PATHWAYS TO DEVELOPING ALMA

A document to inform the scientific discussions leading to the development of a roadmap for improvements in ALMA

ALMA DEVELOPMENT WORKING GROUP REPORT

Alberto Bolatto -- Chair, ASAC

Chair, General Coordination

Stuartt Corder -- Deputy Director, JAO

Reliability & Efficiency lead

Daisuke Iono -- EA Project Scientist

Resolution, FOV, and Imaging Quality & Calibration lead

Leonardo Testi -- EU Project Scientist

Sensitivity, Spectral Coverage, and Flexibility lead

Alwyn Wootten -- NA Project Scientist

Simultaneous Frequency Coverage, and Usability lead

This document is part of a report initially commissioned by the ALMA Development Steering Committee, and subsequently the ALMA Board. The goal of the report is to provide guidelines for the long-term development of the array, and its continued and scientifically fruitful operation beyond 2030. The report is broken up in several documents, of which this is the one devoted to addressing the interface between was is technically possible (or possible to envision for this group of people) and its impact on the science performance and operations of the instrument.

To this end we have classified the possible developments in broad areas of improvement subdivided in smaller branches. The purpose has been to concisely discuss each development path, and whenever possible go beyond its description into a qualitative and quantitative evaluation of its scientific, technical, and operational impact including some very rough level of cost analysis. This document is intended to be informative for the general reader, and includes only broad technical concepts where necessary.

The table in the following pages classifies and summarizes each development in terms of the improvements it enables. It also contains a very rough estimation of the cost and the operational implications. The costing qualifier (very low, low, moderate, high, very high) corresponds roughly to estimated costs in millions of USD in the ranges < 0.1, 0.1-1, 1-10, 10-100, and >100 respectively.

No.	Improvement Area	Item	Degree	Speed/Difficulty	Fabrication Cost	Target Science	Note	Operation effects
01	Sensitivity	More 12m antennas	incremental	Known	High to Very High	All	Correlator, IF transfer	More power generation
02		More ACA	incremental	Known	High to Very High	Large scales	ACA correlator/IF	More power generation
03		New digital system	×2 bandwidth in some cases, otherwise needs new Rxs	Moderate, some research	Moderate to High	All	See also 33, 43	Some power, array downtime
04		2SB B9/B10	×2 for B9/B10	Research/Known	Moderate	High frequency	~20% of all observing time	Downtime for installation
05		Lower noise Rxs	20%-200%,	Moderate to long research	Moderate	All		Downtime for installation
06		New technology devices for Rxs	Potentially large	Long scale research	Moderate to High	All	Quantum-limited amps, ultra-wideband	
11	Resolution	Longer baselines	×2-3, or up to 300 km	Requires construction	Moderate to Very High	SMBHs, photospheres of stars, high-z BH	Need more experience with long baselines	Snow cleanup and recovery
12		Better phase correction	~10%-30%, more for high frequencies. Increasingly important for long baselines	Software, research, maybe some new hardware	Very low	Disks, exgal. All science fields that require high resolution.	Need statistics on current performance of WVR	
13		mmVLBI	VLBI operations for general users	Ongoing	Low to Moderate	High resolution/non-thermal	Need good operation model	Low Agreements with other observatories/networks
21	FOV	Multi-beam Rxs	×N	Extensive; modifications to cryostat, LO, potentially IF transport, correlator	Very high	Nearby galaxies, local SF regions, Galactic surveys	Biggest gain at higher frequencies	Downtime for deployment and testing. Data rate increase, archive cost. Software/pipeline/algorithms development needed

22		Under-illuminated feed	×a few for mapping of bright sources	Not clear how to share with normal system	Moderate	Solar science, GMC mapping	Easier to implement independent subarrays	Downtime for installation
31	Spectral Coverage	B2	New capability	Similar to other bands	Moderate to High	Disks, high-z, SZ, molecules	Could be combined with upgraded B3 and wide band	Downtime for installation
32		B11	New capability	Research, long commissioning	High	Very high-z H2, FIR, local NII 205 um	Very small fraction of time available	Downtime for installation
33		Extend IF for Rxs	×2-3, maybe more?	New Rx, new digital system/IF transport	Moderate to High	Simultaneous isotopologues , line surveys	More correlator to improve sensitivity and spectral coverage	Data rate/Volume increase
34		Correlator	×2 bandwidth in some cases, otherwise needs new Rxs	Moderate, some research	Moderate to High	line surveys	See also 03, 33	Data rate/Volume increase
41	Simultaneous frequency coverage	B2+3	New capability	Some research	Moderate	As B2	Saves a 4K cryo slot for B11	Downtime for installation
42		Multi freq. feeds	×2 ?	Research	Moderate	SLEDs, multi-transition studies	Requires system wide modifications	Data rate/Volume increase
43		Dual feed use?	×2 for large scale mapping	Quick?	Low to moderate?	Galactic GMCs, nearby galaxies	Requires system wide modifications	Data rate/Volume increase
51	Imaging quality and calibration	Deconvolution, combination software	Important for extended /complex srcs.	Quick, some research	Low	Complex sources	Need to understand the best way to add 12m array with ACA	None
52		Better phase calibration	~10-30%, maybe more at high freq.	Research	Low	High frequency, high resolution (e.g.,disks)		Data gathering
53		Better sidelobe calibration	Better image fidelity in mosaics	Measurements	Low	Large mosaics, bright sources		Data gathering

54		Better amplitude calibration	×2?	Calibration source	Low to moderate?	High precision line ratios, absolute calibration		Data gathering
55		Better passband calibration	Very high spectral resolution?	Noise injection device	Low	m/s velocity resolution		Data gathering
56		Better polarization calibration and purity		External wire grids, OMT development	Moderate	High precision/ dynamic range pol.		Data gathering
61	Flexibility	Subarrays	×2-3 speedup for shallow mapping or multifreq. or simultaneous multi-wl monitoring	More LO reference systems	Low	Galactic GMC, nearby galaxies, variable phenomena	Pretty much implemented	None
62		Increase in data rates	Resolution, archival value	Infrastructure	Moderate	Galactic, nearby gals., high time resolution	Increase in processing time, data transmission	Archive space and cost
71	Usability	Better automatic pipeline calibration and imaging heuristics	Better archival products, long term science value	Software	Low	All		None
72		Automatic Analysis and Enriched Archive	Added value products, cube descriptions	Software	Low to moderate	All		None
73		Visualization	Quick first look tools, better 3D visuals	Software	Low to moderate	Complex sources		None
74		Cube analysis tools (source finding, line ids, source decomposition, property measurements)	Better analysis for experts and non experts	Software	Low to moderate	All		None
81	Reliability & efficiency	Remote power recovery	Fast recovery from power or weather	Infrastructure	Low	All	Partially implemented	Increased efficiency, low cost
82		Upgrade of power delivery system	Increased reliability	Infrastructure	?	All		Increased efficiency
83		Cryo cooling improvements	Cheaper reliable cooling systems	Infrastructure	Moderate	All		Refurbish all antennas, downtime
84		Remote inspection for weather recovery	Fast recovery from weather	Infrastructure	Low to Moderate	All		Installing and maintaining cameras

00 Sensitivity Improvements

Lead author: Leonardo Testi

01 - More 12m Antennas

The third high-level ALMA science goal is to provide excellent imaging, which requires an optimized distribution of the antennas, a large number of baselines to effectively sample the Fourier plane and correction for imaging errors. Adding more antennas will improve the collective area of the array with two beneficial effects: improve the image fidelity and the overall sensitivity. This is a "brute force" approach, it would provide a very significant benefit only if we consider doubling the number of antennas (or use an even higher factor).

