Report from the ALMA Science Advisory Committee
May 2004 Meeting

Membership of ALMA Science Advisory Committee

L. Mundy (Chair, USA), P. Schilke (Vice-Chair, Germany), C. Carilli (USA), P. Cox (France), D. Mardones (Chile), P. Myers (USA), J. Richer (UK), L., Testi (Italy), J. Turner (USA), E.van Dishoeck (Netherlands), C. Wilson (Canada)

Ex-Officio Members

A. Wootten (NRAO), T. Wilson (ESO)

Contributing Attendees

D. Emerson, R. Kawabe, R. Laing, R. Lucas, D. Shepherd, D. Silva, M. Tarenghi, T. Wilson, and A. Wootten

1 Executive Summary

This document is a report to the ALMA Board on the ASAC meeting held in Cambridge England in May 2004. The ASAC was pleased to hear about all of the progress in the ALMA project. We appreciate the hard work being done by the many people now contributing to hardware, software, and site development. The ALMA project continues to be on a good tragetory for achieving its major milestones.

Regarding the five specific charges from the ALMA Board, the ASAC wishes to highlight the following points. The phase stability requirements being adopted by the Systems IPT appear reasonable although we recommend that some further simulation work be done to ensure minimal impact on the imaging capability. The total power stability specifications recommended in the System Technical Requirements document remain troubling; we recommend that the project continues to pursue avenues for improving the stability of the receivers for the four total power antennas. ALMA calibration is still an area that needs significant work. We hope that efforts can be made to (1) study the direct impact of calibration errors on derived physical quantities from the most challenging Level 1 science goals, (2) bring to conclusion tests of proposed calibration mechanisms, and (3) build basic knowledge on calibrator source densities and fluxes.

The early ALMA array will be outstanding in its resolution, its high frequency capability, and its location (high site and southern sky). The project needs to focus on exploiting these facets to maximize its early science impact. We recommend that the ALMA project develop "science demonstration projects" with community involvement and do focussed extensions and complements to other major observatories projects. These early science projects will require multi-configuration observations to make public relations and scientific impacts.

Overall, the Operations Plan appears to be well underway but the sections of the Operation Plan G3 on early operation and the integration of new equipment into the array need much more work. We are concerned about the interaction between software and hardware verification, the integration of new hardware and software, and the official start of outside observing. We have particular concerns that the software be given adequate time for commissioning and verification. It is important that ALMA have an easy-to-use data reduction package and produce science grade calibrated data for its first wave of official users.

Please see the the summary points at the end of this document for the next level of detail.

2 Introduction

This document is a report from the ALMA Science Advisory Committee meeting which was held on May 10 and 11 in Cambridge England. The committee is grateful to John Richer and the local staff at Cambridge for their hospitality and their help in making this a successful meeting.

The primary focus of the meeting was the five charges given to the ASAC by the ALMA board. The charges relate to: (1) total power and phase stability of ALMA, (2) ALMA calibration, (3) context of early ALMA science, (4) ALMA operations plans, and (5) science and software requirement prioritization. The committee heard reports in each of these areas from JAO, ESO, or NRAO staff, discussed the issues, and formulated the recommendations which are given in the accompanying sections.

We also heard presentations from Ryohei Kawabe about the status of the ACA and a presentation by Richard Hills and Alison Sterling about the water vapor radiometer for ALMA. We are happy to see that these aspects of the project are proceeding well. It is highly desirable to outfit the early array with these phase correction systems.

3 Charge 1: Total Power and Phase Stability

The ASAC is requested to consider the following topics, and make appropriate recommendations to the Board:

1. Critically evaluate the specifications for total power and phase stability for ALMA and assess the implications for ALMA science goals.

The ASAC heard a presentation by Al Wootten summarizing the current goals and the current status of progress toward the goals. A number of ALMA memos were available which are relevant to the subject including recent work by Mark Holdaway and Larry D'adddario.

3.1 Phase Stability

ALMA will open up a new parameter space of astronomical imaging: it must deliver accurate, diffraction-limited images on baselines 10 km and longer, and at frequencies up to 950 GHz, through an unstable and partially opaque atmosphere. This requirement places stringent constraints on the phase stability of the system.

