Report from the ALMA Science Advisory Committee
September 2004 meeting

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Members of the ALMA Science Advisory Committee
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Excused: Y. Fukui, M. Momose, S. Yamamoto
Ex-Officio Members
T. Wilson (ESO), A. Wootten (NRAO)
Contributing Attendees
D. Emerson, M. Holdaway (by video), R. Kawabe, R. Laing, D. Silva, M. Tarenghi, P. Vanden Bout

1 Executive Summary

The main focus of the ASAC meeting were the charges from the ALMA Board. Regarding Charge 1, the ASAC found it difficult to discuss possible reductions in the baseline project, which in its present state is already the result of compromises and cutbacks. Since both the time to reach a certain sensitivity and the image fidelity scale with the square of the number of antennas, even modest reduction in the quantity of antennas will have significant consequences for the performance of the array, and will considerably diminish ALMA's discovery space. The number of receiver bands, reduced from the original 10 to 4 at present, are such that any permanent loss of a band would result in loss of important parts of ALMA science. The same is true for long baselines, which, together with submillimeter receiver bands, are essential to the highest level science goals. **The ASAC concludes that the loss or reduction of any element of the baseline project will result in significant loss of ALMA science** and recommend to look at saving options associated with delays of non-critical elements, and re-assessment of the priorities of the enhanced project.

On the issue of time allocation policies, topic of Charge 2, the ASAC concluded that the best way to handle large programs is to have a single International Program Review Committee that is empowered to rank and/or choose between large proposals. For smaller projects involving collaborators from more than one partner, the ASAC suggests that a Joint Proposal mechanism similar to the one currently used by the Gemini observatory may be appropriate.

The impact of calibration specifications on the most challenging science goals was studied for Charge 3. It was concluded that relaxing the absolute amplitude calibration specs from 1 to 3% below 300 GHz and from 3 to 5% above would not have a prohibiting impact on major science goals, although it would preclude some interesting planetary science. Repeatability should be maintained at a higher level.

Regarding Charge 4, the involvement of the scientific community in demonstration science was thought to be best achieved by creating teams consisting of astronomers from a wider community and ALMA experts. The teams would execute projects from end-to-end, from the definition of the scheduling blocks through the observations and data reduction all the way to publication. It was felt to be unwise to attempt this too soon. The ASAC recommends waiting until the superior quality of ALMA science can be demonstrated.

The current draft of the Science Verification Plan was presented in preparation for discussions of Charge 5. While the philosophy of science verification is sound, it lacks details, and the ASAC was concerned about sufficient scientific staffing for working on the final plan. Another area of concern is the short time allocated for science verification, which should not be cut further by the desire to keep dates for milestones.

2 Introduction

The ASAC met in Charlottesville, VA, on 27-28 September 2004, to get an update on the project status, and to discuss the charges from the Board. The committee is grateful to Al Wootten and the local staff at Charlottesville for the organization, and to Fred Lo for his hospitality at NRAO.

The prime focus of the meeting was the five charges given to the ASAC by the ALMA Board. The charges relate to: (1) science based criteria for tradeoff studies in view of budgetary constraints, (2) time allocation policies, (3), ALMA calibration, (4) demonstration science, and (5) science verification plan. For Charges 1 and 5, the committee heard presentations by Mark Holdaway (via video) and Robert Laing, respectively. The conclusions of the committee are given in the following sections. Due to the time pressure for Charge 1, an advance version of this section was sent to the Board on October 10. The content of the section on Charge 1 (Sect. 3) has not been changed significantly in this final report.

An update on the project status was given by Massimo Tarenghi, Ryohei Kawabe reported on recent events from Japan, and news on science IPT and outreach issues were presented by Al Wootten. Tom Wilson and Paul Vanden Bout summarized the status of the ARC planning in Europe and North America. At the end of the meeting, a tour of the Band 6 and correlator laboratories was given. The ASAC was pleased to see ALMA hardware materializing.

The ASAC was informed about ALMA workshops planned in Europe, financed by the FP6 Radionet program. In the discussion the desire to have truly joint workshops was voiced by all participants. The partners were urged to find ways of financing and organizing such common workshops or conferences, and to procure means to make travel to these joint events possible. The need for joint project-wide outreach activities was expressed, e.g. by organizing common displays for conferences or symposia. It is important that ALMA is presented as a unified project.

Leonardo Testi was proposed by the European ASAC members as the next vice-chair.

3 Charge 1: Science based criteria for tradeoff studies

The charge is to *"Recommend clear, science-based criteria to be used by the Project in preparing trade-off studies should budgetary constraints make it necessary to reduce planned activities in the baseline project following analysis of the responses to the antenna procurement process"*.

The ASAC revisited and updated the arguments that led to the definition of the baseline project as 64×12m antennas with 4 receiver bands, back-end, correlator and software, and compared its sensitivity, imaging quality and frequency coverage against the Level 1 science requirements and other major science drivers. **The main conclusion of the ASAC is that the loss or reduction of any element of the baseline project will result in significant loss of ALMA science.**

The ASAC emphasizes that, in contrast with the current situation for large optical telescopes, there will be only one ALMA which has to serve the entire worldwide community.

