1 ALMA Development

Continuing technical upgrades and development of new capabilities will be required to maintain ALMA as the state-of-the-art facility for millimeter/submillimeter astronomy over the course of its projected life of 30+ years. In particular, the rapid progress of electronic technology should make new hardware components and subsystems offering improved performance and higher reliability available for insertion into ALMA throughout the project lifetime. Equally important, advances in software and computing will offer improved performance and reliability that translate into more capability and reduced costs of operation. The tri-lateral project has recognized that continued hardware and software development are essential to keep ALMA up-to-date with the rapidly advances in these areas, thereby keeping ALMA at the fore-front of astronomical research for its projected 30+ year lifetime.

The ramp-up of the development funds is hard to quantify formulaically. On the one hand, it is difficult to justify significant development funds prior to full operations for an instrument that is itself vastly superior to anything that proceeded. On the other, it is recognized that years without development funding will erode the base of technical expertise that made ALMA possible in the first place, and that some facilities (e.g., SIS microfabrication laboratories) might retool or even close shop if faced with the prospect of little work. Additionally, it would be difficult to retain the best and brightest technical staff from those groups that provide the construction hardware during the construction assembly-line phase, without intellectually challenging work to keep them engaged.

As a result of these considerations, the Executives agreed that:

1. ALMA shall develop a science-driven long-range development plan. The planning shall start in 2008 with regionalized processes to develop community input to a set of science priorities for ALMA and associated developments. The Executives and JAO shall work together to estimate initial costs.
2. The Board, with input from the ASAC, shall review the proposed development plan and provide policy guidance to generate a scientific vision with both long-term and short-term projects. An approved plan should be in existence by 2009. This will allow each agency to have access to a detailed long-range development plan that justifies their commitment to ALMA development. Once a project is in place, it is managed regionally in coordination with the JAO.

Development projects are the responsibility of the Executives. The normal procedure is that the ALMA Director, in consultation with the user community and Executives, will put forward proposals to the ALMA Board for upgrade and development projects. An international scientific review committee should review each proposed development project. The ALMA Board then decides on the projects, prioritizes them, assigns values and assigns responsibility to one or more of the Executives. Thereafter, development projects are conducted in a manner identical to the conduct of the ALMA construction project. Namely, the Executive having task responsibility will assign a project manager who will report to the Executive regarding matters of cost, and he/she will report to the ALMA Director regarding technical scope and schedule.

1.1 Example Development Projects

Ultimately science priorities will dictate the ALMA long-range plan. Some of the possible technical developments are listed below in order to give an idea of the possible magnitude of activities.

Hardware development for ALMA in the period beyond construction is expected to fall into a number of categories. Some of these items should be considered to be definite, and some will become targets of opportunity as improvements in technology occur and as science requirements evolve to demand new capabilities. Possible efforts are discussed briefly in this section, taking the lead from the ASAC recommendations for ALMA Enhancements in their October 2001 report.

The total cost of these efforts is approximately \$100 M or around \$10M per year for 10 years. For some projects, however, a front-loaded budget profile may make more sense to keep ALMA performance on the cutting edge.

The rest of this section provides an overview of possible development projects to be started during the early years of ALMA operations. Chief among these is the restoration of scope which was postponed during construction to keep ALMA within budget.

Two additional frequency subarrays: During rebaselining, two of four frequency subarrays were deferred. This precludes simultaneous science observations at more than two frequencies, decreasing the science return from observations of objects with rapid variability, including Solar flares. Additionally, there are a number of cases in which a number of subarrays larger than two would be desirable. If the array were be equipped with a receiver band only in a subset of the total number of antennas (as will be true for band 5), then a dedicated subarray would be needed to observe at that frequency band with those antennas. If the second subarray were in use for technical work, then all the antennas without that particular receiver band would have to stay idle.

