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Report from the ALMA Scientific Advisory Committee

Face To Face Meeting

CHARLOTTESVILLE

September 28th & 29th 2008

Membership of the ALMA Science Advisory Committee
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In Attendance
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EXECUTIVE SUMMARY

The ASAC met in NAASC in Charlottesville September 28th/29th 2008. Overall, ASAC is pleased to see the progress with the project since we last met face-to-face in January 2008: we are confident that the Project Scientists and their growing team are on track to commission ALMA as a transformational global observatory. The transition to an observatory continues to take shape with the appointment of a permanent director. Our overall level of concern for the readiness of software since the last report has been reduced, and we are especially impressed by the readiness of the CASA tools for commissioning and simulating operations. We report in detail on the five charges sent to ASAC by the ALMA Board in Section III. Our overriding concern is with the schedule, which is currently under extensive review, and we look forward to hearing about the results of November's substantial project-wide software review at our January face-to-face meeting at the OSF. We see that the key project target for the coming six months is the successful operation of a two-element interferometer at the OSF, successfully transferring the experience of the ATF to Chile.

I. INTRODUCTION

This report describes the ALMA Science Advisory Committee (ASAC) face-to-face meeting held in Charlottesville, and is for submission to the Board at its meeting in San Pedro in November 2008. The committee is grateful to Al Wooten for organizing the ASAC meeting and teleconferences, and to the project scientists and project workers in the executives for their help in preparing and presenting documents and reports for our meeting.

The ALMA Board gave ASAC five specific charges, two of which are preliminary and will lead to more substantial reports in spring 2009, after ASAC meets at the OSF in late January 2009. The answers to the charges can be found in Section III.

We start our report with a general overview of the discussions at our meeting, and on additional questions raised about the project during our discussions of the charges. In particular, we note that the Project Team has been providing ASAC with a very useful insight into the status of recent change requests: in our recent telecoms the committee has found that this news has given us a clearer view of the status of the project. We then address the specific charges. We would welcome future formal charges from the board that include the matters of concern highlighted in Section II.

II. GENERAL DISCUSSION

II.1 ASAC wholeheartedly supports the current re-scheduling process, and looks forward both to reviewing the results as soon as they emerge, and to assisting the Board in reacting to the results and redefining project milestones.

II.2 ASAC was pleased to see that substantial system components continue to arrive at the OSF, and that progress is being made towards antenna acceptance and integration, including the transfer of trained technical staff from the ATF to Chile.

II.3 The continued effort on developing the local oscillator (LO) photonics design, and the procurement of four baseline systems, coupled with ongoing investigations into alternative LO transmission schemes and systems is sensible, and we consider that this high-risk element in the project is receiving all due attention.

II.4 We recognize that the implementation of correction for atmospheric phase fluctuations due to variations in water vapor content is an essential element in meeting ALMA's science goals. We are pleased to see the release of CASA's imaging simulator, and note that the implementation of realistic phase noise in a simulator would be a useful additional tool to the project. We note that variations in atmospheric temperature both affect the phase errors due to water and cause additional phase fluctuations. We had an interesting discussion about possible radar/sonar techniques for measuring the temperature variations along the line of site. We recommend that the project considers investigating using a test system to evaluate the technology and if possible to build up a database of such measurements ahead of interferometry at the AOS.

II.5 The ASAC was pleased to hear that the surface accuracy specification of the 7-m ACA antennas during daytime is set to remain at 20 microns, following the discussion of a change request to relax the requirement to 25 microns. We view access to ACA baselines for high-frequency observations when low-opacity conditions continue after dawn as a potentially important way to improve the efficiency of operations of the joint array.

II.6 The challenging performance specification of the band-3 receiver was only barely met by prototypes, after extensive searching for excellent matching in components. This has lead to a change request to increase the specified noise temperature across the whole of band 3. We note that this leads to a reduction in sensitivity by 7-8% in the middle of the band, but to improved performance as compared with the original specifications at the ends of the band. The more uniform performance leads to a science gain for spectroscopy of HCN and redshifted CO emission from the requested change. The change request describes a target for the performance averaged over both sidebands and polarizations. ASAC recommends pushing back on the request to specify that each delivered receiver should meet the new requirement in both polarizations, as this would maximize the uniformity and depth of polarization observations. Furthermore, we would encourage the project to continue any possible mixer development work that could yield improved devices for inclusion in frontends produced later in the manufacturing run. As a workhorse band that can be operated in most weather conditions, we consider that a relatively small expenditure now which might make the full array significantly faster in this band would be well justified.