The ASAC was given a detailed status report on the issue of phase stability which included the technical justification for the current specifications on delay errors proposed by the System IPT. Phase errors may limit the dynamic range, resolution, and sensitivity of ALMA and will also introduce artifacts into the images. The current specifications for delay errors proposed in the ALMA System Technical Requirements have been set so that instrumental errors are not the dominant errors in the system during 95% of the weather conditions. Even these relatively strict specifications result in an additional sensitivity loss above the loss introduced by the ALMA correlator. Thus, even the current specifications produce a significant loss in sensitivity at the highest ALMA frequencies and so it is important that the specifications on the delay errors not be allowed to degrade significantly from the current proposed level.

The ASAC recommends that the currently proposed technical requirements for delay errors of 22 fsec max rms change in 300 sec (drift) and 65 fsec rms deviation from 10 sec average (noise), proposed by the Systems IPT[1], be adopted for ALMA. This strict technical requirement is important to maximizing ALMA sensitivity at the highest frequencies, which enables major ALMA science goals.

In addition to the loss in sensitivity, the ASAC is concerned that these phase errors may also affect the high-resolution imaging capability of ALMA. One of the three primary science requirements for ALMA is the ability to provide precise images at an angular resolution of $0.1''$. It is difficult to assess whether delay errors will affect the image quality without simulations. It may be that baseline-based calibration, which may be necessary in any case to correct properly for the loss in sensitivity, will also serve to produce good quality images. Such a solution would require no additional hardware to implement, but could have a significant impact on ALMA Software such as the Pipeline, where the working assumption is that antenna-based calibration will normally be used.

The ASAC also recommends that the Science IPT carry out simulations to see how this level of phase stability affects ALMA's high-resolution imaging capability. The results of these simulations should be assessed for their implications on the ALMA Calibration plan and the ALMA Software effort, particularly the Pipeline.

3.2 Total Power Stability

The ASAC was presented with a summary of the technical requirements on total power stability, which were confirmed by the Change Control Board in November 2003. The adopted specification is for a gain stability of $< 1 \times 10^{-3}$ for all antennas at 0.05 to 0.5 seconds and at 100 seconds[2], with a third requirement of $< 4 \times 10^{-4}$ over 0.05 to 0.5 seconds for four antennas optimized for total power[3]. This specification for the four total power antennas is substantially worse than the recommended level of 1×10^{-4} based on detailed simulations presented in ALMA Memo 490 and discussed in the previous ASAC report. The result of the current specification is that ALMA will not be thermal noise limited for continuum total power imaging, which will have a significant impact on ALMA's ability to make wide-field continuum images including emission on all spatial scales. In particular, the simulation results from ALMA Memo 490 suggest that ALMA will take 6-9 times as long to reach a given rms noise level

[1]Req. nos. 451 and 452 in ALMA System Technical Requirements (ALMA-80.04.00.00-005-A-WPE)

[2]Req. nos. 261 and 262 in ALMA System Technical Requirements (ALMA-80.04.00.00-005-A-WPE)

[3]Req. nos. 263 in ALMA System Technical Requirements (ALMA-80.04.00.00-005-A-SPE)

in total power continuum imaging as it would have taken had a gain stability of 1×10^{-4} been achieved. There was some discussion as to whether it would be possible to trade gain stability for sensitivity for the four total power antennas, perhaps by using Gallium Arsenide amplifiers for those four receivers.

The ASAC recommends that the project investigate whether there are useful tradeoffs between gain stability and sensitivity that could be made for the four total power antennas. The ASAC also recommends that this issue of gain stability be revisited when the systems group has been able to perform well-controlled and consistent measurements on the ALMA prototype cartridges in the ALMA cryostat.

3.3 Polarization Stability

In our last report, the ASAC expressed concerns that the current specifications on stability did not adequately address ALMA's goal to achieve high-quality images of polarized emission. Some initial steps towards defining a satisfactory specification were presented, but are still under development by the Science IPT. In particular, the Science IPT is working on simulations of polarization observations with ALMA. The ASAC notes that polarization observations represent a crucial capability for ALMA that will open up new fields of study and are one of the areas where ALMA will provide a truly unique capability. The ASAC looks forward to reviewing the revised technical requirements and simulations on polarization when they become available.