In the following, the various elements of the ALMA baseline project are summarized in order of priority for retaining. Science-based arguments are discussed more extensively in Sections 3.1-3.3. The ASAC notes that it was extremely difficult to address this charge given the total lack of information provided to the committee on (a) the relative costs of the various elements of the ALMA project (in particular antennas versus receivers), and (b) the possible magnitude of the budgetary shortfall facing the project. Furthermore the ASAC felt it was unwise and perhaps dangerous to recommend general science-based criteria without understanding how they might be applied, and what the real consequences would be for ALMA performance.

- **Collecting area:** Much of the new science expected from ALMA is only made possible by the tremendous sensitivity of the instrument. There are many compelling scientific arguments which demand a collecting area ND^2 of at least 7000 m^2, which for $D = 12$ m gives $N = 64$ antennas (see Sect. 3.1). While a 10% loss in collecting area would have a modest scientific impact, any larger reduction would significantly affect the time needed to complete high-profile science cases, since observing time scales as N^2. Moreover, the big step forward of ALMA compared with existing arrays —and hence its discovery space— is eroded with a significant cut in N.

- **Receiver bands:** ALMA should have receiver bands covering a wide frequency range (see Sect. 3.2). The ASAC re-confirms that the 4 receiver bands in the baseline project –Bands 3, 6, 7 and 9– are the highest priority bands scientifically, and that they cannot be replaced with other bands in the context of an enhanced ALMA project. Each of these 4 bands has unique science that would be lost if that band were cut entirely. Moreover, a significant reduction in capabilities already took place in 1999 when the number of receiver bands in the baseline project was reduced from 10 to 4.

- **Long baselines:** ALMA's ability to perform diffraction-limited imaging on baselines out to 14 km is crucial for several of the highest priority science goals (see Sect. 3.3). Implementation of the longest baselines is currently scheduled at the very end of the construction phase, and should not be delayed much further.

- **Imaging quality:** High-quality images are a key deliverable of ALMA. Since image quality scales with the number of baselines and hence with N^2, this is a major driver for a large number of antennas (see Sect. 3.1).

- **Early science:** If deferring Early science observing would lead to savings in the project, the ASAC recommends that this be seriously considered. This would have the additional benefit of having greater impact with the first images (see ASAC's response to Charge 4, Sect. 6). A number close to 16 antennas might be an appropriate value for Early science, but this requires further study by the Science IPT.

In general, the ASAC strongly recommends to consider savings options which delay non time-critical science capabilities rather than cut them permanently. The ASAC discussions focused on number of antennas and receiver bands, but all other parts of the project (software, backend, infrastructure, management) should be looked at critically to identify savings options.

The ASAC believes that the scientific impact of any potential reduction of the baseline project should be considered in the context of planned enhancements. Conforming to the charge, this response is restricted to the bilateral project only, but the ASAC felt that this is not the optimum way forward from a scientific perspective. Finally, the ASAC stresses that it would like to continue to be involved in the discussions on the cost-saving trade-offs being considered.

The following sections summarize the arguments and main science drivers that led to the definition of the baseline project, and lists the science that would be lost if a particular capability were not available. Further discussions of these goals and calculations are contained in the document "ALMA Scientific Specifications and Requirements", ALMA-90.00.00.00.00-001-A-SPE, version E.

3.1 Number of Antennas

The baseline project is for $N = 64 \times 12$ meter diameter antennas. The ASAC does not consider relaxing antenna specifications, such as surface accuracy, but focuses on the number of antennas. The sensitivity and the imaging quality of ALMA are sensitive functions of N, since both the time to reach a given sensitivity and the imaging quality (as reflected in the number of (u, v)-data points in a given time) depend on N^2. Overheads for calibration also become larger if the sensitivity of the array is reduced. ALMA is a 30–50 yr project, and the antennas constructed now are likely to be the only ones built over the lifetime of the array. The large leap forward in sensitivity compared with existing facilities enables not only the Level 1 science requirements, but also increases the chance for new discoveries and unknown science to be done 15–20 years from now.

The Design Reference Science Plan (DRSP) shows a range of projects that ALMA will do. Different kinds of projects will be affected in different ways by changes in N, but since both sensitivity and imaging fidelity scale similarly with N, the effects of changing N are comparable. The large collecting area, specified to be greater than 7000 m^2, will allow deep, intensive studies of single objects, and, as illustrated below, much of the new science will likely come at the faintest possible flux levels, which requires the full sensitivity of the 64 antennas.

Another important component of ALMA science will be short duration observations of objects made in large numbers. The average VLA program is only 8–10 hours in length, often for small samples of objects. "Survey-mode" science requires that the array can image quickly, in a few minutes, with good (u, v) coverage. Even at the best site in the world, at Chajnantor, atmospheric opacities at submillimeter wavelengths are sufficiently high to restrict observations to a relatively short time close to transit. As a consequence, the available observing time per day for any given object is limited, which calls for fast performance and hence large N in order to complete projects on a reasonable time scale. This mode of observations opens up an entirely new window of millimeter science, which is either not possible, or requires a massive effort taking many years to complete, with the sensitivities of current millimeter arrays (see, for example, the BIMA SONG or IRAM NUGA projects). Often only the investigation of a representative sample, rather than studying single, often peculiar objects, leads to a thorough understanding of a phenomenon.

