A ROAD MAP FOR DEVELOPING ALMA

ASAC recommendations for ALMA 2030

Alberto D. Bolatto (chair), John Carpenter, Simon Casassus, Daisuke Iono, Rob Ivison, Kelsey Johnson, Huib van Langevelde, Jesús Martín-Pintado, Munetake Momose, Raphael Moreno, Kentaro Motohara, Roberto Neri, Nagayoshi Ohashi, Tomoharu Oka, Rachel Osten, Richard Plambeck, Eva Schinnerer, Douglas Scott, Leonardo Testi, & Alwyn Wootten

This document summarizes the recommendations emerging from the ALMA 2030 process. The findings are discussed in three documents: 1) the Major Science Themes in the 2020-2030 decade, 2) the landscape of Major Facilities by 2030, and 3) the Pathways to Developing ALMA, which describes a number of possible developments.

After compiling this information, the ALMA Science Advisory Committee discussed together with the Regional Program Scientists and the JAO at its February 2015 face-to-face meeting the best avenues for mid- and long-term improvement of the observatory, arriving at the conclusions presented here. The purpose of these recommendations is to guide the regional ALMA Development process in a coherent fruitful direction, by presenting a list of broad themes we foresee as the highest priority among the developments considered. It is important to keep in mind, however, that the development process also includes a creative, bottom-up element. Innovative technical ideas well grounded in astronomy should also have space in the future development of ALMA, and in that sense this is not an exclusive list. It also assumes that completion of the baseline capabilities of ALMA (adding bands 1 and 2) will proceed.

Separately from these developments, the ASAC notes that a large single-dish telescope equipped with cameras capable of fast large-scale mapping would be an important scientific complement to the interferometer. Such an instrument is outside the scope of the envisioned ALMA development projects, but if built, it would have large potential scientific synergies with ALMA (for example, surveying for sources, or providing the larger source context).

Recommended development paths

1. **Improvements to the ALMA Archive**: enabling gains in usability and impact for the observatory.
2. **Larger bandwidths and better receiver sensitivity**: enabling gains in speed.
3. **Longer baselines**: enabling qualitatively new science.
4. **Increasing wide field mapping speed**: enabling efficient mapping.

<u>Better usability and impact: ALMA Archive</u>

The archive is an integral piece of the observatory. An archive that is easy to use for the non-expert, and goes beyond being simply a repository for PI data is a great potential multiplier for the impact of ALMA. Analysis of the productivity of mature facilities shows that publications using archival data can rapidly overtake the publications from the original proposers acquiring the dataset, as is the case for the Hubble Space Telescope and other facilities. Thus the archive may be what ultimately determines the productivity of ALMA.

In order for the archive to be productive, it needs to be public, searchable, easy to mine, and it needs to contain fully reduced science-grade data products. In addition, the archive should contain value-added products either automatically generated (for example, lists of “detected lines” in the target), or user submitted post publication. Ideally the archive should be fully compliant with the Virtual Observatory standards, to be able to interface across wavelengths. It is also crucial that it can be fully exploited by users outside the community of interferometry and mm-wave experts.

With high sensitivity, position, frequency information, and large bandwidth, ALMA data are intrinsically very rich. A common feature is “involuntary” line surveys of sources, where lines beyond the targeted transitions are detected and mapped. The archive developers are already working on a few features to make it more user-friendly, with the introduction of quick visualizations of datasets, for example. Regional funding is being used to develop the first efforts into archive “enrichment” toolkits in EU, EA, and NA (e.g., ADMIT, the Japanese Virtual Observatory ALMA interface). Developing the ALMA archive into a fully-fledged science-grade minable archive, however, requires significant further development into pipelines and automated analysis. Because it will be unlikely that the quality of an automated pipeline reaches what is possible with experienced user reduction, we think the archive should be designed to accommodate user-submitted products (a version of this has been done for legacy- or treasury-class projects in facilities such as *Spitzer*, *Herschel*, and HST).

<u>Gains in speed: Larger Bandwidths and Improved Receivers</u>

The ability to provide and process wider instantaneous bandwidths, together with continuous improvements in receiver sensitivity, can bring scientifically significant increases in observation speed. The ultimate goal is to correlate an entire receiver band in one go, with no loss of sensitivity. This requires improvements not just to the receivers themselves, but also to the digitizers, the IF transport, the correlator, and the archive.

Increasing the IF bandwidth of the receivers appears as eminently feasible technologically. ALMA currently features a 4 GHz bandwidth per sideband, except in Band 6 where it is 5 GHz. CARMA and NOEMA, by comparison, feature 1-9 GHz and 4-12 GHz IFs, providing 8 GHz of bandwidth per sideband (note that a bandwidth of at least 6 GHz would allow to fit simultaneously ^{12}CO and its common isotopologues in one sideband of Band 3, for example). Doubling the bandwidths of the digitizers, fiber-optics transmission, correlator, and archive seem, likewise, eminently possible with current technology. The expansion of the IF to include an entire band will require considerable research. Nonetheless, it looks like an achievable long-term goal that will bring gains of factors of ~4-6 in speed for many observations. Bandwidth expansions will, simultaneously, enormously increase the legacy value of the archive while increasing the likelihood of serendipitous discoveries.