4 Charge 2: ALMA Calibration

The ASAC is requested to consider the ALMA Calibration Plan, and make appropriate recommendations to the Board on:

- *The science loss as a function of the relative and absolute amplitude calibration accuracy of ALMA; and*
- *astronomical source calibration activities that should be started before or during early science operations, whether on other facilities or (when available) ALMA.*

The ASAC heard an oral presentation by Al Wootten on the Calibration Requirements and Specifications, a summary on the responses about a questionnaire on the impact of calibration accuracy on the science of the DRSP and on current ideas to build a data base of ALMA calibrators.

4.1 DRSP questionnaire and science examples

The responses to the DRSP questionnaire, to which 60% responded, were very useful in evaluating the needs for various projects in terms of calibration accuracy. The results can be summarized as follows: for continuum measurements, the responses center at a calibration accuracy of 1-3% (absolute, relative and repeatability); for line projects, the responses indicate somewhat relaxed specifications of 10% for absolute accuracy, 5% for relative accuracy (both within and between bands) and 3-5% for repeatability; for polarization, the responses are in the range of 1-5%.

In parallel with using this statistical approach, we feel that more detailed assessments of key ALMA projects are needed. The DRSP evaluation does not highlight possible losses in specific areas of science where ALMA could make major and unique impacts.

Studies of high profile science examples are already available and include the cases of protostellar envelopes, high-redshift galaxies and solar system objects. For instance, in ALMA memo 492 Carilli concludes that 3% calibration errors between 250 and 350 GHz will constrain (at 3σ) the temperature of a warm (~ 50 K) dust component to only 20°, while 10% calibration errors between 250 and 650 GHz provide a 3σ constraint of 10°. He shows that a temperature change from 50 to 70 K leads to a factor 4.5 change in derived infrared luminosity. As an another example, detailed analysis of proto-stellar envelopes indicates that at least 10% absolute calibration and 3% repeatability and relative (band-to-band) calibration are required to properly constrain the density and temperature distributions.

The committee felt that it would be useful to look further in detail at programs that are highly demanding in the calibration accuracy (in particular, in planetary science, e.g., the measurement of the sizes and albedos of Kuiper Belt Objects). The ASAC recommends that the Science IPT look closely at the scientific arguments for calibration accuracy based on the responses to the DRSP questionnaire and other available studies, and performs further simulations (e.g., investigate imaging errors for multi-array data combination) involving key science goals. Such studies are desirable to fully evaluate the impact on the science through a loss in the accuracies of the relative and absolute calibration amplitude calibration.

The understanding of flow down from calibration accuracy to science loss requires continued study. Many projects will not be demanding on calibration but the broad scope of science enabled by ALMA makes it difficult to enumerate the direct impact on derived physical quantities. The ASAC recommends that the Science IPT identify and study the impact of calibration on a handful of the most challenging major science goals.

4.2 Amplitude Calibration

Several devices under consideration for the amplitude calibration have achieved the following accuracies: the simple ambient load insertion reached $\sim 10\%$, the dual-load in the sub-reflector which is tested at BIMA reached $< 10\%$, and the simple semi-transparent vane which could reach 3% but has not yet been tested on astronomical sources. Plans are to start laboratory tests for the semi-transparent vane with the grid system at 60 GHz in Madrid.

The ASAC strongly encourages continued calibration testing, both in the lab and on the ATF once the facility can be outfitted for this purpose. We look forward to the results from the current experiments with BIMA antennas by Jack Welch. But, we stress that much more work is needed.

The ASAC notes that the Calibration team has recently lost two major leaders in the field (S. Guilloteau and B. Butler), which has hampered progress in a number of areas. This should change with J. Mangum joining the team soon. Dedicated efforts should be implemented in the key area of calibration, and a clear plan should emerge together with the needed resources. One area that looks particularly orphaned is flux calibration using cosmic sources (planets etc..). In this respect, the project might consider a dedicated horn to determine absolute fluxes of planets once a year. Also, comparison could be made with results from space missions, such as Planck and Herschel. The ASAC recalls that a joint ALMA-Herschel calibration meeting was held in Leiden in December 2002 and encourage the teams to maintain contact in the future.