Restoration of imaging capability: The ASAC concluded that a minimum of 50 simultaneously operating antennas is required to achieve the ALMA science goals. They endorsed the project scope of building a 64 antenna baseline ALMA array. The ALMA configurations have been designed to accommodate 64 antennas. The 64-antenna scope of ALMA was driven by the need to do groundbreaking submillimeter science at the highest resolutions. Studying galaxies in the early universe requires the highest sensitivity and resolution, and is a Primary Scientific Requirement of ALMA. Equally strong requirements are placed on resolution and sensitivity by the imaging of structure and kinematics in the gas and dust of nearby protoplanetary disks on scales comparable to the gaps created by planets, which is the second Primary Scientific Requirement. Imaging of line emission from protoplanetary disks at such high resolution requires the full sensitivity of full complement of 12-meter antennas; with them, ALMA's ability to study the internal kinematics of disks would be unequalled by any other instrument. The third Primary Scientific Requirement is to achieve the highest quality imaging in the millimeter and submillimeter bands, to match the quality of images from HST and ground-based adaptive optics. This too is highly sensitive to the number of antennas. Further details are available in the March 2005 ASAC report.

Additional receiver bands: it is expected that bands 1, 2, and 5, covering 31.3-45, 67-90, and 163-211 GHz will not be built during ALMA construction. In its 2001 report, the ASAC provided a list of science drivers for these bands, excerpted here.

- **The ASAC identified band 1 as among the highest priority unistrumented ALMA bands. ALMA's lowest frequency band 1 offers many unique scientific opportunities. As well as being a vital adjunct to the main ALMA science programs at higher frequencies, band 1 would also bring to ALMA an observational community largely distinct from that at (sub)millimeter frequencies. Its observing programs can be carried out even in poor weather.**
- **Band 2 will cover the low-excitation CO 1—0 and 2--1 lines in the redshift ranges z=0.28--0.72 and 1.6--2.4, respectively. It also contains the lowest J=1--0 transition of many deuterated molecules, making it possible to study the extreme deuterium fractionation processes found in the coldest gas.**
- **Band 5 will be important for red-shifted [C II] lines in the range z=8-11. Moreover, it covers the H_2O 183 GHz and the $H_2{}^{18}O$ 203 GHz line. The 183 GHz line is a strong maser, but can also probe extended thermal H_2O emission under exceptional conditions. The 203 GHz line offers a unique possibility to image an optically thin isotopic water line from the ground at high angular resolution. Such studies would be important complements to H_2O studies carried out with the Herschel Space Observatory at lower angular resolution in the same timeframe.**

The front end dewar is designed to accommodate these bands, and they should be populated as quickly as possible after the construction phase of ALMA ends. Bands 1 and 2 will be HFET amplifier receivers, and band 5 will be a SIS mixer receiver. The Band 1 receiver will likely provide useful response up to about 50 GHz with somewhat degraded performance. There are no significant cost differences among these three bands, and development, fabrication, and installation costs are expected to be about $7M for each band, equivalent to a total development budget of $21M. The work is straightforward and there are no technical risks.

VLBI: the capability of performing beam-combining to provide a signal suitable for Very Long Baseline Interferometry is built into the baseline correlator in the form of digital signal outputs which, if added, will result in the equivalent SNR of a single 88-meter antenna. This would tremendously improve the sensitivity of any baseline including it. With such sensitivity, it would be possible to observe the shadow of Sgr A*, the black hole at the center of the Milky Way, assuming that the accretion flow is optically thin in this region of the spectrum. However, the adder (which may need to be partly digital and partly analog) is not part of the construction project. A VLBI data acquisition terminal capable of recording the combined signal is also not in the construction project. The hydrogen maser frequency standard is **not** in the construction budget and is expected to cost circa $100K (spare included). The local oscillator system is designed to be good enough for VLBI up to about 300 GHz. Designing, building, and installing the necessary equipment to implement VLBI is likely to cost about $2M, exclusive of software expenses.