At the current stage, we would need to restart the antenna production lines, as well as all the hardware required to outfit the antennas. The array was designed for 64 12m antennas; the baseline correlator accommodates that number of antennas. The configuration was also designed for 64 antennas, differences with the current 50 antenna design are mainly in locations in the compact array, thirteen 64-antenna configuration pads were not built. The power consumption of the array will also scale linearly with the number of antennas. Owing to maintenance needs, only 47 of the 50 12m antennas in the main array will be available on average for high-resolution imaging. Two conclusions of an NRC committee[1] which investigated the effect of smaller numbers of antennas on ALMA performance were that (a) the Level One goal of high-contrast imaging of protostellar disks could not be met by an array of 50 operational antennas and (b) that image fidelity would be degraded by a factor of two with such an array compared to the planned 64 antenna array. An additional 4-6 12m antennas added to the current 50 antenna complement of the 12m Array would increase sensitivity for the 12m Array by 8-13%, decreasing integration time by 17-27% and increase high resolution imaging quality by as much as a factor of two in image fidelity. All considered, most likely this will involve a cost per additional antenna very similar to the original cost in the construction project. The overall cost of doubling the array could be of the same order of magnitude or the whole original bilateral ALMA project (infrastructure costs will not be needed, obviously, with the possible exception of upgrading the power plant).

The ballpark number for the cost of one array element (fully equipped telescope) in construction is of the order of 10M$, but this figure may very significantly change for a new production run, depending on the number of elements to be produced and possible design/production changes. Experience indicates that building systems designed several years ago frequently requires redesign, as several of the original components will not be available in the market anymore and/or there are small numbers of specially fabricated components. This adds increasing risk and cost to

[1] The Atacama Large Millimeter Array (ALMA): Implications of a Potential Descope issued by the US Committee on Astronomy and Astrophysics (CAA) Board on Physics and Astronomy (BPA) Space Studies Board (SSB) (2005)

any future addition of antennas.

02 - More ACA antennas

The current number of ACA antennas (both 7m and 12m-TP) is based on the evaluation that approximately 25% of the projects would need zero-spacing data and it would typically take four times the time on the ACA to reach the required signal to noise level as compared to the main array (in the overlapping region of the (u,v) plane). These estimates were based on the analysis of the ALMA DRSP (see http://www.eso.org/sci/facilities/alma/documents/drsp.html) and on dedicated simulations. The current number of ACA antennas (both 7m and 12m-TP) is based on the evaluation that approximately 25% of the projects would need zero spacings and it would typically take four times the time on the ACA to reach the required signal to noise level as compared to the main array (in the overlapping region of the (u,v) plane). These estimates were based on the analysis of the ALMA DRSP (see http://www.eso.org/sci/facilities/alma/documents/drsp.html) and on dedicated simulations.

Increasing the number of ACA antennas would allow the ALMA observatory to speed up the short- and zero-spacing observations. Depending on the usage pattern for the ACA, this could be highly beneficial as the typical programs now require a factor 2-4 more time on the ACA than on the 12m array to reach the correct sensitivity level in the short spacings. The same cost considerations as in the expansion of the 12m array apply. Note that it would be likely necessary to expand the ACA infrastructure on the ground (pads and cabling). The ACA correlator will also need to be upgraded to handle the correlation of more stations, in addition to the current 16 inputs, designed to cover the simultaneous inputs of 12-7m and 4-12m antennas. The expected cost for each additional, fully equipped ACA antenna is expected to be approximately 8M$.

03 - New digital systems

One can envision different types of upgrades to the digital system, from the backend through the correlator. Sensitivity gains would be realized by reducing losses and improving digitization efficiency, allowing simultaneous correlation of more antennas (although the gain in this case would be limited to two additional array elements, including all 66 available antennas, unless the number of these is also increased), and allowing wider bandwidths to be used in connection with receiver upgrades. While the first two gains are incremental, the latter could be substantial. The scientific gain of significantly increasing the instantaneous bandwidth of ALMA by a factor N will be in improving the continuum sensitivity (~square root of N), allowing more efficient spectral surveys (~N), and enabling simultaneous observations of several combinations of molecular lines (this will depend on the exact IF arrangement of each new receiver bandwidth). These will all boost the science productivity for unit time on sky.

Note that the current ALMA Band 6 already offers a wider bandwidth (2x5GHz) than what the current ALMA backend system can digitize and transport. Bandwidth increases of factors 2-4 are technically possible in the receivers (and already studied and ready to be implemented in some cases, e.g. Band 9 upgrade to 2SB-16GHz/pol and Band 2-3 cartridge with 16 GHz/pol bandwidth).

ESO has done a very preliminary investigation of the cost required to improve the digitization and backend system to digitize and transport double the bandwidth. The cost is expected to be significantly lower than the original cost of the backends. In fact, considering that such an upgrade could occur on a timescale of ~5 yrs, there is scope for studying, prototyping, and possibly testing at the OSF on a 2-antenna interferometer a new digitization board that would provide better reliability, lower costs, and double the bandwidth. ESO is starting a study contract with Universite de Bordeaux to carry on a preliminary investigation and prototyping for these next generation digitizers. The impact on this upgrade on operations would be an increase in the data rate and data volume from the array (it the digitizer and transport upgrade is connected with wider bandwidths and a correlator upgrade). This is a significant consideration since the data rate is already limiting observations. A newly designed more modern system could have benefits in the maintenance area, the concept that Université de Bordeaux is developing could allow to replace several components of the current system with a new single electronics board, for example. Work is needed to study the impact and cost on the correlator of expanding the instantaneous bandwidth.

04 - 2SB B9/B10

The system temperature, which characterizes the sensitivity of the observations, is approximately (see ALMA memo 170 for a full treatment)

$T_{SYS} \cong f\,[T_{RX}+\eta_{SP}\,T_{SP}+(1-\eta_{SP})\,T_{SKY}\,(1-e^{-\tau})]\,e^{\tau}$

where f is 1 for a SSB and 2 for a DSB system, T_{RX} is the SSB receiver temperature, η_{SP} and T_{SP} are the spillover fraction and the corresponding temperature, T_{SKY} is the temperature of the sky, and τ is the optical depth of the atmosphere (τ=0 is perfectly transparent). This is an approximation that assumes equal gain and T_{SKY} in both sidebands for a DSB system.

Bands 9 and 10 are the only DSB receiver cartridges in the ALMA system. This reduces the sensitivity in interferometric mode as noise from the image sideband contributes very significantly to the overall budget. Moreover, in single dish mode the signal from the two sidebands cannot be easily separated, which leads to a number of problems when combining with interferometric observations. A two-sideband (2SB) architecture would suppress the signal and noise contributions from the image sideband. The gain in sensitivity by eliminating the noise from the image sideband can be substantial for spectral lines: typically a factor approaching 2 as the brightness of the sky is significant at these high frequencies, but it can be much higher if the image sideband falls in an opaque region of the atmosphere. For continuum the corresponding factor is approximately sqrt(2). For single dish observing, the line overlap and confusion from the image sideband would be removed.

ESO contracted NOVA at the end of 2010 to study the feasibility of upgrading the Band 9 cartridge to 2SB operations with an option of delivering 2 full 4-12GHz IF sidebands per polarization for a total of 16 GHz/pol. Such an upgrade would significantly improve the sensitivity and the instantaneous frequency coverage of the receiver. The study concluded that the upgrade is technically feasible and we have a design ready for implementation. Detailed costing needs to be evaluated, but the proposed upgrade scheme involves an in-situ replacement of some of the modules, with minimal impact on the other cartridge systems, making this a very attractive option for the future. An NRAO-funded study focuses on Band 10, for which receivers employing balanced sideband-separating mixers based on new-technology promise reduction in Tsys by a factor as large as 4 along with higher dynamic range (and calibration accuracy) and flat gain and noise characteristics over a full 4-12 GHz IF band.