The ASAC strongly encourages continued testing of calibration mechanisms to determine if any can provide the project's required level of accuracy. The overall area of absolute calibration needs dedicated effort within the project.

4.3 Astronomical source calibration

A proposal was discussed for a large survey for phase calibrators for ALMA. Such a phase calibrator list is a key area for ALMA, and the project needs to start planning, and perhaps perform the first observations. Most immediately, information on the high frequency source areal density is also needed for modeling of fast switching. The current ALMA plan allows for the possibility of pre-observation phase calibrator searches, but this should not deter the project from pursuing large lists of sources prior to operation.

The project should have a clear plan, and support preliminary observational efforts, such as the survey of compact flat spectrum radio sources proposed by M. Holdaway, C.L. Carilli & R. Laing, to the extent that these programs do not delay commissioning/testing. The ATF and early ALMA are possibly good sites for such work, since the observations will produce useful results for calibration, and will be relatively easy projects with which to stress system and gain experience early. Such programs could involve postdocs as well. In the very near term, the ASAC supports efforts to investigate sources from the calibrator 'lists' of the IRAM 30-meter, OVRO, and the JCMT.

The project should plan for phase calibrator surveys with the ATF and ALMA; the project should also make maximal use of parallel efforts at the IRAM 30-meter, CARMA, JCMT, APEX, and PdBI. The ATF and ALMA efforts must be focussed on the essential needs and not interfere with commissioning and testing.

5 Charge 3: ALMA Early Operations in Context

Comment upon the modes being proposed for Early Science Operations in comparison to contemporary ground and space facilities planned for those years.

The ASAC heard talks by David Silva about the Operations Plan and early operations. Al Wootten, Debra Shepherd, and others present contributed information about the expected status of ALMA for early science operations.

5.1 Modes of Observations

The expectations for ALMA are high. Therefore, care should be taken that the first results from ALMA are not disappointing to the general scientific community, and to the public. **The ASAC feels strongly that ALMA should, in its early years of operation, concentrate on types of observations where it will excel: submillimeter wavelengths and high angular resolution.** During the "early science" period ALMA will likely have eight working antennas, so in the millimeter wavelength range ALMA performance will be comparable to, or only marginally superior to, that of other existing arrays such as CARMA, the IRAM PdBI, and the NRO array. However, ALMA will be by far the most sensitive submillimeter interferometer, having some four times the collecting area of the only competitor, the SMA, and being on a superior site. Hence, submillimeter projects should have high priority, and it is highly desirable to have at least one submillimeter band available.

The availability of a wide range of configurations is essential to demonstrate the unique science capabilities of ALMA. It is very important that some high resolution configurations, with baselines larger than 1 km, are among them. This will allow observations whose resolution cannot be matched by any other interferometer. It is also important that good u,v coverage be available for highly rated projects to demonstrate the promise of the full ALMA. The early science configurations being designed by John Conway are likely to be appropriate in this regard. *We stress the importance of maintaining the project's current plan to cycle through the configurations during early science.*

The observing modes of the interferometer can be limited in complexity, but should include single field interferometry, pointed mosaics (no OTF), and single-dish total power line observations (no continuum). The mosaics should be large enough to show that ALMA can make good mosaic maps, but need not be extended over large numbers of primary beams. To aid calibration, the availability of fast switching and WVRs is highly desirable in general, and critical on the longest baselines and at the shortest wavelengths.