In the following science examples, dual polarization, full bandwidth receivers and DRSP sensitivities are assumed for these time estimates. The focus is on the primary science goals and a few other challenging projects —mostly new science which has emerged since the primary science goals were set forth—, as representing the best of ALMA science, and the primary drivers for the array's design.

- **Detecting CO and [C II] in a Milky Way galaxy at z=3 in less than 24 hours of observation** is the first Level 1 science requirement. Figure 1 shows the integrated line fluxes of different types of galaxies as functions of redshift, together with the 1σ sensitivity limit for 24 hrs of integration (not including overheads). It is clear that N=64 is needed to reach this requirement. A similar calculation is given in the appendix of the "ALMA Scientific Specifications and Requirements" document.

ALMA can also potentially detect spectral lines such as the redshifted [C II] 158 μm fine-structure line in the very first generation of galaxies, at $z > 6 - 7$ (see Figure 1). Optical telescopes are already detecting strongly lensed galaxies (magnification factor of ∼30) at $z = 7$ in an evening's integration: ALMA will detect numerous unlensed normal galaxies in the dust continuum at $z \sim 10$ in a similar period with 64 antennas. The capability of detecting lines would allow an estimate of the **dynamical masses** of these galaxies and not just their luminosities.

- **To map dust emission and gas kinematics in protoplanetary disks** is the second Level 1 science goal. It requires the highest resolution and Band 9 to resolve structures on 1 AU size scales. In 8 hours, the 1σ rms continuum sensitivity is 3 K in Band 9, illustrating that very long integration times are needed even with $N = 64$.

  Gas kinematics are even more difficult to image than dust emission in protoplanetary disks: to resolve structure in spectral lines with ≤ 1 km s^{-1} velocity resolution in a single protoplanetary disk at ∼20 milli-arcsec (3 AU, Jovian planet region) at the ∼10 K (1σ) level will require 90 hours of integration in Bands 6 or 7 with $N = 64$.

- **Exoplanets.** Planets are now known to exist beyond our own solar system, a research area which was only just emerging at the time ALMA was designed. In fact, only very recently has the first image of an exoplanet been announced. At distances of 5 pc, Jupiter has a diameter of 0.1 milli-arcsec and a 345 GHz flux of less than 1 μJy; this would not be detectable with ALMA. However, larger mature or younger hotter planets can be seen with ALMA.

- **Transient or rapidly time-variable objects, such as supernovae, gamma ray bursters, or X-ray bursters.** For these time-varying sources, the ability to obtain a high quality image in a single, short integration (e.g., time resolution comparable to that of X-ray telescopes) is imperative. Other examples include Galactic center flares, comets, accretion flow variability (AGN, protoplanetary disks), planetary weather and moon observations. Snapshot images with good fidelity are required in confused fields. The timescales of variability of these objects are often as short as seconds.

3.2 Receiver bands

The atmospheric windows accessible to ALMA from the Chajnantor site range from 10 mm (31.3 GHz) to 0.35 mm (950 GHz), and can be covered in 10 frequency bands. The general scientific arguments for choosing at least 4 receiver bands in the baseline project are:

- **The ability to trace gas with a wide range in physical conditions.** The CO molecule is the prime tracer of molecular gas in galactic and extragalactic sources. In low-density ($< 10^3$ cm^{-3}), cold (< 30 K) quiescent gas only the lowest CO levels up to $J = 3$ are excited, whereas warm ($T \approx 100$ K) dense ($> 10^4$ cm^{-3}) gas heated by star formation or other energetic sources emits strongly in the higher excitation CO lines. Even higher densities (up to 10^9 cm^{-3}) and temperatures (up to 2000 K) can be probed with lines of other molecules. To disentangle the various physical components, observations of several transitions of CO and other species spaced in frequency are needed. This flexibility in diagnostic probes is essential to address