II.7 After our meeting in January 2008, ASAC supported an investigation to reoptimize the configuration of the array on baselines from 5-10 km to provide better *uv* coverage. This was a timely discussion owing to the imminent detailed design of the network of roads, pads and fiber runs at the site. The simulations that have been carried out indicate that the *uv* coverage can be improved by adding about 10 pads and moving several others, but that the improvement to the quality of the final maps is only significant in circumstances that will be encountered rather rarely, i.e. observations with very high signal-to-noise ratio at high angular resolution. Given that the costs of these changes are substantial, and that the design of the layout of roads and optical fiber trenches has been completed, we do not recommend making this change. We do however suggest that redundant cables are buried, to allow for future expansion without any retrenching back to the core, thus reducing the cost of any future decision to increase the number of pads, and removing any risk of damaging existing cables.

II.8 The design and site preparation of the central core has proved more complex than anticipated: the initial plan for a three-tiered terraced core included inter-level steps that were too high, and would lead to shadowing of antennas. ASAC was pleased to hear that an alternative plan to install the initial interferometer baselines on the simpler ACA foundation is viable, thus allowing more time to redesign and construct the more complex central core foundations without delaying AIV/CSV.

II.9 The committee discussed the status of the planned six Band-5 receivers; while this appears to be a modest issue in commissioning, it could impact operational efficiency if the locations of the small minority of antennas equipped with these receivers have to be chosen specially. Equipping ALMA with band-5 receivers is an issue under consideration by the development working group. However, plans for the integration of the expected six receivers should be drawn up.

II.10 NRAO director Fred Lo talked with ASAC during our visit to Charlottesville. We understand that he is leading reactivated discussions of a board subcommittee to consider the ongoing issue of time allocation for ALMA. ASAC remains committed to helping the Board to understand the impact of the time allocation policy on the science output of ALMA.

III. RESPONSE TO BOARD CHARGES

III.1) ASAC should continue to monitor and assess the readiness of ALMA software, in particular to review the outcome of software CDR number 6 and the ongoing work on detailing the software requirements for Early Science. These topics should be covered in the ASAC's written report for the Board's November 2008 meeting.

ASAC was pleased to hear that the functionality, stability and number of users of the offline reduction package CASA has continued to improve, and would like to congratulate members of the project team on this success. We note the success of recent releases, and support the decision to change the schedule for the release of new versions to every six months from every three months, thus providing more substantial and internally-consistent updates. We are pleased to see that high-performance computing requirements for reducing data from the full array are being worked on by the CASA team, but remain concerned that the effort being applied to these longer-term developments should not distract from making ready the more modest software that is needed more imminently to support commissioning and early science. The ongoing lack of a replacement for Joe McMullin as CASA Group Supervisor continues to reduce the efficiency of oversight and the assignment of scientific priorities within the CASA project. We urge the Board to continue to push for this position to be filled urgently, or to seek a suitable reorganization of responsibilities within the project to recover this capability.

We saw a brief demonstration of the Observing Tool (OT) from Leonardo Testi, who was running the OT on his laptop, and received an informal verbal report by Robert Laing about the testing of the control software at the ATF. There appears to have been substantial progress in these areas. We look forward to a much more thorough analysis of these issues in January 2009. In particular, the experience of extended operation of the control software on real hardware at ATF has provided the development team with the valuable chance to improve the system. Progress in total-power operation has included the demonstration of large-field mapping, and a final campaign is planned to address software latency prior to the closure of ATF. This experience emphasizes that minimizing the delay between the closure of ATF and the establishment of 2-element interferometry at OSF is crucial.

We understand that before ASAC meets again in January, Alison Peck and Lars-Ake Nyman will have set up the procedures for testing and accepting the software for ALMA commissioning and operation at OSF. In addition, the project is holding a substantial ALMA-wide software review in November. We look forward to reviewing the status of the system in January, when we hope to see the state of the commissioning program directly at the OSF.

ASAC emphasizes that our concerns about CASA from previous reports have been largely satisfied. While we will continue to take an interest in the progress of CASA, it seems more important to concentrate our efforts at present on reviewing the readiness of the online software components - control software and the OT - for activities throughout the project, that is from component acceptance and testing, to science commissioning and then early and full operations. Following the forthcoming reviews, we look forward to reporting on these aspects of the system in March 2009. We remain concerned that there could be a potential disconnect between the software needs of the changing project, and the effort being expended by the software development teams.

The board specifically charged ASAC to report on the outcome of Software CDR-6. In light of the forthcoming November software review, and following informal discussions between the ASAC chair and Richard Hills that revealed the very specific, technical and fine-grained nature of the material presented at Software CDR-6, ASAC has decided to defer comment on issues involved in CDR-6 until March 2009.

Software remains an urgent concern. ASAC believes that the current ongoing reviews are necessary in order to evaluate the state of software development that could impact science readiness, and that the overall leadership of the project is aware of and reacting to these dynamic issues with all due diligence.

III.2) ASAC should continue to review AIV/CSV activities and to recommend necessary and desirable changes. Any significant new issues in this area should also be included in the report for the November 2008 meeting, but the Board expects a more detailed examination of these topics after the ASAC meeting in Chile in early 2009.