05 - Lower noise Rxs

At frequencies below ~100 GHz, the existing ALMA Band 3 receivers and the current designs for Band 1 and 2 are just meeting the ALMA requirements, which are a few times the theoretical quantum limits. In the Bands 4 to 7, the current receivers are performing very close to the theoretical noise levels. At higher frequencies, sensitivity gains could be substantial (possibly a factor of 2 or even larger) but difficult to quantify without a dedicated study. In the above-mentioned study for the B9 upgrade, it was shown that it is now possible to produce reliably mixers with significantly better noise specifications than the ones that populate the existing B9 cartridges. Replacing all the mixers is however a significant cost and likely this makes sense only in the framework of a more ambitious cartridge overhaul that would also deliver a 2SB mode and 16GHz/pol useable bandwidth.

In the lower frequency bands, the preliminary results from a B2-3 study indicate that significant gains are possible by using very good performance MMIC devices for the whole band with less stringent cooling constraints (compared to SIS junctions). The removal of the 4 K stage in the insert could allow enough space for cold reimaging optics. The combination of better devices, the removal of warm optics, and a wider IF bandwidth (16 GHz/pol) would result in significant performance gains even in the Band 3 range. The cost of such an upgrade would be the production of a full set of Band 2-3 receiver cartridges (plus upgrades to the IF transport and correlator in order to process the enhanced bandwidth). The current limitations are thought to be in the development of sufficiently wide band and low noise temperature active MMIC devices. There are few foundries in the world that could develop these, and a few development projects are currently being carried out in USA and in Europe (in the framework of the Radionet3 EC-FP7 project) with good prospects.

06 – New technology Rxs

New technologies may allow leaps in receiver bandwidth or noise temperature. These technologies are more experimental than the ones discussed in the previous section, and thus require investment in long-term research.

An ALMA/NA funded study (Woody 2013) investigated the use of JPL TKIP (traveling-wave kinetic inductance parameter[2]) amplifiers for ALMA at 55-175 GHz. These amplifiers hold the promise of significantly improving the system noise temperature, particularly in the lower bands that are not atmospheric noise limited while simultaneously increasing the instantaneously available bandwidth on the sky. The current Band 3 receiver noise temperature could be reduced from ~5h/k, ~25 K, to ~2h/k, ~10 K and the instantaneous bandwidth could be increased from 16 GHz to >32 GHz.

[2] Eom et al, Nature Physics 8, 623 (2012)

Realizing these improvements, however, would require changes to some parts of the existing front-end cryogenics and receiver cartridges. A receiver based on TKIP technology has yet to be demonstrated.

A Band 6 NA study being extended investigates a redesigned superconducting mixer circuit in which the Nb/Al-AlOx/Nb SIS junctions are replaced with Nb/Al-AlN/Nb junctions. By using Nb/Al-AlN/Nb SIS junctions with a relatively high critical current density (JC), the junction capacitance can be reduced. With a modified mixer (embedding) circuit, this allows the RF bandwidth to be increased substantially if accompanied by increases in the IF transport system and eventually the correlator. For example, this can improve ALMA's speed for observing isotopic CO lines in B6 by a factor of 2-3 since they could be fit within the same observation. Improving the receiver noise temperature from 80 K to 40 K SSB would reduce Tsys by a factor greater than 1.4 over more than 88% of the observing time, and by a factor of ~1.8 under the best observing conditions. The corresponding improvements in observing time are factors of 2 and ~3, respectively.

10 Resolution Improvements

Lead author: Daisuke Iono

11 - Longer Baselines

Traditional VLBI measurements are so far limited to compact, non-thermal high-surface brightness emission such as synchrotron and maser. The addition of ~ 5 x 12m antennas within a 300km range of ALMA fills the gap between VLBI and the connected array, and it will realize angular resolution of < 1mas and with sensitivity to detect Tb < 1000K (i.e. the thermal universe). The baseline plan is to connect the pads through fiber-link and build five new 12m antennas equipped with the workhorse ALMA bands (e.g. band 3,6,7). Maximum delay (~ 1 msec) can be compensated within a buffer (~16 MB) of a new correlator.

The science case includes, for example, BH formation in SMGs, mass accretion processes onto AGN engines, imaging stellar photospheres, distance measurements to stars and exoplanet characterization through astrometric measurements of host star motion. The idea of the ALMA Extended Array is to add five additional 12-m antennas (or pads) within 300 km from the central cluster of ALMA. A completed concept study can be found at: Kameno, S., Nakai, N., and Honma, M. (2013), ASP Conf. Ser. 476, 409. See also http://alma-intweb.mtk.nao.ac.jp/~diono/meetings/EA_Development_Meeting/Program_files/Kameno.pdf. Note however that the relevant ALMA continuum sensitivity for 1 hour is about 20 uJy: we use the correspondingly corrected numbers below.

Conventional VLBI measurements so far are limited to compact, non-thermal high-brightness sources such as synchrotron radiation from AGN jets or maser from star forming regions, evolved stars, and circumnuclear regions of AGNs. The intermediate-length baselines up to 300 km will allow us to study the lower surface brightness emission, namely emission that are thermal origin; for example accretion of matter onto the super-massive black holes (SMBHs) of AGNs, or photospheres of nearby giants/supergiant stars. The high-z universe can be studied at 10-pc scale, allowing us to search for SMBHs in forming galaxies, which is ultimately linked to the galaxy-BH co-evolution scenario. The 1 hour continuum sensitivity is 20 uJy, which corresponds to a detection limit of Tb ~ 3,000 K (5 sigma) with an angular resolution of 0.6 mas at Band 7. This will result in a factor of ~20 improvement in resolution compared to the 16 km baseline array. This, of course, relies on integrations of 1 hour being possible for these very long baselines without self-calibration.

Some of the technical issues to be investigated are; (1) study of the feasibility of long coherent integrations on long baselines without self-calibrations (the data for 10 km baselines would provide a good starting point for understanding the properties of the atmosphere at the site. Further testing with specially purposed small remote antennas may be desirable), (2) understanding sub-mm coherence at long baselines (e.g. is the current central LO distribution accurate enough? how do we calibrate the phase?), (3) a detailed site survey for the additional pads, and (4) fiber connection at distance of > 100 km, (5) next generation correlator. The construction of the new pads could be done parallel to normal ALMA operation and should not interfere with it, but commissioning tests using the ALMA correlator must be done and will require some CSV time, once the new antennas and pads are installed. In addition, acceptance tests must be performed once the new antennas are delivered to JAO.

The estimated cost for installing 5 new antennas with baseline lengths of 300 km is shown below. The largest expenditure will likely be the new antennas, although infrastructure (e.g., roads) and fiber optics is also likely to be expensive. A mitigation plan could be to use the existing ALMA antennas and only build new pads, although in practical terms it means that the distant antennas will be removed from the usual configurations. To use existing ALMA antennas likely requires disassembling them for transportation and rebuilding at the new pads, rather than moving the antennas via the transporter. The best model for powering, maintaining, and servicing the distant antennas and the associated infrastructure will have to be studied. Another option to reduce the cost is to use VLBI-type recording to replace fiber connectivity. Fiber optics cabling to distant pads is likely an expensive item. Note that the planned LLAMA (the Large Latin-American Millimeter Array) antenna in the north of Argentina with a baseline of ~180 km to the ALMA site is essentially a step in this direction.

New Stations and antennas	19.7 MUSD/station x 5 = 98.5 MUSD
Fiber line/data transport	?? MUSD
New infrastructure	?? MUSD
Computing	2 MUSD/5 years
AIV/CSV/SE	6 MUSD
Management	2 MUSD

12 - Better Phase Correction

Accurate phase correction is a key part of interferometric calibration and imaging, as imperfect phase calibration will lead to poor image quality and affect the science interpretation. Better phase correction will result in higher fidelity imaging, and this affects all science. Based on the results from the latest CSV tests (Asaki, Matsushita et al.), the longest baseline that achieves the ALMA RMS spec [10(1+PWV) microns] is up to ~ 400m, even after WVR correction. A 2 km baseline currently achieves 70 micron RMS (PWV=1.3 mm, 333 GHz), which is still x3 worse than the ALMA spec. This is equivalent to saying that the observed visibility amplitude is reduced to ~90% of the true value, as the coherence is proportional to $\exp(-\sigma^2/2)$ where σ is the phase rms in radians (Thompson, Moran, & Swenson 2001).