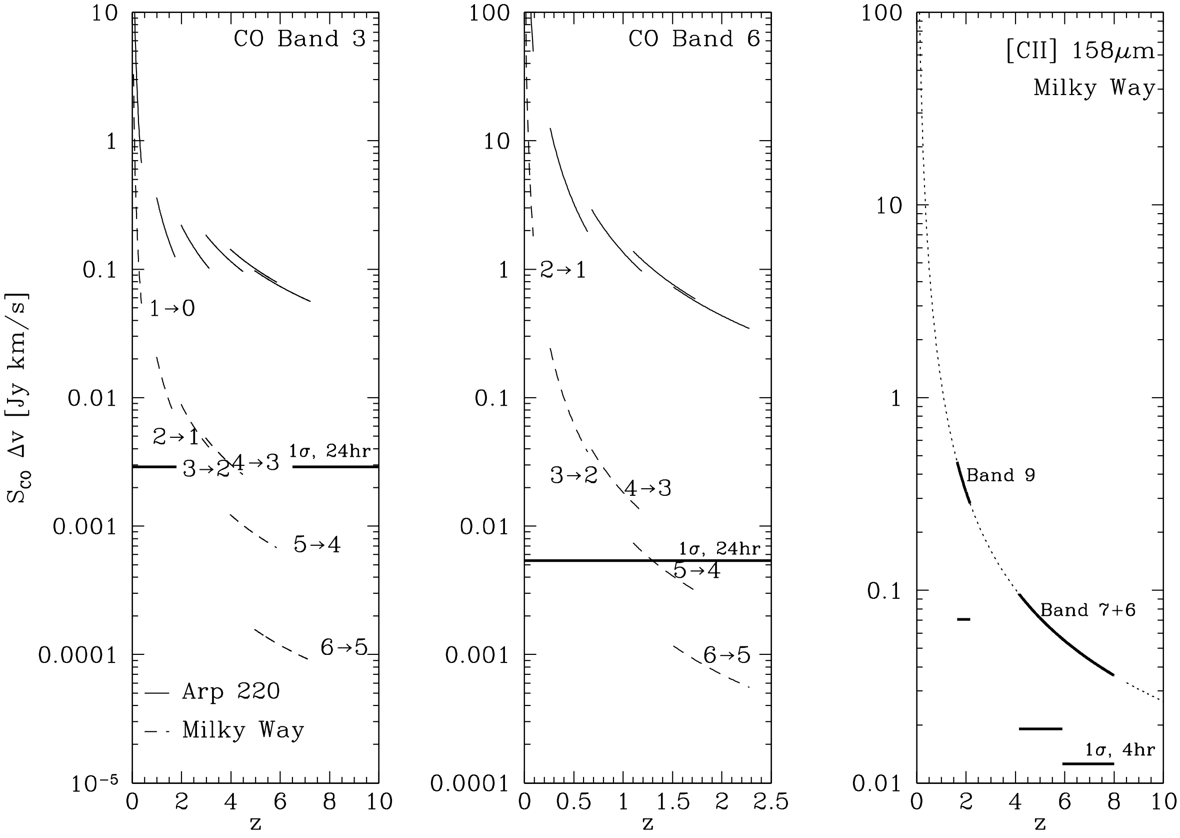

Figure 1: Left and middle panels: Integrated strengths of CO lines as functions of redshift for Milky Way (green dashed lines) and starburst Arp 220-like (red solid lines) galaxies, in the Band 3 (left panel) and Band 6 (middle panel) frequency ranges. The 1σ noise after 24 hrs integration (not including time for calibration) is indicated. Right panel: Integrated strength of the redshifted [C II] line for a Milky Way galaxy. The solid parts of the curve indicate the redshift ranges covered in Bands 6, 7 and 9, whereas the dashed parts are not observable with the baseline project. The 1σ noise after 4 hrs integration is indicated. The calculations assume H_0=71 km s^{-1} Mpc^{-1}, $\Omega_{\rm tot}$=1.0 and $\Lambda = 0.7$ (van der Werf, priv. comm.).

the second Level 1 science requirement to study the physics and chemistry of protostars and protoplanetary disks, where a large range in physical conditions is inherently present.

- **Coverage of CO and [C II] lines over a large range of redshifts.** In distant galaxies, lines are shifted to lower frequencies by a factor $1+z$. Figure 1 illustrates the redshift ranges over which a particular CO or [C II] line occurs in one of the baseline receiver bands. Milky-Way galaxies emit primarily in CO lines with $J \leq 3$, whereas starburst galaxies have their strongest lines at $J = 5-4$ and $6-5$. The [C II] fine-structure line at 1.9 THz (158 μm) cannot be observed with ALMA in galactic objects, but becomes visible at $z > 1.6$ in Band 9. This line is the major coolant of low-density gas and a probe of distant massive star formation, with the CO/[C II] ratio sensitive to local conditions. [C II] may be the only gas tracer of the first galaxies at $z \sim 10$ accessible to ALMA, since all strong CO lines have shifted to frequencies below 84 GHz by this redshift.

- **Measurement of spectral energy distributions, and thus luminosities and masses.** The continuum emission to be observed with ALMA is dominated by thermal radiation from cold dust. In the (sub)millimeter regime, the emission is largely optically thin and increases steeply with frequency according to at least ν^3. For typical dust temperatures of 30–100 K, the dust flux peaks at 60–200 μm for galactic sources, but this peak shifts to the ALMA wavelength range for $z > 2$. By covering a large range in frequency, ALMA can determine both the total luminosity of the source and the dust temperature, which then gives a direct estimate of the total dust mass.

- **Measurement of dust properties.** By observing the dust emission at multiple frequencies, not only the dust mass, but also the dust properties (e.g., whether the dust grains have grown in size) can be determined. This is particularly important for protoplanetary disks, where coagulation and settling processes are expected to lead to very different dust properties compared with normal molecular clouds.

- **Ultimate spatial resolution.** The synthesized ALMA beam scales inversely with frequency. Thus, the highest spatial resolution of 10 milli-arcsec can only be obtained by having receivers at the highest frequencies.

- **Ability to probe a wide variety of molecules.** The ALMA frequency range contains a myriad of molecular lines important for astrochemical and excitation studies (see also above). Large, potentially prebiotic, molecules are best observed at the lower frequencies, whereas many light hydrides can only be observed at higher frequencies.

Based on these criteria, the ASAC ranked Bands 3 (84–116 GHz), 6 (211–275 GHz), 7 (275–373 GHz) and 9 (602–720 GHz) as the 4 highest priority bands in its March 1999 report. The current ASAC confirms this prioritization and emphasizes that all 4 bands are essential for the ALMA science goals. They cannot be replaced by other bands that are being considered in the context of the enhanced ALMA project. Moreover, these 4 bands are an excellent match to the weather at the Chajnantor site, as illustrated by the good agreement between the distribution of time over receiver bands in the ALMA DRSP compared with the statistics of the transparency and phase stability at the ALMA site. Finally, the ASAC re-iterates that these 4 bands already represent a significant descope compared with the 10 receiver bands in the original ALMA plan.