5.2 Targeting Early Science

A program for early science should be developed. Just scaling the existing DRSP down to the small early arrays is not useful, since many programs are not easily scalable, and changes would not optimize the science quality. The ASAC believes that a full blown early science DRSP effort is excessive; **the ASAC recommends the development of "science demonstration projects" to exemplify ALMA scientific capability and public appeal.** These would fall into two categories:

- Public demonstration images. The purpose is to demonstrate the capabilities of ALMA to a general audience. The goal is to create a small library of high-profile, pretty images which would be available to the general public and the science community. Although scientific publications using these data are important, scientific novelty is not a prerequisite. These projects could be defined using contributions from groups such as the ASAC, the project scientists, and the science advisory committees to the Executives, without a call for proposals from the community.
- Science demonstration projects. The purpose is to demonstrate the capabilities of ALMA to the general astronomical community. The projects should span a wide range of scientific topics, and should span a wide range of instrumental capabilities. The data should be made available to the public immediately without proprietary rights. We propose that the best way to define these projects is to issue an open call for ideas - not specific proposals - to a wide audience. The Board could then call on an appropriate committee to evaluate contributed ideas and work with ALMA staff to implement projects.

The key distinctions between demonstration projects and open-call early science is that the demonstration projects would be run by people most knowledgeable about the instrument and their data would be immediately made public to interest and inform the public and science community.

To maximize the scientific impact, some key ALMA programs should include coordination with programs to other facilities, such as the space observatories HST, Spitzer, Herschel and Planck, as well as ground-based single-dish facilities such as APEX, JCMT/SCUBA2, and LMT, and interferometers such as SMA, CARMA, and the IRAM PdBI. Examples would include observing redshifted galaxies found in the GOODS projects or by Planck, debris disks found by Spitzer, and maps of star forming regions studied by Herschel/HIFI in water lines or spectral line surveys. Advantage also should be taken of the fact that ALMA will be the only millimeter/submillimeter observatory in the southern sky, and observations of unique southern sky objects such as the Magellanic Clouds, Centaurus A, and η Carina should have high priority.

Organizing the early science program would seem to be an appropriate activity for the ALMA project scientist, with input from the ASAC and the scientific community.

6 Charge 4: ALMA Operations Plan and Operations for Early Science

The ALMA Operations Plan (if it becomes available in sufficient time), commenting particularly on issues that impact the Early Science.

The ASAC received ALMA operations plan G3 for reading and comment. At the meeting we had a presentation by David Silva and engaged in discussion with David and Darrel Emerson.

6.1 General Operations

The ASAC is impressed with the progress in planning for operations. The Operations Plan is an excellent tool for detailing the requirements for operations and identifying resources in anticipation of the needs. **The ASAC agrees with the overall principles outlined in section 7.1. The one-observatory philosophy with data quality monitored maintained by the ALMA Observatory is important. We support the primary goals: (1) producing reliable science quality images as the default product, (2) maintaining an archive for all raw and calibrated data with easy user access, and (3) making the observatory accessible to non-experts and experts alike.**

There are some areas where the operations plan needs additional work. The final data flow from the correlator to the ARC and the user is not fully defined. The final plan should have a specific goal for the mean time from data acquisition to delivery of images and u,v data to the end user; we suggest that this time be of order a week. We expect that the antenna relocation plan will need to be more flexible than currently envisioned in section 10.2.1. Some arrays will have more demand, some will have less. Some projects will require that the array not change significantly over the period of weeks.

The details of the time allocation process are still vague and need to be addressed in the final plan. In particular, the organization of joint projects between scientists of different partners, the policy for dealing with duplication of large proposals, and the policy for "legacy" projects with ALMA are areas of concern for the ASAC.

Finally, the ASAC stresses the importance of proper funding for further development of ALMA in the operational phase, both for software and hardware upgrades of the array and development of new data reduction tools. These upgrades are essential to assure that ALMA remains a front-line scientific instrument for its entire projected lifetime.

6.2 Early Operations

In the specific area of early science, **we agree with the science-related assumptions that underlie the Early Operations Plan: the requirement of 6-8 antennas, the selection of limited modes of operation for early**

observations, and the plan to have part-time science operations in the early years. We concur with the project's position that early science operations should not delay continuing construction significantly. The plan to schedule science into blocks of time is acceptable. We recommend that the earliest science blocks should be days rather than weeks in length because key science and technical people are required to make progress and they cannot work 24 hours/day for long.

