Report from the ALMA Development Working Group

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EXECUTIVE SUMMARY

Over the summer a working group established by ASAC following a charge from the ALMA Board, held a series of telecons to discuss possible science-driven developments 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 or multi-band observations using the whole array, and the possibility of leveraging other facilities to increase observing efficiency are also possible.

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 a M3/M4 system to under-illuminate the primary and increase the primary beam size is 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 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, extending over 10's of arcmins using mosaicking with the current baseline ALMA would require many hours, leading to a match to the STINGS/SINGS projects requiring 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 fairly complete frequency coverage. As a result, filling in the currently unsupported bands will aid this science area. Alongside, 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 $z\sim15$-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 more antenna would both 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 the project is now implementing 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 (~1.7 arcmin) at 50 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, demonstrating this performance 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-vapir monitors, radar/somar 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 while 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. 50 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 antenna, 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 area, 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 ALMAs 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 7-11.
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.