The ASAC wholeheartedly supports the project scientists' plan to merge the AIV and CSV processes, with priority for staff time and effort being given to AIV tasks until interferometry has been demonstrated at AOS, and thereafter being transferred to CSV.

Progress made with software testing at the ATF implies that the need for establishing 2-element inteferometry at OSF is urgent, and should proceed with the minimum delay after the closedown of ATF. The project scientists have elevated the priority of 2-element interferometry as compared with single-antenna testing in current plans.

There has been general progress with recruitment; however, we continue to view that the availability of numbers of high-quality AIV/CSV astronomers remains a key issue for the schedule and success of the project, and encourage the project and executives to continue to take whatever steps are necessary to attract suitable staff. The possibility of combining University and ESO/NRAO fellowships with years split between service at JAO and back in a research environment in the executives is something that we recommend trying.

ASAC is concerned that modifications to the structure of the new buildings at the OSF that are currently underway to accommodate commissioning should be implemented in a way to minimize any delays to the AIV/CSV process. In particular, we note that the full specifications for thermal stability and durability of the connections between antenna pads and correlator, which are necessary for successful operation of the full ALMA array at AOS, are likely to be overkill for the purposes of acceptance testing at OSF.

III.3) The ALMA Board has charged the Project to draw up a long-term ALMA Development Plan in consultation with the international astronomy community. The plan should set out the scientific context for transformational science with ALMA in the next two decades, in the era of for example JWST, ELTs and SKA, and recommend developments necessary to achieve this vision. The ALMA Board views this plan as having a high strategic priority, and is coordinating its development across the entire ALMA partnership. The process of generating the ALMA Development Plan should be led by the JAO Project Scientist and the ASAC (with support from the Executives). The first stage will involve an examination of the scientific drivers by a team of astronomers, chosen to be representative of the broad astronomy community that is expected to use ALMA. It is therefore important that the proposed team include people with a broad perspective and expertise at wavelengths outside the range that will be observed by ALMA as well as people with experience of mm-wave interferometry and instrumental development. This team should take time to work with the community, e.g. by sounding their own 'networks' and holding local discussions, before making a first-order draft of potential long term developments, grouping them in high, medium and low scientific priority, and identifying the ones which require long-lead technical developments. The ASAC should review and comment on the report (again with members taking soundings through their networks) before submitting it to the Board. The Board would like to receive a progress report on this at its November 2008 meeting and, if possible, the full report by March 2009. The Board suggests that it would not be appropriate to hold a large community workshop devoted to this topic, but recommends that discussion sessions be planned as part of other workshops (e.g. at one of the annual ALMA-oriented science workshops, or at more general meetings on future astronomical facilities). It is anticipated that a larger-scale activity will follow after the start of Early Science.

The regional SACS, ASAC and the development working group have all been generating ideas and science drivers for development planning. In addition, the September 2008 NAASC workshop in Charlottesville that immediately preceded the ASAC face-to-face meeting included an extra follow-on session on ALMA development. A significant fraction of the participants at the NAASC workshop delayed their departure from Charlottesville to contribute to the discussion. This was a very successful format, and ASAC encourages its members and the ALMA project staff to engage the organizers of forthcoming scientific meetings to facilitate further such discussions. ASAC also compiled a list of names of leaders in the field who could help the project to further the next stage of the development plan.

The report from the working group, as a starting point for the process was reviewed by the ASAC following our face-to-face meeting and is submitted to the Board independently of this report. *(Secretary's note: for convenience, the working group's progress report is attached* *to this one.)* ASAC notes that the preparation of the report/white paper on ALMA that will be submitted to the Decadal Review process organized by the US National Academies will be the responsibility of ANASAC, whose members share a more direct knowledge of the process of planning in the US community than the ASAC.

III.4) The ASAC should review the plans for provision of ALMA Regional Centers and report to the Board's March 2009 meeting.

We received updates on progress with recruitment and activities at all three ARCs. The board charged us with making a more substantial report in March 2009. We note that the ASAC face-to-face meeting at the OSF will follow directly after a meeting of the executives' ARC leaders in Chile. ASAC would like to hear in January about the readiness of the ARCs for early science, especially from a project-wide level. We would appreciate hearing from head of science operations, Lars-Ake Nyman, about the functionality of all three ARCs working together. ASAC appreciates that each regional ARC is required to deliver different services to its community; however, we would prefer to focus on the overall performance of the ARCs within the project, and leave the details of the provision of these regional services to the scrutiny of EASAC, ESAC and ANASAC.

III.5) Noting that 2009 is the International year of Astronomy, the ASAC should examine the Project's activities in the area of outreach, both to the general public and to the astronomical community, and make suggestions as to how they and the ALMA Project could enhance these activities.

