ASAC Members in attendance

Chris Carilli (NRAO Socorro)
Yasuo Fukui (Tokyo)
Diego Mardones (U. Chile), by video conference from Santiago
Munetake Momose (Ibaraki University)
Lee Mundy (Maryland)
Jean Turner (UCLA)
Christine Wilson (McMaster)
Pierre Cox (Paris)
John Richer (Cambridge) – Chair
Peter Schilke (Bonn)
Leonardo Testi (Arcetri)
Ewine Van Dishoeck (Leiden)

ASAC Ex-officio Members

Ryohei Kawabe (NAOJ)
Tom Wilson (ESO)
Al Wootten (NRAO)

Project Representatives

Massimo Tarenghi (JAO)
Anthony Beasley (JAO)
Dave Silva (ESO)
Darrel Emerson (NRAO)
Mark Holdaway (NRAO), by video conference from Socorro

Apologies

Satoshi Yamamoto (Tokyo) Andrew Blain (Caltech)

Appendix D: Agenda for the ASAC Meeting of February 24-25, 2005 in Garching

to be included

Appendix D: ASAC Rules of Procedure

1. The ASAC is an advisory body, and its decisions are to be reached by consensus, so complicated voting rules are not required.
2. No quorum is necessary for the meeting to be deemed 'official' but it must be approved of and chaired by either Chair or Vice-Chair. If neither of these can chair the meeting, the members present shall nominate an acting chair.
3. Decisions shall be by consensus, on motion put by Chair
4. Dissenting opinions shall be recorded.
5. Any item can be added to agenda at any time by consensus of committee.

Appendix E: ASAC Liaisons to Project IPTs

Operations	*van Dishoeck , Carilli*
Site	*Mundy , Schilke*
Antenna	*Schilke , Turner*
Front End	*Wilson , Cox*
Back End	*Myers , Testi*
Correlator	*Myers , Testi*
Computing	*Testi , Mundy*
System Engineering and Integration	*Carilli , Richer*
Science	*Richer , Mundy and all ASAC members*
Outreach	*Cox , Turner*