In the following, examples of important science that would be lost if a particular receiver band were not available are summarized.

- **Band 3:** This band covers CO $J = 1 - 0$ in the local universe, as well as the bulk of low excitation lines of other molecules. It is the key band to search for CO at $z = 0 - 3$ in Milky Way galaxies. The full ALMA sensitivity is needed to meet this requirement. This band also contains the SiO 86 GHz maser, important for commissioning and for studies of evolved stars.

- **Band 6:** This band covers CO $J = 2 - 1$ in the local universe, as well as the bulk of medium excitation lines of other molecules. It is important for constraining the dust SED, and for observing CO at $z = 0.4 - 2.5$. It is the key band to detect [C II] in the first galaxies at redshifts $z = 6 - 8$.

- **Band 7:** This band covers CO $J = 3 - 2$ in the local universe, as well as the bulk of medium excitation lines of other molecules. It is the key band to perform blind searches for dust emission from distant galaxies out to the highest redshifts, as well as to map dust emission in the local universe. This band is also optimized for dust polarization studies, and covers the [C II] line at $z = 4 - 6$. It contains the H_2D^+ line at 372 GHz, which is a unique diagnostic to measure the ionization fraction and dynamics of regions with very strong depletions, such as pre-stellar cores and the midplanes of protoplanetary disks.

- **Band 9:** This band covers CO $J = 6 - 5$ in the local universe, as well as the high excitation lines of other molecules, and is essential to probe warm dense gas. At the extreme end of the ALMA frequency range, it is key to constraining the dust SED and dust properties in local and high-redshift sources. It covers [C II] at the important epoch of $z = 1.6 - 2.1$, when a strong evolution in star formation is thought to have occurred. Finally, the ultimate spatial resolution is achieved at the highest frequencies, needed to image gaps in protoplanetary disks.

3.3 Baseline Length

The baseline project specifies a maximum baseline length of 14 km. Changes in the maximum baseline length affect all of the Level 1 science requirements.

- **Imaging of high redshift galaxies.** The average galaxy at $z = 3 - 5$ has a diameter of less than $0.5''$. To resolve and obtain a few pixels across the galaxy to study its morphology and derive the dynamical mass will require better than $0.1''$ resolution for redshifted lines. At Band 3, where the redshifted CO lines will appear, a maximum baseline length of $\sim 8 - 9$ km is required to meet this goal.

- **The study of dust emission and gas kinematics in protoplanetary disks.** To resolve kinematic structure and gaps caused by protoplanets in the disks, a resolution of 1 AU is needed. The closest star-forming regions are at distances of ~140 pc, so that 1 AU corresponds to resolutions of at least 10 milli-arcsec. Baselines of at least 14 km are needed to achieve this resolution at the highest frequency, Band 9.

- **The ability to provide high-quality and high resolution imaging in the millimeter and submillimeter bands to match that of HST and ground-based AO-equipped telescopes** is the third Level 1 science requirement. These telescopes currently routinely achieve spatial resolutions of $\sim 0.05 - 0.1''$. The next generation of AO systems and 20–30 m class ground-based telescopes will push this resolving power even further. To match the resolutions of even current optical telescopes, baselines greater than 9 km are needed.

> Top-level projects requiring high quality images and high spatial resolution include studies of gaps in proto-planetary disks, the Galactic Center and its central black hole (SgrA*), and central regions of local starbursts and Active Galactic Nuclei (AGN).

High-resolution and high fidelity imaging requires not only multiple configurations and long baselines, but also the ability to measure and correct the atmospheric path length changes using fast switching of the array antennas and Water Vapor Radiometers to measure and correct atmospheric phase distortion. Without these corrections, ALMA's image quality will be limited to $\sim 0.5''$ resolution under average weather conditions, whereas astronomers expect routine images at $\sim 0.1''$ resolution.

4 Charge 2: Time Allocation Policies

The second charge from the ALMA Board reads as follows: *Following thorough assessment of the pros 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:*

- *how to facilitate joint projects between scientists of different partners,*
- *how to handle large proposals with significant scientific duplication, and*
- *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.

The ASAC approached this charge from the perspective that both joint programs and large programs (whether joint or from a single partner) are important for maximizing the science return from ALMA. It is important that ALMA's proposal policies do not place barriers in the way of these kinds of proposals. ALMA will carry out both small and large programs, as they are both essential tools in producing dynamic, high-impact science. For example, smaller programs can produce very important new results or unexpected discoveries, while many high-impact science projects can only be achieved with a large investment of observing time.

The ASAC reviewed the procedures currently in use at three different observatories (ESO, Gemini, JCMT). One of these (ESO) operates with a single TAC while the other two are multi-partner observatories with multiple TACs plus a combined international TAC. Most of the possible difficulties that we considered would not be an issue were ALMA to adopt a structure based on a single Program Review Committee (probably divided up into sub-committees by scientific area). A single Program Review Committee (PRC) places no barriers to proposals with collaborators from more than one partner, makes it easy to limit duplication (either of sources or, if necessary, of science goals), and would be able to produce a single ranked list of proposals that could be passed to the observatory for scheduling. However, given the current plan for ALMA, which is based on one PRC for each partner, as well as presumably separate PRCs for Japan and Chile, we feel the following items will provide a good framework to allow ALMA to do the best science possible, and to do that science efficiently.