ASAC received a report from NAASC's new EPO staff member (and former STScI staff member) John Stoke, and heard about planning for the International Year of Astronomy (IYA). ASAC is committed to raising the profile of ALMA EPO, and looks forward to continuing to working with EPO efforts throughout the project. We are confident that the level of public interest in IYA will outclass that in the current `International Year of the Potato'.[1]

Outreach to improve and unify ALMA's websites for both public and astronomers would be a valuable goal for the year. The lack of consistent information and the difficulty of finding documents and information on ALMA on the web makes it difficult for ASAC members to find key references, and is hindering astronomers from the non-mm community from getting better knowledge about ALMA. Better information resources would also allow more and better outreach and communication to the public, by better engaging the large number of effective communicators already at work in the professional astronomical community.

ASAC supports ongoing efforts to improve information resources within the project. ASAC continues to see advantages in having the JAO maintain an efficient and proactive EPO team in Santiago, both to provide a consistent message from the Director of the Observatory, and to provide a common set of information and resources to the EPO teams within the different executives that can then be tailored to match outreach efforts in their own communities.

[1] ASAC in no way intends to understate the importance of the world tackling hunger and food cost inflation. However, we're not sure that IYP has been a success in raising the international profile of these issues in 2008.

Report from the
ALMA Development Working Group

October 31th 2008

Membership of the Working Group
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EXECUTIVE SUMMARY

Over the past few months a working group that was established by ASAC in response to a charge from the ALMA Board has held a series of telecons to discuss the scientific drivers for the future development of ALMA. The goal was to ensure that ALMA remains at the cutting edge of capability in mm/submm-wave astronomy out to 2030. Further discussions were held by the regional science advisory committees (ANASAC, EASAC and ESAC), by ASAC at its face-to-face meeting in September 2008, and by members of the community at topical scientific meetings. The working group included or contacted experts in all the science areas to be addressed by ALMA, and considered hardware and software, long- and short-term and large and small projects. We see the desire to increase the collecting area of ALMA as clear, and pressing, across all science areas: in particular, a minimum requirement of 50 operational 12-m antennas, in addition to the 4 antennas dedicated to total-power measurements, may require a total antenna number of 54. At this preliminary reporting stage, we discuss the science-driven developments that are interesting in Section II, and then in Section III we discuss the themes of development by section of the project. We have not yet moved to the step of producing ranked order of these ideas, and look forward to the Board's feedback for our ongoing effort.

I. INTRODUCTION

The working group considered a wide range of options in terms of expected cost, complexity and timescale, including issues that merge into developments covered by contingency in the commissioning of the existing baseline array.

There are several areas of development that are broadly applicable across the whole project, including a general increase in the number of antennas, a more flexible and powerful correlator, more powerful and adaptable software tools for imaging and visualization of large data cubes, and a more effective atmospheric phase correction system. In some cases, specific science areas would benefit from specific new capabilities. In general, the arguments for implementing an increased number of receiver bands are usually led by a particular science area. The development of simultaneous multi-beam observations and of multi-band observations using the whole array, and the leveraging of other facilities to increase observing efficiency would all bring important advantages.

Previous discussions of priorities in the original ALMA science case, and subsequent de-scoping reports remain relevant in general; however, it is important to revisit these issues as the likely capabilities of the baseline array become clearer, and as the background knowledge of supporting observations and theory develops.

II DESIRABLE DEVELOPMENTS BY SCIENCE AREA

II.1 SOLAR PHYSICS

ALMA has antennas that are designed to be capable of pointing directly at the Sun. However, the primary field of view of the existing array is much smaller than the solar disk: at 1mm, the current 12-m telescopes have a 20-arcsec primary beam, as compared with the 2900-arcsec solar disk, thus requiring 20,000 beams to cover the disk. A modest development to introduce an M3/M4 system to under-illuminate the primary and increase the primary beam size appears viable. Reimaging to an effective 2-m primary would reduce the number of beams on the disk to 600, and a 1-m primary to 150. Because the radio Sun is very bright, and such high-resolution observations of the Sun open up an unprecedented capability, this would be a useful development.

II.2 SOLAR SYSTEM OBSERVATIONS

Observations of solar system objects would benefit from a variety of developments. A larger number of simultaneous subarrays, and even more a simultaneous multi-band capability, would allow a greater number of more useful observations of time-varying events: molecular lines in comets, allowing a clearer picture of outgassing and chemistry; thermal emission from asteroids, and planetary winds. For imaging planetary moons, a more extended array could be useful: a 10km baseline at 350 microns corresponds to an angular scale of about 7 milliarcsec, or a linear scale of 50 km at 10 AU. Direct observations of features from interplanetary probes show that there are much smaller ice, impact and volcanic features: increasing resolution with the possibility of a 20-50km baseline would be useful for specific 10-km scale features. Imaging of Pluto, Kuiper belt objects (KBOs) and moons of the giant planets would all benefit from the availability of longer baselines. In particular, the resolution or partial resolution of new KBOs has an importance for project-wide EPO beyond their direct scientific interest. Moreover, a direct molecular spectroscopic capability is difficult to achieve from a small space probes, and no such capability is currently deployed. Solar system investigations using ALMA are thus a capability that is impossible to duplicate, even by flying a direct probe. There are precedents for space-agency funding of ground-based facilities in support of flying missions.