Another finding is that the current WVR correction does not improve the phase RMS when the PWV is high (> 3 mm) or very low (< 0.5 mm). For high PWV conditions, this failure is probably due to the increasing optical depth of the 183 GHz water line monitored by the system. In low PWV conditions the atmospheric phase perturbations are probably dominated by the dry air component, to which the current system is not sensitive. The good news, however, are that the outer scale turnover of the structure function (e.g., Carilli & Holdaway 1999) appears to be at ~ 500 - 1500m, which means that the phase RMS will not increase significantly for baselines longer than ~ 2km (Matsushita et al.).

A simple mitigation scheme is to use fast-switching (with cycles of 10s), for which tests indicate that the RMS phase of baselines longer than 3 km meets the ALMA spec. The current baseline plan is to use both the WVR and fast switching.

There are several limitations to the current phase calibration system;

- The WVR system assumes uniform weather conditions among all antennas. That is, the coefficients derived for the WVR correction assume the same weather conditions for all antennas. This may introduce errors. A possible mitigation plan is to install new weather stations near the longer baseline antennas.
- The WVR only looks at the water vapor component of the atmosphere and the dry component is not taken into account. First and foremost, an evaluation of the oxygen sounder data is necessary. See http://www.mrao.cam.ac.uk/~bn204/publications/2010/2010-08-General.pdf
- We do not have a phase monitor at the site. Thus it is difficult to evaluate the phase condition before/during the science observation. An installation of a phase monitor system will allow us to characterize the phase screen (and possibly use the data for real time phase correction), and it will also help us in the decision making process of dynamical scheduling. Installation of 50 BS/CS antennas and associated equipment will cost ~0.1 MUSD.

13 - mmVLBI

The science case with the mmVLBI ranges from Galactic to extragalactic science and fundamental physics. Science cases include;

- Nearby supermassive black holes -- produce the first Schwarzschild-radius scale images of nuclear black hole accretion disks and jets, allowing astronomers to perform new tests of general relativity in a strong-field environment,
- High-resolution imaging of AGN jets -- understand the internal jet structure, the role of magnetic fields in jet launch and collimation, and connections with very-high-energy photon emission.
- Spectral-line VLBI of absorbing systems -- measure the chemical evolution of the universe over cosmic time and test whether the fundamental constants of nature are variable. In some cases VLBI may be key to separate a complex absorber into smaller systems, for example in the case of material in a gravitational lens absorbing against images of a background source.
- VLBI observations of masers -- refine estimates of the physical conditions and dynamics in the circum-stellar gas around young stellar objects as well as in the circumnuclear

environment of AGN.
- Astrometry -- clarify the structure of the Milky Way and obtain geometric distances to Galactic and extragalactic objects.

Phasing all the ALMA dishes together to allow ALMA to act as a single large VLBI aperture requires the array to operate in a specialized mode. This mode, however, will likely be commissioned soon as part of the APP (ALMA Phasing Project). Note that although the APP makes VLBI possible, it is not sufficient. In particular, the observatory would need to develop a VLBI network and an operations model that enables such observations. In particular, the ALMA paradigm of delivering "science ready" images to the user community would require developing a VLBI pipeline.

Associated developments also include new monitor and control software as well as low-level software for sub-system tasks necessary while doing VLBI, including post-processing software to calculate the antenna-based phases and delays to create a coherent sum of all antenna signals. An entirely new digital sub-system will accept the phased sum output from the ALMA correlator and process the data for recording on the new generation of hard-disk based VLBI recorders. These recorders will be located at the OSF and linked to the AOS by optical fibers via the planned AOS-OSF fiber bundle.

References:
"High Angular Resolution and High Sensitivity Science with a Beamformed ALMA" Fish et al.
"Phasing ALMA for (sub)mm-VLBI Observations" Doeleman et al.

20 Field of View

Lead author: Daisuke Iono

21 - Multi-beam Rx

One of the main weaknesses of ALMA is its small FOV (21” at 300 GHz). This is a limitation for surveys requiring large area mapping, such as galactic star formation regions, nearby galaxies, high-z surveys, Magellanic Cloud studies, and solar observations. For example, roughly 100 pointings are required to map the Hubble Ultra Deep Field at band 6. According to studies done by Y. Tamura (U. Tokyo), the expected number of mm/submm sources is ~600 after spending 500 hours on-source with the full array. This observing time will decrease by N_{pixel} for a fixed sensitivity, assuming the continuum bandwidth is maintained. Wide field of view will also be important in terms of synergetic studies with future instruments such as e.g. SKA, TMT, EELT. Hence the attraction to develop a multi-pixel array to obtain an instantaneous sky coverage increase by N_{pixel}.

A number of additional developments are necessary to realize the multi-beam receiver on the ALMA antennas. For example, wide-field high-z mapping for continuum or for line detection when the redshift is unknown need to use the full bandwidth of the correlator. A N pixel receiver also needs a N times bigger IF transport system and correlator behind to take full advantage of it for high-z mapping, since exchanging area for depth does not work: there are many more faint sources. For low-z molecular cloud mapping, by contrast, a strategy could be to do only a few lines at a time (or just one) and split the correlator among several pixels. Multi-beam heterodyne receivers have been developed in order to achieve fast mapping and high spectral resolution on single-dish telescopes. SuperCam, developed by the University of Arizona, has 8 by 8 pixels, is largest of such receivers so far [J. Kloostermana, SPIE, 2012].

ALMA has tight technical specifications based on scientific requirements and many engineering constraints (weight, size, thermal load, etc). A multi-beam receiver based on current heterodyne technologies faces a number of technical challenges. For example: design of optics, development and packaging of RF devices such as superconducting-based low-noise mixer or semiconductor-based low-noise amplifier, powerful and efficient local oscillator, thermal load reduction, and on-chip integration. These developments are band-dependent.

Some of the foreseen challenges are:

- Fitting the multi-beam optics though the cryostat window while keeping the polarization and aberration constraints.
- Fitting multiple sideband-separating SIS mixers on a 4 K stage within the thermal load allowances, or else developing low-noise RF amplifiers operating at the frequency of interest.
- Developing an LO source that can power the multiple mixers while preserving the phase noise requirements.

- Miniaturization and integration of the components to fit within the available real state.

Some of these challenges are discussed in detail in Appendix A. The discussion is based on studies done by T. Kojima (NAOJ), see
http://alma-intweb.mtk.nao.ac.jp/~diono/meetings/EA_Development_Meeting/Program_files/Kojima.pdf.
The offshoot is that considerable development work is necessary before multi-beam receivers are viable for ALMA. In addition to the technical challenges of building a multi-beam receiver, installation of this system in ALMA will require major upgrades in the sub-systems downstream, such as the IF/LO, ACD, Correlator, Data storage, and Software (online, and data reduction).