4.1 Large proposals

The ASAC feels that the best way to handle all large programs (both joint programs and those from a single partner) is to have an International PRC (IPRC) that is empowered to rank and/or choose between large proposals submitted to ALMA in a given semester. Each partner PRC will review all the large proposals that involve them and pass on their comments to the IPRC; however, the PRC will not rank the large proposals, either relative to each other or relative to the smaller programs. Having a single IPRC which evaluates all large proposals helps in a number of ways:

- there is no need to distinguish between large proposals from a single partner and large proposals from multiple partners, as they all go to the same committee for evaluation and, ultimately, ranking
- since the same committee sees all the large proposals, it is in the best position to arbitrate between cases of scientific duplication

The ASAC feels that scientific duplication in large proposals is to be discouraged. Large proposals use up large amounts of resources (ALMA observing time) and scientific duplication in such programs will limit ALMA's ability to carry out other scientific programs, which may be equally exciting and valuable. For example, it is a clear waste of ALMA resources to have three teams (one from North America, one from Europe, and one from Japan) each spend one month of observing time to map the Hubble Ultra Deep Field at 350 GHz!

For this system to function well, the IPRC must have the necessary broad scientific expertise to provide a good evaluation of large programs. (The IPRC cannot simply be the sum of the chairs of the partner PRCs, for example.) In addition, we suggest that, as is currently done with ESO, there be a cap on the percentage of ALMA time that can be allocated to large proposals in any semester. For ESO, the current fraction of time is 30%; for ALMA, this is TBD. The definition of what constitutes a "large" program is also TBD; however, clearly any program requiring a month of ALMA observing time would be classified by anyone as a "large" program! The minimum observing time required to be classified as "large" may also change from the period of Early Science to full operation. The question of when to start large programs with ALMA is one that needs further consideration, particularly as the capabilities of the array will grow rapidly for the first two years of operation, and the time to execute a given set of observations will diminish considerably.

4.2 Legacy programs

The ASAC sees no need to invoke a special mechanism for legacy programs at this time with ALMA. Legacy programs are distinguished from large programs by having a short (even zero) proprietary period. Having good mechanisms for handling large proposals will allow legacy-style science to proceed in the longer term.

In the short term, demonstration science may be viewed as an early version of a "legacy"-style program, as it will have a short proprietary period and will likely involve observations of targets of interest to many different researchers, although they will neither have the completeness nor the impact of a fully grown legacy project.

4.3 Facilitating joint proposals between partners

Issues relating to large proposals with collaborators from more than one partner are addressed in section 4.1. Large joint proposals will be facilitated by the IPRC review structure discussed in that section.

For smaller projects involving collaborators from more than one partner, the ASAC suggests that ALMA adopt a Joint Proposal mechanism similar to the one currently used by the Gemini observatory. In this system, identical versions of joint proposals are submitted to the PRCs representing all partners involved in that proposal. Each partner PRC would then evaluate and rank the joint proposals at the same time and in the same way as they would proposals involving collaborators from only a single PRC. The final ranking would be done by the IPRC as a weighted average of the partner PRCs. The possibility of a proposal being submitted to just the PRC of the PI (and the time allocated by only that PRC) should also be allowed.

4.4 Source duplication

The ASAC feels that duplicate observations of a given position in the sky should be discouraged unless there are good scientific reasons (variability studies are an obvious exception to this rule). The ASAC suggests that duplication might be defined as:

- same sky position
- similar sensitivity
- similar angular resolution
- for continuum observations, similar frequency
- for line observations, same frequency
- for line observations, similar velocity resolution and bandwidth

where in all cases above the exact meaning of the word “similar” remains TBD. For example, new continuum observations of the same, non-variable source might be allowed if they required a sensitivity a factor of two better and/or a frequency more than 20% different from the sensitivity and frequency of existing or scheduled observations.

4.5 Scientific duplication

The ASAC is not concerned about duplication of scientific goals by two or more small programs. There is some merit in having, for example, two teams studying small samples of debris disks, each being allowed to work on their own sample (subject to the caveat of no direct source duplication). The issue of scientific duplication in large proposals is discussed in subsection 4.1.

5 Charge 3: Calibration

Charge 3 reads *Help the Science IPT to plan their study of the impact of calibration on a handful of the most challenging major science goals, in particular by providing ASAC’s views on the types* *of projects you feel are the most challenging from a calibration point of view. Review and comment on the Science IPT's report when finished.*

The ASAC examined this charge by focusing on the amplitude calibration and the specifications which are given in section 3.3.9 of the Project Plan, namely:

- visibility amplitude fluctuations <1% below 300 GHz and <3% above 300 GHz.
- 0.1% polarimetric measurements require L-R gain fluctuations to be $< 5 \times 10^{-4}$ in 5 min (i.e., between calibrations).

In section 3.5, it is further specified that:

- the flux scale should be accurate to <1% below 300 GHz, and <3% above 300 GHz.