Continuous improvement to receiver sensitivities will also result in significant gains in speed across all science. Besides improving receiver temperatures (through removal of warm optics, or improved devices), the dual sidebanding of the currently DSB Band 9 and Band 10 receivers would yield important gains in speed at the higher frequencies of ALMA operation. Long-term sustained research in better devices or new technologies (such as TKIP amplifiers) has the potential to yield significant breakthroughs that are equivalent to doubling or tripling the collecting area of the array with its present instrumentation.

New Science: Longer Baselines

ALMA just recently demonstrated the potential of 10 km baselines in mm-wave interferometry by producing breathtaking images of the HL Tau protostellar disk and the SDP81 gravitational lens, among other targets. The designed maximum baseline of ALMA is 16 km. Doubling it to 32 km will provide an angular resolution of ~8 mas at 230 GHz (reaching this resolution at optical wavelengths would necessitate a 16 m diameter telescope in space). This is the size of the photosphere of α Centaurus A, and it is equivalent to a resolution of 1 AU at the distance of the Taurus molecular cloud (140 pc), ~10 pc at 240 Mpc, or a resolution of ~60 pc in the high-z universe (the size of a large Giant Molecular Cloud in the Milky Way). With the current system the Rayleigh-Jeans 1-sigma noise equivalent in a 24-hour continuum integration would be ~1 K at that angular resolution. This means that it is certainly possible to image warm dust structures with a moderate optical depth ($\tau \geq 0.01$), and it is easy to detect stellar photospheres, which have resolved brightness temperatures of several thousand degrees.

A further doubling of the baseline to ~60 km would lower the sensitivity to 4 K (assuming no improvements to the system), which means that a wide range of structures can still be imaged (from warm dust in protoplanetary disks to AGN tori). This angular resolution corresponds approximately to the diameter of the main sequence B7 star Regulus, 20 pc away. High signal-to-noise imaging of stellar photospheres at high-resolution opens up the possibility of measuring star-spots, temperature gradients, and stellar shapes in nearby stars.

Longer baselines will also allow for very accurate astrometry of nearby solar-type stars, enabling the search for planetary companions through their orbital effects. A Jupiter-like companion of a solar mass star induces a wobble of ~0.01 AU (i.e., ~1 mas at 10 pc) on the primary: because high signal-to-noise measurements can centroid with very high precision, and because ALMA astrometry should be extremely stable over long periods of time, it is likely that ALMA can look for companion-induced wobbles in stars out to several tens of parsecs. The bottom line is that increasing the resolution of ALMA has the potential to lead to qualitatively new scientific insights about the universe, and even more so when coupled with the sensitivity/bandwidth increases that we recommend in the previous point.

An intrinsic advantage of an interferometer is that the increase in angular resolution can be done progressively, by adding new antenna stations at larger distances. It is possible to progressively increase the length of the maximum baseline over the designed 16 km to understand the technical and practical limits of the equipment (e.g., LO distribution noise, line-length correction, and ultimately correlator) and the normal coherent correlation technique.

Correlation on long baselines requires using atmospheric phase correction techniques, currently 183 GHz water vapor radiometry in combination with fast switching in ALMA. Devoting effort to perfecting the atmospheric phase correction is something that should proceed in parallel with the investigation of the longer baselines. This will likely pay off not only on long baselines, but also on the fraction of usable time at the highest frequencies.

<u>Wide Field Mapping Speed: Multi-beam Receivers</u>

One of the major limitations of ALMA is its relatively small field of view (~1 arcmin at Band 3 and inversely proportional to frequency), determined by the diameter of the antennas and their primary beam. There is considerable scientific interest in increasing the field of view to enable faster wide field mapping of extended objects. Survey and imaging science will benefit from this.

The primary way to attain potentially large gains in mapping speed is to develop multi-pixel array receivers for interferometry. Such receivers are likely to occupy a significant fraction of the (already tightly packed) available focal plane space, and are likely feasible for only one band at a time and with only modest pixel counts without major redesign of the antenna optics. Nonetheless, it makes a lot of sense to investigate the tradeoffs in replacing a high-demand band (e.g., band 6 or 7) single-element receiver with a multi-pixel receiver.

The technical and scientific tradeoffs involved in developing and using multi-pixel receivers in ALMA are complex and require investigation to evaluate feasibility. Upgrading even one band to a multi-pixel receiver requires a number of improvements in elements downstream (IF transport, correlator, archive), and possibly upstream (LO distribution). Some of these improvements may be parallel with improvements required by larger bandwidths. In particular, for many science projects that require mapping of one spectral line, it may be practical to share bandwidth among pixels (large scale mapping of continuum sources would not be practical with such a scheme).