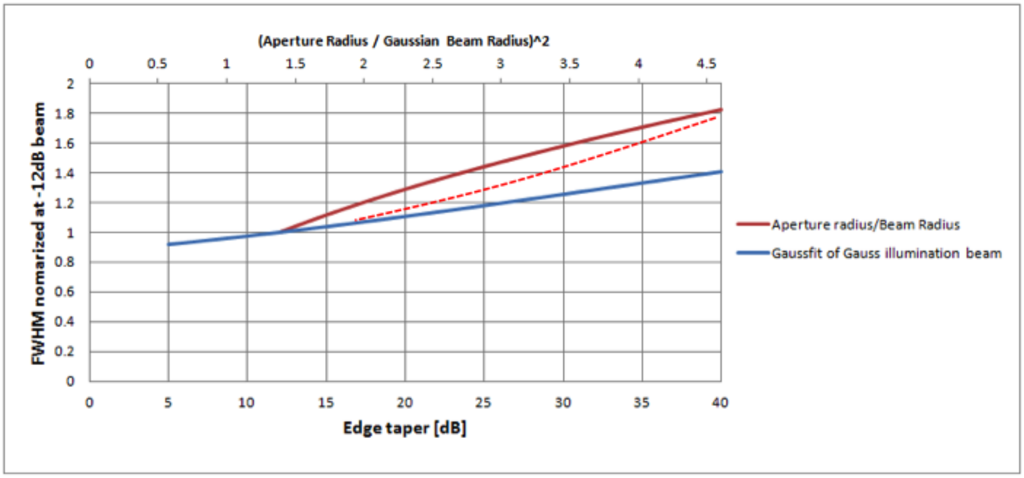
There are major operational implications to consider too. A major reconstruction will be required. A carefully designed plan is necessary in order to keep the array operation going but at the same time install the new system in parallel. It may be possible to keep 2/3 of the array operational while commissioning 1/3 of the antennas, spending ~ 1 year for implementation and testing (per 1/3 of the array) for a total of 3 years. The renovation of the correlator could occur simultaneously.

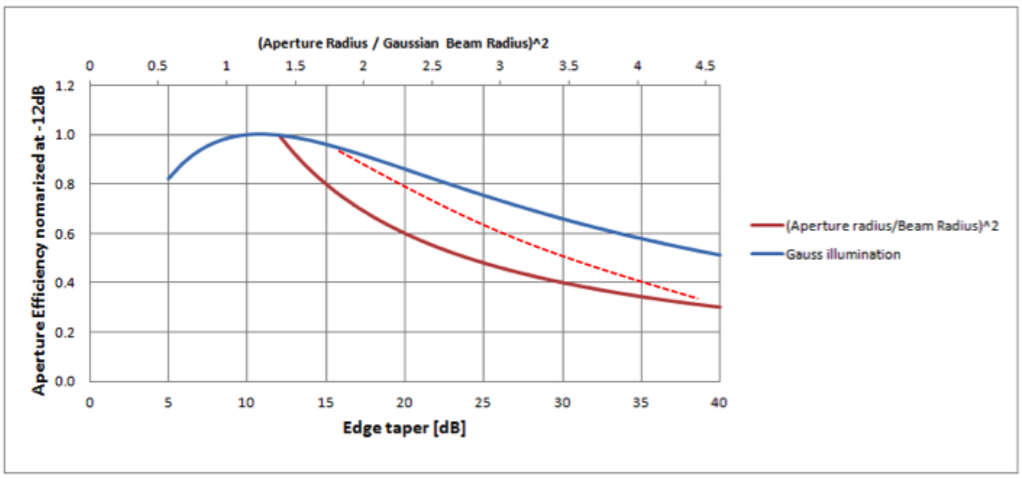
The precise estimation of the cost of a multi-pixel receiver is very hard, as it depends on the band, the technology, and the implementation (e.g., the number of pixels). A study that may shed some light on these topics is currently funded under NA and be complete in a year, but clearly further study is warranted. We can venture a very "order of magnitude" estimate by looking at the cost of a new ALMA band. The band 5 receivers cost approximately 30 MUSD, which is split approximately equally among development, components, and fabrication/integration. To first order, a multi-pixel system may require twice as much development, and the cost for components would be multiplied by the number of pixels. For example, a simplistic order-of magnitude estimate for a 9-pixel receiver in each antenna may be ~120 MUSD for receivers alone. Precise estimates require studies.

22 - Under-illuminated Feed

Another way to increase the FOV of the array is to introduce a lens in the system to under-illuminate the primary dish. The advantage of this method is in the low effort/cost required for its development. The disadvantage is the loss in sensitivity. Because of the loss in sensitivity, science cases will be limited to instances where the tradeoff between sensitivity and survey area is meaningful. Possible examples are large scale mapping of bright lines in Galactic molecular clouds, or observations of our Sun.

An under illuminated feed can produce a beam that is larger than a fully illuminated surface, at the cost of reducing collecting area (aperture efficiency) and sensitivity. Note that there is no gain in "short spacings" covered, since the antennas cannot be pushed closed together. The following plots and figures fome from a study by M. Sugimoto (JAO/NAOJ). Figure on the left shows the expected FWHM (normalized to the -12 dB beam) as a function of the edge taper [in dB], and the figure on the right is the corresponding sensitivity loss. Note that the real curve depends on the actual illumination pattern of the receivers, and it is likely close to the dotted line. For example, if we were to decide to increase the FOV to 1.8 times the current diameter, we have to change the illumination taper to 40 dB (in terms of Gaussian optics). In this case, the efficiency drops to 0.3 with respect to the current efficiency (which is ~0.7). Further discussion of the increased noise due to the insertion of a lens in the system can be found in Appendix B.





In terms of impact on the system, there would be some impact to the operation/CSV/control-software because the insertion of the lens will certainly change the focus. It may also affect the pointing, baseline, beam shape, and phase stability. Finally, we would also need to accommodate the loss of sensitivity in the sensitivity calculator and CASA.

The estimated cost for different design concepts is ~ 0.4-1.5 MUSD total. This includes components, labor, commissioning for pre-production studies, and production for 50 antennas

A variation on this idea is a combination of under-illumination and multi-pixel receivers. In principle it is possible to subdivide the collecting surface into patches illuminated by different pixels in the receiver. If cross-correlations were performed between the patches, this would also increase the short spacings coverage and the sensitivity to large angular scales. Unfortunately, this approach suffers from a number of drawbacks, including the large cost and complexity of multi-pixel receivers, the need for a very large correlator, and the unknown stability of the illumination patterns among others.

30 Spectral coverage

Lead author: Leonardo Testi

31 - Band 2

This is the last of the original ALMA Bands that is missing from the complement (considering that B1 and B5 are being developed/produced now). Completing this band will cover the full range of transparent windows at Chajnantor from 35 GHz through 1THz. The key science goals will be complex organic molecules and deuterated molecules in the Local Universe, high redshift low-excitation molecular gas and spectral surveys at high redshift. Design and prototyping of critical components and an overall design for this band, which could possibly end up covering the entire range from 67 through 116GHz with an instantaneous bandwidth of 16GHz per polarization, is actively being studied in North America and Europe. The cost for production would be roughly comparable to that of any other ALMA band (few tens of MUSD). The most critical item for such a broad band would be the performance of active devices, optics, waveguide and OMT. All these are actively studied and some of the risks on the passive components have been retired as part of a design/prototyping study carried over by a consortium of European institutes. More work is needed on developing the active and passive components for such a broadband system. In the meantime, NA has funded a 2014 development project with the goal of producing a traditional Band 2 receiver prototype, which will allow a determination of the costing and performance attainable for a Band 2-only receiver.