The implementation of a full suite of Band-5 receivers (currently 6 are being manufactured) would help the study of water (including its different isotopic makeups) and the fundamental lines of H_2S and HDS in the solar system (and the wider ISM). In particular, the water cycle on Mars, and the origin of external sources of water on the giant planets can be carried out best using lines in Band-5. The measurement of the oxygen isotope ratio in a variety of environments is enabled by sensitive high-quality spectral imaging in this band. The richness of lines and mix of narrow and broad features present make this science area one that would also benefit from an increase in the instantaneous IF bandwidth that can be imaged. The development of efficient and fast mosaicking software is very important for mapping solar system objects, many of which are larger than the primary beam.

II.3 THE GALAXY, MOLECULAR CLOUDS CORES, DISKS AND STAR AND PLANET FORMATION

This science area includes one of the level-1 science goals identified in the original ALMA proposal. Since this case was made, advances using *Spitzer Space Telescope,* the BLAST balloon-borne camera and the ground-based BOLOCAM Galactic Plane Survey have provided much more information about the complexity and scale of structures in representative regions of the Milky Way's ISM, and have provided much more information about the sizes and spectra of stellar nurseries. However, while providing an abundance of detail, they have perhaps not surprised us in confirming the richness and subtlety of the interplay between gravity, magnetic fields and feedback processes. As knowledge builds, it is increasingly important to understand magnetic fields via polarized emission: both from direct spatial polarization maps, and the effect of magnetic field confinement on line profiles. An ongoing program to better understand the polarization performance of the array, and potential routes to modify receiver optics to increase polarization accuracy and sensitivity to further this goal is desirable. Additional software development will likely be required for accurate wide-field polarization images.

The innermost, and therefore hottest, regions of protoplanetary disks, with brightness temperatures of hundreds of K could be detectable on significantly longer baselines than 10 km. The availability of additional antenna/antennas, analogous with the Pie Town antenna for the VLA would provide a potentially valuable insight into the formation of rocky planets.

Surveys for both known and unknown lines would benefit from increases in IF bandwidth, while further gains in speed to map interesting regions would be achieved by implementing multi-beam feeds and additional antennas. The availability of longer baselines would allow even more precise imaging of masers in strongly excited regions. The implementation of multi-beam receivers is most appropriate in the higher frequency bands, for which the optical design is most practical. Additional software development will probably be required to produce the highest fidelity images.

Continuum images in bands 9, 10 and 11 are suitable for providing precise measurements of total luminosity in cloud cores, immune to the need for extrapolation from the Rayleigh-Jeans tail of the thermal spectrum. Although some of this will be possible using comparison with images from *Spitzer* and *Herschel*, the much finer angular resolution of ALMA will allow greater accuracy, remove confusion and potentially reveal binarity.

VLBI observations of Sgr A* offer the prospect of tracing the orbit of hot material at the last stable orbit before fueling the black hole at the Galactic Center. This work can **only** be carried out at wavelengths shortwards of about 1mm: at longer wavelengths, interstellar scintillation blurs out the necessary size scales (~ 10 micro-arcsec). As a direct probe of the details of strong gravity, the equipping of ALMA with inter-element phasing, and VLBI clocks and recording equipment is a relatively inexpensive and unique scientific opportunity. This work provides an alternative view of the Galactic Center, and complements efforts using optical interferometers, most clearly ESO's VLTI.

The availability of Band-1 receivers would also allow new studies of the most excited molecular clouds in the Galactic Center, with high-mass star formation being highlighted by the 44-GHz methanol maser line. The innermost regions of the youngest protoplanetary disks, in which the optical depth might exceed unity even at 100 GHz, are also sure to be detectable in band 1.

II.4 NEARBY GALAXIES

Mapping molecular clouds in nearby galaxies requires the full resolution of the array. Imaging compact HII regions and super stellar clusters in the process of formation would benefit from good atmospheric decorrelation correction performance on the longest baselines.

To map nearby galaxies, which extend over 10's of arcmins, using mosaicking with the current baseline ALMA would require many hours, so that to a match to the STINGS/SINGS projects would require of order a year of observing time. The development of multi-beam receivers would allow the full range of dynamics and environments to be captured in nearby galaxies more rapidly. This is especially true for the higher-frequency bands, for which the optical design of multi-beam receivers are most practical. Additional software development will probably be required to produce the highest fidelity images.