As discussed in previous reports from the ASAC, notably the October 2003 report, the 1% accuracy level will be difficult to achieve. The multi-load design, which has not yet been tested, might achieve 2%; the semi-transparent vane could reach 3% or better, but is still under study and will be tested soon on the sky.

It should be noted that the *accuracy* of the flux measurement discussed here, which is the measure of how close the flux is to the true flux of the source, should be distinguished from the *precision*, or repeatability, and relative flux calibration between bands, which are generally of more concern to astronomers . The ASAC notes that this specification is ill defined at present, since it does not stipulate under which atmospheric conditions and for which percentage of the time these specifications are to be reached.

The ASAC considered the Project Book and the DRSP to define the projects where the needs for calibration are the most demanding.

From the Project Book, the main driver for 1% calibration is high fidelity imaging and mosaicking. This requirement relies more on stability and repeatability than on absolute calibration, although good absolute calibration is required in the case of adding data from different configurations, arrays (the ACA), or single dishes, unless a cross-calibration scheme can be devised using the data itself, e.g. self-calibration using common models/baselines, or a common, non-variable amplitude calibration source with known structure.

The primary science goals described in the Project Plan do not fundamentally require 1% absolute calibration. This has been discussed in a series of memos and reports: ALMA memo 492 (Carilli), on the spectral energy distribution of high-redshift galaxies, and reports to ASAC on DRSP programs by Dutrey and Bacmann, who describe the requirements for the study of protoplanetary disks. The main results can be summarized as follows.

- Detecting CO and [CII] in a Milky Way galaxy at z=3 in less than 24 hours of observation: calibration constraints are not very strict for this goal, and 3-5% accuracy is sufficient for line excitation analysis or for constraining the spectral energy distributions of the sources.
- To map dust emission and gas kinematics in protoplanetary disks: as in the previous case, a 3-5% accuracy in the amplitude calibration is adequate for such measurements.
- $0.1''$ resolution imaging with high fidelity (1000/1): this could drive the calibration to 1%, although self-calibration could be used frequently in this type of projects. The science IPT is still investigating the affect of 3% calibration errors on image fidelity.

The DRSP provides a broader view of potential projects which can be performed with ALMA, although they do not all represent the most challenging major science projects which drive the ALMA project. A study of the requirements of the programs described in the DRSP by M. Hogerheijde report that:

- There are only a few programs on planetary science where 1-3% absolute requirement are essential (see below).
- 30% of the projects, need a repeatability to a level of 1-3%
- 50% of the projects need band-to-band relative calibration of 1-3%.

In planetary science, there are a number of programs that will be enabled by 1% calibration. Some examples for this are:

- the study of the surface of Titan: liquid hydrocarbons vs water ice (constraining the index of refraction will need better than 3% calibration)
- The observation of SO_2 in the atmosphere of Venus, as a probe of volcanic activity
- The study of the thermal state of Mercury interior to test for molten core via absolute energetics.

Overall, whereas the 3% absolute calibration specification will preclude some interesting science in planetary science, it is not seen as being so compelling as to dictate unrealizable specifications on the telescope.

In summary, **the ASAC feels that the current specifications of 3% below 300 GHz and 5% above 300 GHz for the absolute amplitude calibration are commensurate with the major science goals of the ALMA project. It is important though to maintain the repeatability (precision) and relative flux calibration between bands at a more accurate level.**

The ASAC recommends that the developments and testing of the calibration schemes and devices should be pursued aggressively in the project, and that, in particular, astronomical tests should be performed as soon as possible.

6 Charge 4: Demonstration Science

Consider in more detail how the choice of objects for demonstration science with ALMA might be made and in particular how to facilitate involvement by the broader community in the process.

When the ASAC defined the term *Demonstration Science* in the May 2004 report, it was meant to contain two different kinds of approaches:

- *Public demonstration images:* to convey the capabilities of ALMA to the general public. The criteria for the selection are of rather esthetic nature, scientific novelty is not a prerequisite. The proposal and selection process would be internal, e.g. by the Project Scientists, science advisory committees.

- *Science demonstration projects:* to illustrate the capabilities of ALMA to a broader astronomical community. To make this successful, the projects should contain a wide span of the technical and scientific capacities of ALMA, to show to a large range of the astronomical community how ALMA can benefit their science. To facilitate involvement of non-radio-astronomical experts, the process should not require deep knowledge of the system, a call for ideas rather than for detailed proposal was thus advocated.

The ASAC took the charge to be mostly concerned with the science demonstration projects, but would like to add a few remarks that apply to both.

Both activities will take place when the array still only has a few antennas, therefore the performance will be very far from the performance of the final array. Also, it will not be much superior to images from currently existing arrays, which will have improved by the time ALMA early science starts. Care should be taken that this information is passed on to the intended audience, otherwise the discrepancy between expectations and result may be damaging to ALMA's reputation.