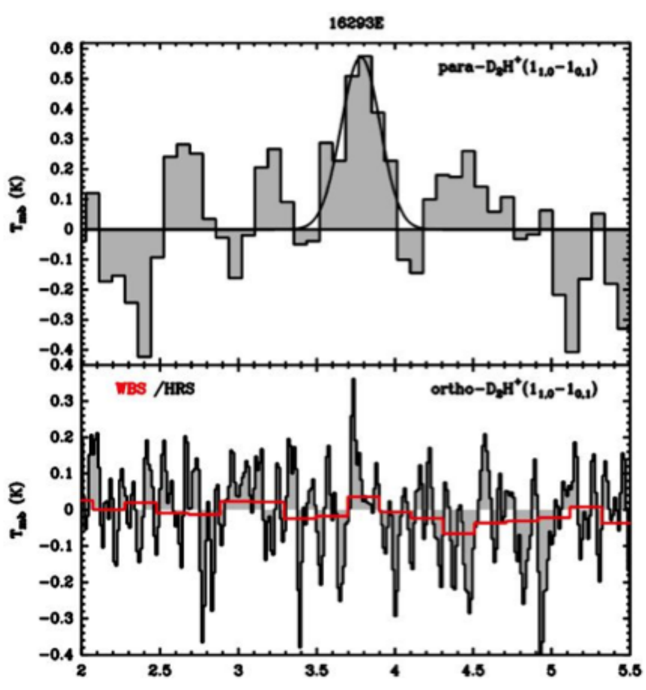
ALMA's two highest-level science goals are directly related to Band 2 science. The first is that ALMA should have 'the ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.' In the Milky Way at z~3, CO excitation and ALMA's frequency coverage identify the target line as the J=3-2 line at 86 GHz, in Band 2. In fact, ALMA covers this line through a late-construction expansion of the Band 3 frequency range. Since the enshrinement of this goal, the role of Dark Energy in the expansion of the Universe has become evident and the distance of a galaxy at z~3 has increased, making the 37 μJy line more difficult to detect (Baker et al. 2009). A receiver meeting the Band 2 specification of T_{rx}~30K will bring detection within reach. In 1 day of integration it would attain ΔS~15μJy, yielding 2σ per 100 km/s channel; in a galaxy with Δv=300 km/s it would achieve a 4σ detection in integrated intensity.

The second high level goal is that ALMA should possess 'The ability to image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.' Disk midplanes are the sites of planet formation, the main reservoirs of mass and probable sources of complex organics which may be incorporated into those planets. Furthermore, disk midplanes are cold—ices form and as ices are sticky good larger body seeds are available. To characterize disk midplanes requires access to range of low-energy lines of ions, deuterated molecules, isotopologues and organics. These lines are found in ALMA Band 2, making it a band of primary interest for investigation. With the 2SB dual 8 GHz windows provided by the prototypes currently being developed in both North America and Europe, both the deuterated lines and their ^{13}C counterparts would be accessible for study in a single science goal, subject to correlator constraints.

32 - Band 11

The original ALMA project had foreseen 10 frequency bands covering the millimeter and submillimeter windows up to ~1THz. Just above the ALMA original limit there are three transparency windows in the region 1.1-1.6THz that have reasonable transparency (up to 40%-50%) under the best conditions at Chajnantor. The APEX telescope has a receiver operating at 1.3THz demonstrating the feasibility of observing at these wavelengths, albeit only for a very limited number of hours per year. The key science goals of a Supra-THz receiver for ALMA cover galactic and high redshift astrophysics, two examples from the Science Case document by Rigopoulou et al. (2014) are briefly summarized below.

An ALMA Band 11 could allow, in combination with ALMA Band 9, the study of para/ortho ratio of the doubly deuterated of H_3^+, the key ion in the interstellar medium chemistry. The figure below shows measurements of the two forms of D_2H^+ in the IRAS 163296 protostar with the CSO and Herschel (Vastel et al. 2012).

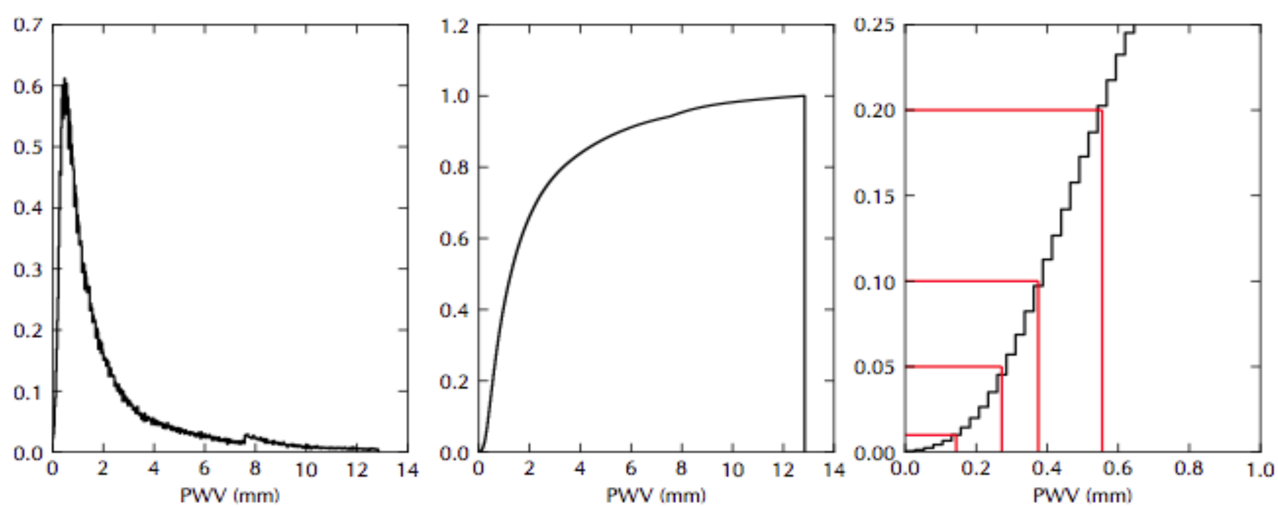


Band 11 will also allow us to investigate the [CII] line emission in intermediate redshift galaxies. This line, the major coolant of the cool ISM of local galaxies, has been proposed as a major probe of the star forming medium at high redshift. Band 11 will allow us to trace the [CII] emission in galaxies from redshifts 0.2 to 0.9, a critical phase in galaxy evolution when global activity winds down to present-day values. Band 11 will also allow us to cover the mid-infrared molecular hydrogen quadrupole lines (J=2-0 at 28.22 um, J=3-1 at 17.04 um) at very high redshift (z≥6), opening the possibility of probing directly the bulk of the warm molecular gas forming the first generations of stars.

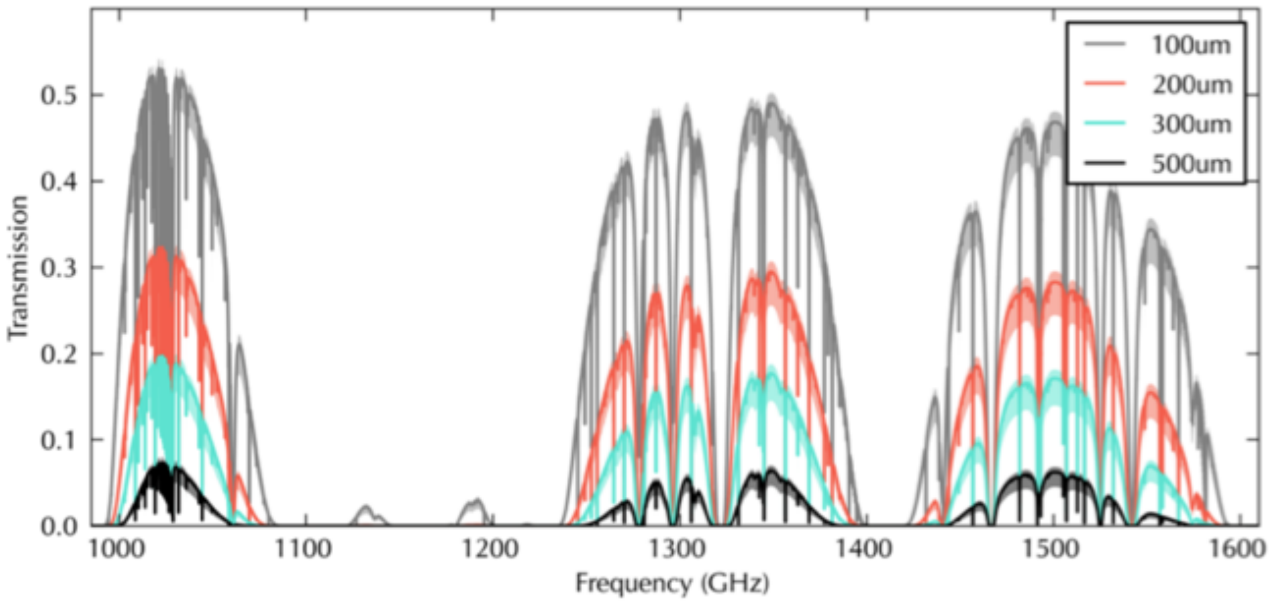
Initial studies are being carried over and the receiver cartridge appears to be technologically feasible. Such cartridge would require a space in the cryostat close to the optical axis of the system that is currently unavailable, but several options have been discussed. One possibility could be to see a development of a Band 11 receiver in the framework of a new focal plane system for ALMA. A second possibility is to replace one of the existing cartridges. For example, the combination of bands 2-3 into one cartridge powered by LNAs occupying the band 2 slot (see section 41) will leave the current band 3 slot available, which is connected to the 4 K stage and could be used for a high frequency cartridge (the currently open band 2 slot is not connected to the 4 K stage and cannot be used for an SIS system). This position, however, may be too far off-axis and introduce aberrations. A third option would be to develop a Band 11 receiver as part of a dual frequency cartridge. For example combining an upgraded Band 9 with Band 11 has been mentioned as an option. Although attractive in principle, such option would need to be studied in detail, due to the likely trade offs with other receiver performances (e.g., polarizations, bandwidth, power consumption). The cost of a Band 11 cartridge per-se would be probably at least similar to the full production run of either Band 9 or Band 10 (several tens MUSD).