II.5 DISTANT GALAXIES

The level-1 science goal of imaging an analog of the Milky Way at z=3 remains achievable with the baseline ALMA. The sensitivity goals of the instrument are such that 50 operational antennas, as noted by the Blandford committee, are the minimum required to enable this capability. As a result, this supports an effort to increase the number of antennas by as many as possible. The existence of molecular gas and dust at redshifts corresponding to the end of reionization has been amply demonstrated during the last few years. In fact, the development and distribution of metals in the ISM has become an increasingly important question. The forthcoming availability of *JWST* allows this question to be addressed using rest-frame optical lines redshifted into the IR. However, the ability to investigate emission from the ISM is unique to the mm/submm bands. Perhaps the most topical question is how the tight relationship between the mass of the stellar bulge component of a galaxy, and the central supermassive blackhole was established. High-resolution observations of the cores of feeding AGN at high redshift, incorporating dynamical information, provide a direct insight into this question, and potentially another level-1 goal for ALMA.

As interesting galaxies extend across the full range of redshifts from 0 to beyond 10, the ability to compare different samples on a like-for-like line-for-line basis requires rather complete frequency coverage. As a result, filling in the currently unsupported bands will aid this science area. In addition, an increase in IF bandwith supported by sensitive receivers would allow a greater volume to be probed for serendipitous sources, along with improving continuum sensitivity for mapping total luminosity of these galaxies. Band-2 is the most needed, to observe CO(3-2) from modest redshifts, while Band-5 is able to cover CII emission from the end of reionization, and Band-10 can reach fine structure line emission from modest redshifts.

One of the most inventive uses of ALMA will be to study molecular absorption features in the ISM of galaxies that lie along the line of sight to distant powerful compact radio sources. The ability to correlate a wide bandwidth at high resolution simultaneously would increase the efficiency of these important observations significantly. This is a unique way to probe the conditions in the quiescent ISM of galaxies out to high redshifts. In addition to narrow absorption lines against background objects, absorption by clouds in the ISM of a galaxy with an enshrouded AGN can also be observed. Such observations would require high-resolution, wide-band correlator settings, a driver for a second-generation correlator.

Receivers with wider simultaneous bandwidths will also allow a greater range of science in these areas, especially near the central regions of galaxies, where dust and gas enshroud growing blackholes out to z>8. The first metal enrichment, likely at z~15-20 can also be accessed in these bands. The growth of the first galactic mass blackhole, is likely to be something that is invisible in radio synchrotron emission (from SKA) owing to CMB-quenching and invisible to *JWST* owing to extinction. In terms of discovery potential, maximizing both ALMA's sensitivity and frequency response is critical, continued mixer development and adding more antennas are both required to maximize this potential for discovery. CII emission from z=15 is redshifted into Band 3 at 110 GHz. The ability to reveal these processes could lead to an extra level-1 science goal for the mature ALMA.

II.6 COSMOLOGY

The ability to measure a large number of precise redshifts and shapes for galaxies, and to extract information about the growth of large-scale structure in the Universe, and thus see the effects of the evolution of dark energy is a goal of the Sloan-III, DOE Dark Energy Survey (DES), Pan-STARRS and LSST projects. ALMA's sensitivity in a narrow field will provide the ability to better understand the astrophysics of the galaxies used in these surveys. High-quality imaging in support of weak lensing observations is also a possibility, but these should be possible using the baseline ALMA.

ALMA's excellent imaging quality should allow the mm-wave Sunyaev-Zeldovich (SZ) effect to be mapped in exquisite detail. Since the initial suggestion of Band-1 for this purpose, X-ray imaging of nearby clusters of galaxies has revealed much more substructure within clusters than expected. The potential use of the SZ effect for measuring the evolution of the population of clusters, and understanding the feedback processes at work within will support the results of these missions. The SPT and ACT experiments are finding new large samples of SZ clusters, for which ALMA follow-up imaging will be essential to study the detailed astrophysics.

X-ray observations of relativistic jets in radio galaxies have revealed more information about interactions between jets and the surrounding ISM and IGM. ALMA's resolution and imaging capabilities should be able to study relativistic synchrotron and free-free emission from all these sources, and from cooler, keV shocked gas. The mix of sensitivity and mm-wave performance will open a new window on these high-energy processes.

The implementation of Band-1 would also allow a wider range of (potential maser) radio-recombination lines to be imaged in hot gas within and around galaxies.

II.7 NEW OPPORTUNITIES

The possibility of setting strict new limits on any variation of the fine-structure constant using offsets between absorption line frequencies as a function of redshift is a possible science goal that would become easier with wider/multi-band observations.

III. INDIVIDUAL PROJECT AREAS FOR DEVELOPMENT

III.1 ALMA Compact Array (ACA)

From the DRSP there is significant pressure of demand on imaging using ACA to provide short-spacing information for ALMA. An increase in the size of the ACA, or the provision of additional short/zero-spacing information would be desirable. This could potentially involve a dedicated wide-field survey telescope, perhaps a modified ATF antenna, or APEX, or possibly through a collaborative development with a new facility such as CCAT.