The Early Operations Plan needs to be further expanded to anticipate how new hardware and software will go through commissioning to validation to regular use on the growing array. In particular, the phasing-in of additional receiver bands and antennas needs to be clarified as they may have a significant impact on the plan. The quality assurance plan for operations also needs further development. We stress the importance of timely data delivery to the proposers, on time scales of weeks after the observations.

The ASAC is concerned about the timing of the first call for proposals, which is scheduled at a time when commissioning and science verification of the instrument is still in full swing. Rather than a full-blown early call, the ASAC recommends the concept of science demonstration projects in the first few months of operations; see the previous section for more about this proposal.

There are two areas of concern for early operations which the project recognizes, but are sufficiently important to be mentioned here. First, the project needs to continue its effort to get operations funding in line with operations need, including proper funding of the ALMA Regional Centers. We agree with the project's assessment that considerable man-power resources are needed to support reasonable early operation. Specifically, there is a steep learning curve for the community during the first few years of operations and there will be a strong demand for face-to-face user support (currently not considered part of the core funding), in addition to the core user support functions. Second, it is critical that scientists be able to work with early data with reasonable tools. The project needs to track carefully the development and testing of scientific software tools (see next section).

Overall, **we recommend the project to seek ways to involve experts from the community in the commissioning, science verification and early science operation activities, both as a benefit to the project and as a way to disseminate expertise back into the community.** The ASAC concurs with the project that these involvements should be for significant periods of time (of order months), but notes that there may be possibilities for faculty to arrange sabbatical and leaves of absence given enough lead time.

7 Charge 5: Science and Software Requirement Prioritization

Review the prioritization of the Science Software Requirements in response to the PDR committee's recommendation to: a. prioritize the requirements in light *of schedule and cost drivers, and b. science priorities, and the importance of achieving early-science operations. This should be done in the context of the science operations plan, not independent of it.*

Robert Lucas and Debra Shepherd, SSR committee lead and SSR scientist in charge of the software test plan, gave a review of the Science Software Requirements status on behalf of the Computing IPT.

7.1 Status of Science Software

The ASAC welcomed the initial results of the user tests which showed that all subsystems successfully achieved their goals during this first phase of development. It was noted that the most critical subsystems in terms of user acceptance risks are the Data Reduction Package and the Observation Preparation subsystem. The Computing IPT should continue to ensure participation of external potential users to the tests of these subsystems.

In response to its PDR comments, the Computing IPT is reconsidering priorities in light of schedule and cost drivers, science priorities, early science operations, and science operation plan They have already made some preliminary decisions on priorities based on development schedule and early interactions with the Operations Group. In particular:

- The quick-look pipeline system is now envisaged only for the observatory staff and it is not foreseen to be available for external eavesdropping.
- Expert mode of the Observation Preparation subsystem will only be available in collaboration with observatory staff members.
- The development of the "Breakpoints" in observing programs is deferred.
- The development of the Graphical User Interface to the Offline Data Reduction Package has been deferred after early science operations.
- The science pipeline heuristics is not expected to be ready for early science operations

The Computing IPT anticipates that it cannot meet the Q3 2007 Early Science deadline with a working ALMA data reduction pipeline producing scientifically accurate images. It is anticipated that pipeline software and rudimentary heuristics will be available. This is caused by the lack of time to commission the pipeline heuristics with real ALMA data before the start of Early Science Operations. As an example, it is difficult to fully characterize the data in the different bands and modes for the purposes of constructing automated editing routines before there are significant numbers of antennas on site.

The full reprioritization of the software cannot be finalized until the science operation plan is completed.

7.2 Software Concerns

The ASAC broadly agrees with the changes being consider above by the Computing IPT. The ASAC strongly reaffirms that one of the keys to the success of ALMA in attracting a large user community beyond the few astronomers already familiar with mm-interferometry is the ability to deliver to the end user data products that are ready for science analysis, at least for the most common and standard observing modes. This picture has been presented at all community meetings so far and has created strong expectation in the potential ALMA users. Failing to reach this goal early in the project will likely limit the breath of support in the astronomical community. This is especially aggravated by the combined delay of the commissioning of the pipeline heuristics and the development of the graphical user interface for the offline package, both very visible components to non-expert users.