Science cases for a Supra-THz band for ALMA and the required environmental and instrumental conditions for productive observing have been investigated in the framework of an ALMA Upgrade Study. The final reports are currently being written and will soon be available. These will also include some preliminary figures for the sensitivity that may be reached by a Supra-THz receiver for the ALMA array.

An analysis of the expected transparency conditions at Chajnantor was performed as part of the ESO funded European study on the opportunities for Supra-THz interferometry with ALMA. Analysis of precipitable water vapor at the site suggest that precipitable water vapor columns of less than 100um and 270um, should be achieved in 1% and 5% of the time respectively (averaged over the whole year). Experience with APEX operations at Chajnantor at 1.3 THz, show that these conditions are usually available during the June-August months. The histograms of water vapor content measured in the 1995-2004 period are shown in the figure below, no information exists about phase stability. The three panels show the normalized histogram, the total cumulative histogram and a zoom of the cumulative histogram on the best conditions. The availability of adequate observing conditions for a given array configuration will not only determine the time available for observations at this band, but also the pace of commissioning operations and the ability to appropriately calibrate the data.



The computed atmospheric transparencies in the Supra-THz region using various assumptions on the precipitable water vapour are shown in the figure below. High transparency in the 1-1.6THz windows is expected for pwv<200um (Graves et al. 2014).



33 – Extend Rx IF

The current 2SB receivers have an IF of 4 GHz in each sideband and polarization. This is a limitation of both the receiver design and the digital IF transport system. Extending the Rx IF would, when coupled to a new IF transport system, yield large improvements in accessible bandwidth. This instantaneously accessible bandwidth would permit, for example, simultaneous isotopologue observations (e.g., ^{12}CO and ^{13}CO are currently not simultaneously observable in B3, and only for very limited setups and narrow lines in B6) and a more intelligent placement of spectral windows. With an expansion of the correlator, these improvements would translate into factors of a few faster line surveys, line searches, and better continuum sensitivity.

The expansion of the available bandwidth can be done progressively. The first step is to plan for receivers with a broader IF. This is already the case for the Band 6, which provides 5GHz per polarization in each sideband. The Band 2(+3) prototype receiver prototypes being developed in Europe and North America will be capable of delivering 16GHz per polarization. Similarly, among the options that are being investigated for the Band 9 2SB upgrades, there is the possibility of broadening their instantaneous bandwidth while supressing the image sideband.

Wider IF bandwidth will immediately allow more flexibility in spectral line observing, without the need of upgrading the current backend and correlator systems. The full benefit of the wider IF will be obtained by upgrading the backend and correlator systems in order to fully use the available instantaneous bandwidth for continuum and spectral line use.

34 – Correlator

The current ALMA correlators are very versatile and capable of handling very complex low (continuum) and high spectral resolution modes. The full flexibility of the main array correlator with the tunable filter boards has not yet been fully exploited, and the ACA correlator is in principle capable of delivering even more complex modes. The main limitations in the medium-long term from the current correlator capabilities are in the ability to process all antennas together (although the current baseline correlator is in principle capable of correlating 64 out of the full set of 66 antennas), and the ability of processing completely more than 8 GHz per polarization, although linearity limitations have also been an issue in the testing of the single-dish capabilities.

Requirement SCI-90.00.00.00-00030-00 of the ALMA Scientific Specifications and Requirements document (ALMA-90.00.00.00-001-B SPE) requires resolution of a self-absorbed Gaussian line in gas at 10K, to measure infall motions in a prestellar core. The linewidth corresponding to this is 0.1 km/s. With a correlator mode (mode 31; ALMA Memo 556) providing a bandwidth of 31.25 MHz and 3840 effective channels, ALMA should achieve a resolution of 0.046 km/s at 3mm, using the as-yet unimplemented double Nyquist mode. In Band 7, one could achieve the goal but with the baseline correlator, ALMA falls short of meeting this target in Bands 1,2,3,4,5 and 6. Advances in digital electronics since the design of the baseline correlator may make higher resolution modes achievable through an upgrade in the correlator circuitry. It may also be possible to achieve faster dump time for the data--implementation of the correlator Frequency Division modes slowed dump times relative to those in the Time Division mode for some configurations. Investigation of this correlator upgrade should also be investigated through a dedicated study.

In the long term it would be interesting to investigate the possibility of upgrading the correlator to make use of the wider bandwidth receivers that are being developed. Possible options for upgrades of the correlator merit dedicated studies. Obviously the correlator is a major expense and it cannot be replaced on a short timescale. On the other hand, experience suggests that major correlator developments require a long timescale from conception to inception (~10 years), so it is never too early to start thinking about what the next generation may be like.

40 Simultaneous frequency coverage

Lead author: Alwyn Wootten

ALMA's cryostat will include ten receiver cartridges. Owing to its thermal budget, only three may be operated at one time. Changing to a new band that is not among those thermally 'ready' may involve tens of minutes, though switching to one of the 'ready' bands may involve only seconds. Simultaneous coverage is important to follow spectral energy distribution changes in, for instance, solar flares. For flares, one may configure ALMA into two (currently implemented) different subarrays, each observing at different frequencies. Other rapidly changing sources, from comets to AGN, may also benefit from simultaneous or near simultaneous observation.

There are several ways to extend simultaneous frequency coverage—one may extend the boundaries of an existing band or one may combine bands into a single cartridge in such a way as to effect simultaneous observations. Splitting the array into pieces to achieve simultaneous coverage means that each subarray will have fewer antennas, and hence poorer sensitivity and imaging quality for a given integration time. Furthermore, since the spatial frequency sensitivity is different for each array, the measurement of spectral index through comparison of images made with different subarrays is subject to uncertainty.

41 – Dual-band Receivers

Achieving a broader spectral reach through extending the boundaries of a specific band does not really achieve simultaneous frequency coverage. It may, however, allow the incorporation of different cartridges covering different frequencies into the dewar.

For instance, by combining ALMA Bands 2 and 3 and using a MMIC or other receiver, one could, possibly, cover the band 67-116 GHz in the Band 2 15K cartridge slot. This would free the 4K slot currently housing the B3 receiver for another band. One might, for instance, devote that position to a receiver covering some portion of the spectrum above the current upper receiver complement cutoff of ALMA at 950 GHz (Band 11). A disadvantage of this approach could be that the very broad coverage of the B2/3 receiver would pose challenges for polarization separation using ortho-mode transducers, this risk has however been retired by the ESO study which demonstrated two separate designs and prototype OMT and horns with excellent performances over the full B2/3 bandwidth. Current devices are also unable to achieve the superb performance required by ALMA in the limited Band 2 range, achieving the performance on the full B2/3 range will be even more difficult. This is important as some key science lies at the opposite ends of the B23 coverage—CO at the high end and deuterated molecules at the low end. Research would be needed in mixer technology and in polarization separation to design this broadband receiver. These possible limitations and tradeoffs are currently being studied as part of the activities in North America and Europe. Furthermore, performance for a high frequency cartridge using the current Band 3 slot might be compromised by its off-axis position—some coma may be present. Again, research would be needed into the technology of the high frequency cartridge as well as into the imaging characteristics of the off-axis receiver. While one would achieve broader frequency coverage, no single band in this proposal would likely be as sensitive as would be achieved in the lesser coverage achieved with receivers deployed as they are currently.