III.2 Receiver bands

Previous analyses, including the 2001 ASAC and 2005 Blandford report, supported the selection of bands 3, 6, 7, and 9 for the ALMA baseline. The priority for implementation of the incomplete bands was ordered 10, 1, then 4 and 8, then 2 and 5. Bands 4 and 8 are being provided by Japan and these are to be followed by Band-10. During our discussions, the addition of a >1THz Band-11 in the THz range was suggested, to allow the highest-resolution imaging, and probing higher-frequency lines in the Milky Way. We also discussed a new 20-GHz 'Band-0', which would add a new capability to Southern Hemisphere observations, but given the capability of eVLA in this range we saw a less pressing need to extend ALMA to new lower frequencies.

Measuring the colors of both cloud cores and distant galaxies is more accurate with a greater range of available bands, and the highest frequency bands can fix accurately the total power from these continuum objects, down to spatial scales where space-borne instruments like *Herschel* are limited by confusion noise.

In general, the performance of receiver devices in the ALMA project has been excellent, with the engineering teams achieving results that are much closer to the quantum limit than the specifications required. While this fundamental limit cannot be bettered, advances in fabrication and simulation/design techniques allow substantial further improvement in broad-band detectors, and at higher frequencies. Continued effort in device development is sure to enable a more powerful ALMA in the future, and can be carried out at a modest cost in a University/national-scale laboratory. A huge improvement would be achieved by equipping ALMA with multi-beam receivers, especially at the highest frequencies.

III.3 Correlator

Studies for a next-generation correlator have been carried out by the Japanese executive, and the performance of relevant electronic components continues to improve quickly. The existing dedicated processors used to construct the ALMA/eVLA correlator, and the correlator for CARMA are being challenged from two directions: i) Software-based correlators, running on mainstream general-purpose supercomputers, as specified for LOFAR, and ii) FPGA processor-based correlators, being developed for several projects. The initial ALMA correlator is capable of producing excellent results from the full array in early operations; however, the potential widening of the IF response, the desire for more higher, resolution windows on multiple lines, and the possibility of multi-beam feeds mean that an increase in capacity of several orders of magnitude in correlator performance would be useful to the project on the medium to long term. Since developments are likely to be based in software or run on commercial-off-the-shelf hardware, development work on correlator performance is an inexpensive, high-priority, long-term goal. The gain in increasing correlator bandwidth is proportionally greatest at longer wavelengths, especially for an implemented Band-1.

III.4 Supporting facilities

ALMA's least powerful attribute is mapping speed. Wide-field interferometric imaging at mm/submm wavelengths can be achieved using mosaicking; however, the addition of multi-beam receivers would accelerate mapping performance, especially if a super-arcmin field is required. Multi-beam feeds are easier to implement at higher frequencies, owing to the smaller physical size of the necessary optics. It is not impossible to see a 30-40-element focal plane array operating in band 9; however, in band-1 there is limited physical space to use a multi-beam receiver. Of course, the primary beam is much larger (~2.5 arcmin at 40 GHz).

The advent of modest (~1000 deg^2) mm-wave images from SPT, ACT, and smaller (10-100 deg^2) but higher-resolution images from APEX and JCMT/SCUBA-2 will provide a finding image for ALMA. There is also a wide array of expected imaging from space: the *Spitzer* legacy, *Herschel* key programs and the forthcoming *WISE* and *Planck* all-sky surveys will provide this. A private effort to develop a 25-m 10-micron surface accuracy telescope overlooking the site (CCAT) would provide a rapid finding capability for ALMA. The development of 10-kilo-pixel cameras, first with SCUBA-2, and now with an array of cheaper technologies (for example, the NSF ATI-funded 4-color mm-wave MKIDCam with PI Jason Glenn for the CSO) probably reduce the urgency of developing wider-field mapping capabilities with ALMA, when considering the identification of targets alone. However, the development of such facilities will make even more demands on ALMA for resolving and understanding detected targets, while high-resolution mapping of the ISM and nearby galaxies will continue to require ALMA's high-fidelity interferometric mapping capability, and cannot be replaced by single-aperture telescopes.

III.5 Atmospheric phase correction

The correction of decorrelation from the atmosphere is essential to the performance of ALMA, especially at the highest resolutions and frequencies. The current scheme for antenna mounted water-vapor radiometers, along with demonstrated fast-switching performance of the antennas onto nearby calibrators should provide a suitable route to achieving the necessary performance. However, reaching this performance routinely will require significant ongoing development work. In addition to real-time correction for the atmosphere, a way to make accurate forecasts of forthcoming conditions would allow the array to operate efficiently without having to curtail observations if the conditions were to improve or degrade significantly. The utility of different local weather monitoring resources, water-vapor monitors, radar/sonar meters, and perhaps different weather radars should be evaluated. The price of baseline ALMA justifies the expenditure of order $1M on technology to allow the array to be used more efficiently by several per cent. Enabling simultaneous observations in multiple frequency bands could also enable accurate phase correction on a second-by-second basis.