In view of this, and of the loads on the system and the science verification team, **the ASAC thinks it wise not to rush the start of demonstration science. To ensure a successful completion of this activities, the ASAC recommends that they are only started once the array has reached a size of about 16 elements. The ASAC regards demonstration science as the start of early science observing, which should take place *before* an open call for proposals is issued.**

Concerning the public demonstration images, the ASAC notes that single pointing images with early ALMA will not look very impressive to an audience used to high quality optical images, since the ALMA images will have a low spatial dynamic range. Multi-configuration observations and/or mosaics will needed, which means that the adequate observing and data reduction tools must be available, and that multiple configurations and sufficient time must be allocated. Pictures with overlays of e.g. an optical picture with a dark cloud or dust lane, and ALMA images of gas/dust in this dark patches would be an example of demonstrating unique ALMA science. It may be useful to show single-dish and ALMA images of the same field side-by-side, to demonstrate the new structures revealed by the improved ALMA resolution. Complex spectra of stars or star forming regions may also qualify for public demonstration.

For the science demonstration projects, the ASAC is convinced that a call for ideas, associated with workshops on the use of ALMA, would be a good way to reach a broad community and to ensure their participation. **The proposers selected by a proto-TAC should then be teamed up for the project with experts from the ALMA science verification team, to ensure that the ideas are transferred into a viable ALMA observing project.** The selection process should make sure that the full range of ALMA's technical possibilities and scientific capabilities is represented. However, the emphasis should be on projects which are simple and self-contained, which do not require extensive mosaicking, or complex processing to succeed.

This collaboration should continue throughout data acquisition, data reduction, throughout publication of the data. The rationale behind is that, particularly in the early stage of ALMA, in which tools such as the pipeline are not yet available, or only in a restricted form, one wants to make sure that the data coming out of ALMA are properly reduced and released. The data should become public immediately, for more sophisticated analysis, but this process ensures that they will get published in a timely manner. Groups participating in these efforts would also have, through the experience they gained with the array, an advantage in the first regular call for proposals for early science.

7 Charge 5: Science Verification Plan

Consider the project's plans and progress towards a Science Verification Plan.

The ASAC received a draft of the current Science Verification Plan (SVP) in September, and heard a presentation by Robert Laing. The plan is developing but it is clearly at an early stage. The current document includes the defining philosophy and a good list of the required tests but lacks details about the methodology of the tests, the criteria for success, and the schedule for completion. The ASAC believes that the SVP is important to the project. It is vital that the verification be done with systematic, well-documented procedures and results. The final product will establish the heritage of each antenna and become essential to high-quality maintenance of the array during operations. The ASAC felt confident that these were the goals of the team writing the SVP, but takes this opportunity to support those goals.

The ASAC was concerned about two aspects of the SVP. First, ALMA needs to ramp up scientific staffing to work on the SVP details. This staffing includes the Project Scientist, who leads the work, and additional scientists to participate in it. The ASAC suggests that this is an area with flexibility to include expertise from the community (and ESO and NRAO staff), but a core of full time scientists are need soon to anchor the effort. The second area of concern was the short time allocated for Science Verification. There are only 13 months in the current schedule between 3 antennas and early science. This is a short time for characterizing 5 antennas, checking out observing modes of the antennas and correlator, and confirming science level interferometric operation for outside observers. With the current worry that antenna arrivals may slip by months, **the ASAC stresses that this science verification time should not be cut in an attempt to keep the Early Science milestone from slipping.**

The ASAC recommends that Science Verification activities be ramped up as soon as possible. In light of the short SV time in Chile, the core Science Verification team need to be identified now so that they can utilize the prototype antennas at the ATF to define and test procedures, and evolve software, in advance of arrival of antennas in Chile.

8 Summary Points

- The ASAC concludes that the loss or reduction of any element of the baseline project will result in a significant loss of ALMA science (Charge 1). In particular,
  - both observing time for reaching a given sensitivity, and image fidelity scale with the square of the number of antennas, so any significant reduction of the number would result in a significant erosion of ALMA's discovery space.
  - all receiver bands of the baseline project are vital to important science that would be lost if a band was cut entirely.
  - the long baselines are essential for reaching the major science goals of ALMA, among them imaging planetary formation in protostellar disks.
- The ASAC recommends that all saving options such as delaying early science operations, or delaying or reducing other less critical science capabilities should be considered in the context of the enhanced project (Charge 1).
- The ASAC feels that the best way to handle all large programs (both joint programs and those from a single partner) is to have an International PRC (IPRC) which is empowered to

rank and/or choose between large proposals submitted to ALMA in a given semester. For smaller projects involving collaborators from more than one partner, the ASAC suggests that ALMA adopt a Joint Proposal mechanism similar to the one currently used by the Gemini observatory. The ASAC sees no need to invoke a special mechanism for legacy programs at this time. (Charge 2)

- Relaxing the amplitude calibration requirements to 3% below and 5% above 300 GHz does not incur loss of major science goals of ALMA (Charge 3), although it is important that repeatability is maintained at a higher level.
- Demonstration science, with a goal of involving a large part of the astronomical community, would best be performed by joint teams of representatives from this community, and experts from the ALMA science verification team. These teams would execute a project from defining the observing procedures all the way through publication of the results (Charge 4).
- The ASAC recommends that demonstration science and the first call for proposals afterwards, which together define early science, should not be started too soon. Careful management of expectations is needed, since the early ALMA will have a performance very far from the final observatory (Charge 4).
- The ASAC perceived the science verification plan as being moving into the right direction, but was concerned about sufficient scientific manpower to work out the necessary details in a timely manner, and about the short time allocated to it (Charge 5).
- The ASAC highly recommends that the science verification activities are ramped up a soon as possible, and the prototype antennas be used to define and test the procedures (Charge 5).