Upgrades of Front End Cartridges: it is likely that by the time ALMA construction is finished, improvements in SIS mixer technology will result in receivers with better performance than those built for ALMA, particularly in the higher frequency bands. This could increase the sensitivity of the array. These improvements will come from better consistency in Nb wafer yields, better knowledge of how to design SIS mixers, and possibly from the use of materials other than Nb, which could be significantly better for Bands 5-10 and particularly for Bands 9 and 10. These latter bands use DSB mixer designs. In these bands the ALMA beam is small compared to most sources, and total power image reconstruction most important. However, for the total power component the sidebands cannot be separated, compromising ALMA's imaging capability. It would be very useful to retrofit bands 9 and 10 with 2SB cartridges. At some point, the improvement in array performance possible will make it worthwhile to retrofit all old cartridges with new mixers. It is likely that it will be possible to change only the mixer-preamps, rotating all cartridges through a retrofit process over a period a few years. A further improvement in sensitivity could be achieved by front ends which could present a broader bandwidth to the system for processing. For example, 2SB receivers employing 8 GHz amplifiers could present 32 GHz for processing, doubling the continuum sensitivity and the region of spectrum over which spectral lines could be simultaneously accessed. A suite of such broad bandwidth receivers should be implemented along with a suitable backend upgrade.

ALMA operations should support some continuing research in SIS mixer development (perhaps $1M per year including labor) and then support cartridge upgrades when significant benefits are possible. Since only a retrofit is needed, the construction and installation costs are likely to be much less than the original construction costs. A reasonable estimate for implementation is about $2-5M per band for bands 6-10.

Second Generation Correlator: the capability of the baseline correlator, enhanced by the tunable filter bank card and complemented by the ACA correlator, will be significantly greater than originally required, and delay the need for a replacement. However, a second-generation correlator may eventually be required for a number of reasons. Some improvement in signal-to-noise ratio will be possible by always correlating three bit instead of two bit samples. A unified architecture for an array comprised of the complete ALMA scope of 80 antennas will provide improved images. Some ALMA bands (e.g. band 6) provide more bandwidth than the current correlator can process; improved receivers should present both sidebands to a new correlator with twice the current 16 GHz bandwidth.

It is likely that a new correlator with significantly enhanced capabilities will cost between $15M and $50M, depending on just how much advanced performance is demanded by the science. There will also be significant expenditures in computing and archiving hardware associated with the greater amount of data generated.

Absolute calibration system: In the array of antennas there is one small horn whose gain can be known to an accuracy of $\leq 1\%$. The goal is to transfer this gain to the other antennas, keeping that accuracy. In this way the absolute calibration of the array can be improved.

Back End upgrades: by the time ALMA construction is completed and the array is commissioned, it is likely that commercial components for high-speed digital data transmission will be much less expensive than at present. At some point, there may be cost advantages in maintenance that would warrant replacing the present digital data transmission components. Advances in semiconductor technology will undoubtedly make high-speed digitization with commercial components much less expensive, and extend the maximum bandwidth possible with a single digitizer. It is conceivable that, ten years from now, it will be possible to use one 4-bit digitizer per 8 GHz IF band instead of multiple 3-bit digitizers for multiple down-converted 2 GHz IF bands, and build the second generation correlator to use 4-bit samples, thus achieving very close to the maximum possible SNR from the received analog signals. This would also significantly reduce the component count in both the analog and digital sides and result in better reliability and maintenance savings.

Improvements in local oscillator technology are likely to result in improved performance in the areas of phase noise, phase stability, power, and added IF noise, particularly in the highest frequency bands. The improvements in array performance may at some point warrant changes in the local oscillator system.

Since these items are dependent on exactly where technology goes, it is impossible to estimate any cost; but ALMA operations will support a number of engineers, who should be encouraged and funded to keep up with the available technology and formulate plans for incorporating it into ALMA at the appropriate time.

Antenna upgrades: it has been the experience at all mm-wave observatories that improvements in antenna hardware can be made from time to time which result in improved performance in one way or another. A short list includes metrology upgrades, servo system upgrades, surface treatments, thermal modeling, and other electronics improvements. The antenna group should be expected not only to maintain the antennas, but also to evaluate their performance and think of possible ways to improve performance and reliability. This work would be outside the scope of normal day-to-day activity, and at some point the expenditure of modest sums might result in significant performance and cost savings. It is impossible to estimate a budget, but we believe some expenditures of this nature will be desirable.

Computing upgrades: basic computing upgrades (e.g. faster processors, larger Archive, new data warehousing techniques) are part of the general ALMA running costs. Above and beyond these costs, ALMA should fund development projects to develop new data processing and imaging tools, VO data-mining tools, as well as improved user support and operations management tools. An annual effort of 10 FTEs (circa $1.2M) is anticipated.