III.6 Software

An ongoing effort to improve data archiving, accessibility, pipeline reduction, visualization of large data cubes, and to generate tools from the project that are appreciated and used throughout both the ALMA community, and the wider astronomical community is very desirable. It is hard to see where new software capabilities (and the enabling hardware) will lead over the decades ahead; however, this kind of capability is important, and in no way should its position as item 6 imply it is an afterthought!

III.7 Number of interferometer antennas

As noted by previous reports, the sensitivity and imaging fidelity of ALMA scales with increasing number of baselines, and all the areas of ALMA science benefit from improvements in these areas. Looking into the far future, it is unlikely that new technologies will enable a shift in the cost paradigm for these high-quality antennas, and it is our view that the acquisition of as many more of the current antennas as is possible and prudent should be considered a priority. Fifty operational 12-m antennas (in addition to the 7- and 12-m antennas of the ACA) were considered to be necessary to meet the level-1 science requirements in 2005. When the likely transport and servicing overheads are included, this is likely to require at least 4 additional 12-m antennas, over the currently contracted 50. In the longer term, the inevitable possibility of attrition further supports the acquisition of additional antennas on the current contractual terms while they remain in production.

III.8 Optics and related improvements

Improving the polarization performance of the array, which may involve modifying the receiver optics, would be very desirable for understanding the role of magnetic fields in star-forming regions. Sub-illumination optics would make solar observations much more feasible. Increasing the number of sub-arrays available for science operations, and adding a simultaneous multi-frequency-band capability would be important for any time-varying objects, such as comets and GRBs.

III.9 Maximizing angular resolution

Extending the maximum baselines available to 20-50 km would enable high-resolution science in the solar system, nearby star-forming disks and nearby star-forming galaxies. The ultimate resolution through equipping ALMA to join a mm-wave global VLBI network would enable unique tests of strong gravity in the immediate environment of Sgr A*.

IV SUMMARY

The results of the working group discussions on ALMA developments can be summarized as follows. **Note that the numbering does not indicate prioritization**:

1) The acquisition of additional antennas for ALMA is a very desirable goal. 50 operational antennas is a desideratum for achieving the baseline performance. The availability of each antenna is currently not known accurately; however, assuming a 5-10% fault rate seems reasonable, and consistent with the long-standing idea that a 64-element ALMA would have 60 antennas in service at any time.
2) The ability to combine the signal from the array in phase for VLBI recording. The key science capability enabled by this development is the ability to image the region of the Galactic Center where strong gravity effects are likely to be visible.
3) A vigorous effort to test and develop phase correction schemes. This might require the acquisition of more and more sophisticated site monitoring equipment. Better site weather prediction to allow better selection of observing programs.
4) The availability of additional subarrays for prompt simultaneous monitoring of bright time-critical targets – gamma-ray bursts, supernova shock breakouts, cometary outgassing and planetary weather – both in line and continuum
5) The ability to operate more than one receiver simultaneously would improve the diagnostic ability of ALMA for both galactic and extragalactic targets. It would increase the sensitivity of time-critical observations mentioned above, and should allow more precise atmospheric phase monitoring and correction.
6) Increases in the number of receiver bands. Band 1 would enable imaging of the Sunyaev-Zeldovich and, along with Band 2, enables the detection of well-understood CO emission lines from the end of reionization. The completion of band 5 would enable the detection of water and the oxygen isotope ratio in the solar system and ISM, as well as complete the redshift coverage for specific extragalactic lines. Bands 10 and 11 continue uniform redshift coverage of fine atomic structure lines, and enable the high-resolution imaging of, and the precise determination of luminosities of cores within, molecular clouds. We consider the demonstration of effective phase correction is essential for the implementation of bands 10 and 11.
7) Development of sub-illumination optics to increase the primary beam size, most specifically for solar observations.
8) Ongoing development work for mixer, RF optics, and LO distribution technology to enable more-sensitive, wider-band receivers.
9) Ongoing development work into implementing new commercial-device-based correlators, and monitoring of supercomputer based software correlators to expand ALMA's current absorption line spectroscopy, along with eventual support for wider bandwidths and multi-beam receivers.
10) Long-term work to operate ALMA using multi-beam receivers, especially at the shorter wavelengths, from bands 6 - 11.
11) Efforts to develop new imaging algorithms for efficient and accurate mosaicking, along with advanced visualization and telescope control tools to maximize the efficiency of operating the arrays and extracting scientific results from the data. Pipeline and archive tools to increase the accessibility of ALMA to non-experts and users who work mostly from the ALMA archive.
12) Efforts to improve the optics and software to maximize our ability to make wide-field polarization images.
13) Extending the maximum baselines to 20-50 km to improve the maximum angular resolution achievable with ALMA.
14) Improving the sensitivity for short-spacing data by enhancing the ACA or adding a dedicated single-dish facility.

We note that over the next few months, ANASAC is to lead the preparation of a white paper for the US decadal review. The development working group looks forward to continuing its discussions, along with the science advisory committees, and awaits the Board's consideration of this document in November.