A general concern was expressed that the commissioning plan was not allowing for enough time to commission all the software system before the beginning of Early Science Operations. The software system should be considered as an essential part of the instrument and as such a proper commissioning time should be in place for that as well.

The pipeline unavailability during early science implies that ALMA users will have to reduce the raw data using the data reduction package, most likely using the command line or possibly a script. The lack of a Graphical User Interface (GUI) may deter general users from using ALMA during the early science phase. However, the ASAC agrees that a good command line interface is better than a poorly designed GUI for early science. The ultimate goal for ALMA data reduction beyond the pipeline should be an intuitive and easy-to-use GUI.

The ASAC reaffirms the importance of having an easy-to-use data reduction package and producing science grade calibrated data, starting from early science. Achievement of these goals is necessary for ALMA to attract a large community of scientists from beyond the millimeter community. The ASAC is concerned that the current commissioning plan does not allow sufficient time for pipeline development with ALMA data from on-site antennas to meet the Q3 2007 Early Science milestone.

The ASAC recommends that it be charged to examine the prioritization when this process is complete and urges the project to complete the plans for Science Operations and Early Science, and the subsequent Requirements reprioritization, as soon as possible.

8 Summary of Main Recommendations

1. The ASAC recommends that the currently proposed technical requirements for delay errors of 22 fsec max rms change in 300 sec (drift) and 65 fsec rms deviation from 10 sec average (noise), proposed by the Systems IPT be adopted for ALMA. This strict technical requirement is important

to maximizing ALMA sensitivity at the highest frequencies, which enables major ALMA science goals (Charge 1).

2. The ASAC recommends that the project investigate whether there are useful tradeoffs between gain stability and sensitivity that could be made for the four total power antennas. The ASAC also recommends that this issue of gain stability be revisited when the systems group has been able to perform well-controlled and consistent measurements on the ALMA prototype cartridges in the ALMA cryostat (Charge 1).

3. The understanding of flow down from calibration accuracy to science loss requires continued study. The ASAC recommends that the Science IPT identify and study the impact of calibration on a handful of the most challenging major science goals (Charge 2).

4. The ASAC strongly encourages continued testing of calibration mechanisms to determine if any can provide the project's required level of accuracy. The overall area of absolution calibration needs dedicated effort within the project (Charge 2).

5. The project should plan for phase calibrator surveys with the ATF and ALMA; the project should also make maximal use of parallel efforts at the IRAM 30-m, CARMA, JCMT, APEX, and PdB. The ATF and ALMA efforts must focussed in the essential needs and not interfere with commissioning and testing (Charge 2).

6. ALMA must have high angular resolution and high frequencies during Early Science to make significant and unique science impact. This is where the early instrument can make ground-breaking contributions (Charge 3).

7. The ASAC highly recommends that ALMA plan for science demonstration projects which are released to be the public immediately. These projects should have significant and broad value to the community and the general public; the data would be released with no proprietary period to foster community knowledge of ALMA's capabilities (Charge 3).

8. The Operations Plan is off to a good start and will be of high value in directing the project. We agree with the underlying assumptions for the Early Science Operations but much detailed work remains to be done in this area. We hope that the ASAC will be asked for additional input into the time allocation policy (Charge 4).

9. The ASAC shares the project's concern that the funding ramp up for science operations is not sufficient to be ready for commissioning, science verification and early operations (Charge 4).

10. It is critical that the core data reduction software be ready for early science. Work toward this goal needs to be monitored and sufficient time should be allowed for software commissioning. Failure to have science

quality user-friendly software will jeopardize the early credibility of the project in the community at large (Charge 5).

11. We recommend that the ASAC be asked to re-examine the prioritization of Software Requirement after the operations plan for early science and the software requirement considerations have gone through their next step (Charge 5).

12. ALMA needs to carefully manage community expectations and science production during the first couple years of early science. The current schedule appears very aggressive and the capabilities of the early array will not be outstandingly superior to concurrent arrays and large telescopes. Time allocations and array scheduling need to be designed to maximize science while minimize negative impact on construction. If the Board has the goal of creating dramatic scientific results during initial early operations, it will be essential utilize the full set of early array configurations and submillimeter frequencies.