42 – Multi-frequency Feeds

An alternative method by which one could achieve simultaneous frequency coverage would be to employ two or more receivers within one package. One might, for instance, develop nested horns that could address harmonically related frequencies simultaneously—such as Bands 9 and 11 or Bands 7 and 9 for instance. NA received a proposal to study this but it did not get selected owing to referee skepticism.

Scientific advantages include the coverage of multiple frequencies, though the beam sizes would differ. Quite often molecular transitions are also harmonically related—one might observe several transitions of a given molecule, at quite different energies, with a single integration.

There would be some penalty in flexibility. The agility of placing windows in frequency might be compromised without careful consideration to design. Weather conditions suitable for one band might be marginal for another, restricting observation to the best weather in the most atmospherically compromised band.

43 – Dual-feed Use

One might double the sky coverage at a given frequency by deploying one of more feeds in the same cartridge. While this may provide little advantage for point sources, wide field imaging experiments would gain by approximately the number of feeds deployed. This development could provide throughput advantages for imaging of extended objects in our galaxy or in nearby galaxies. One possibility would be to allow independent tuning of the two feeds so that the target field could be imaged in two sets of frequency windows at once. Alternatively, one could achieve rapid spectral scanning by tuning the two feeds to cover contiguous bands. While there was a multibeam study proposal submitted to NA it was not approved over higher ranked studies. The cost of this development would intermediate between that of adding a new cartridge and the single cartridge itself.

50 Imaging Quality and Calibration

Lead author: Daisuke Iono

51 – Deconvolution and Combination Software

Radio synthesis imaging was revolutionized by the invention of the CLEAN algorithm, enabling synthesis imaging of complex objects even with relatively poor Fourier plane coverage. There are many different deconvolution algorithms in use but one aspect that is common to many of the best algorithms is the use of the multiscale approach. Examples of multiscale methods are as follows.

- Multiresolution CLEAN: The dirty image and point-spread-function are smoothed and decimated to emphasize the broad emission. The image resulting from CLEANing this dirty image is then used as an initial model for a CLEAN deconvolution of the full resolution image. An experimental version of this algorithm is already implemented in CASA.
- Multiscale Maximum Entropy: The performance of Maximum Entropy deconvolution could be improved by decomposing the image to be estimated into several channels of different resolutions. A hierarchy of scale sizes is specified and an image reconstructed by estimating pixels in the combined space such that the convolution equation is satisfied.
- Wavelets: Numerous authors have described the virtues of wavelet analysis and its application to deconvolution. Various authors have described an extension of the Maximum Entropy Method to wavelets as basis functions.
- Pixons: The Pixon method has been extended considerably, and the original algorithm drastically improved. Performance is extremely good, especially as measured by the statistical whiteness of the residuals. However, there has been no published success in applying the algorithm to synthesis observations because a key assumption, that the PSF is compact, does not hold for Fourier synthesis.
- Adaptive Scale Pixels: This has good deconvolution performance but is computationally expensive.
- Compressive Sampling: Compressive Sampling theory shows that under quite general conditions, a sparse signal can be reconstructed from a relatively small number of random projections (See Wiaux et al. 2009).

Possible developments would investigate implementation of these and other methods, with priorities assigned according to science demand. Research is required for understanding the basic theory, the application, and the algorithm.

Combining the data from the ACA and the 12m array: The feathering technique, which is already implemented in CASA, is being adopted for cycle 1 and 2. The feathering technique adds the single dish and (the CLEANed) interferometer data in the uv domain and Fourier transforms back to the image plane for the final image construction. Other techniques that are commonly used are (1) linear addition of two images in the image domain, (2) non-linear algorithms (e.g. Maximum entropy method). The former is available in CASA as a Toolkit, the later is currently in an experimental phase and requires more testing with real ALMA/ACA data.

Reference: Cornwell, 2008, IEEE, 2, 5, p793
Stanimirovic, 2002, ASPC, 278, 375

52 – Better Phase Calibration

Accurate phase correction is a key part of interferometric calibration and imaging, as imperfect phase calibration will lead to poor image quality and affect the science interpretation. Better phase correction will result in higher fidelity imaging, and this affects all science. Observations at the high frequency bands often suffer from lack of nearby bright, unresolved calibrators. The idea at ALMA is to transfer the phase measured at band 3 to higher frequency bands measured (almost) simultaneously. Current limitations are, for example, (1) it takes ~1.5 seconds to switch between bands, which can be a significant overhead, (2) lack of the general understanding of the phase screen and atmosphere. Another limiting factor could be the accuracy of the antenna positions. The accuracy of the baseline determination is currently xx microns, and the ALMA spec for baseline accuracy is 65 microns. Improving the calibrator database in terms of sky coverage and flux monitoring is also a long-term goal of the project, especially at the high frequencies.

53 – Better Sidelobe Calibration

Even if phase calibration were perfect and atmospheric effects were completely removed, image fidelity (defined as the difference between the "true" intensity distribution and the result of the imaging process) would quickly hit the limitation imposed by the imperfect knowledge of the telescope primary beam. This is a particularly key limitation for sources that are extended with respect to the primary beam and thus require mosaicing. Given the size of the ALMA field-of-view at high frequencies, this is a potentially important limitation for a wide range of observations.

There exist computational approaches that allow the inclusion of information about fully sampled voltage patterns for each antenna into the imaging process, but they are not yet fully implemented and tested in CASA. These approaches are anyway computationally intensive, besides requiring good measurements of the voltage pattern for each antenna far away from the primary beam. A way to improve this situation is, for example, to more accurately measure the voltage pattern for each antenna. Another path is to pursue new algorithmic development to better and/or more quickly include the voltage pattern information into the inversion and imaging process, for example developing adequate approximations to simplify the calculations, or perhaps to develop specialized hardware to speed up the calculations. The relative costs and benefits of a better treatment of the antenna pattern need to be evaluated in detail.

54 – Better Amplitude Calibration

Accurate amplitude calibration at millimeter and submillimeter wavelengths is a difficult goal to achieve due to the temporal variability of the emissive and absorptive properties of the Earth's atmosphere and the lack of accurate astronomical flux standards at these wavelengths. ALMA Scientific Specifications and Requirements state 5% absolute and 1% (3% above 370GHz) relative flux uncertainties. Accurate amplitude calibration is essential in all science topics of ALMA, but it is particularly important in the areas of flux monitoring, and measuring of SEDs and SLEDs. The purpose of this development is to improve the accuracy of the amplitude calibration.

Bright sources with known model flux (e.g., planets and asteroids) are used for primary flux calibration. Quasars can be used as secondary calibrators. While this is defined as an observatory task, all cycle 0 projects had a primary flux calibration observation within each scheduling block. According to the CSV tests the repeatability of the current flux calibration measurement is of order few percent.

The current single dish (ACA TP) calibration scheme uses the 2-temperature load calibration device (ALMA Calibration Device). This yields the system temperature, and allows us to convert the correlator units to Ta*. (See "ALMA Cycle 2 Technical Handbook v1.1" page 152 for equations). It then uses the "amplitude calibration observation" to derive the main beam efficiency and the size of the primary beam, which are both necessary to derive the Kelvin to Jansky conversion factor.

The system is reasonably good although it involves a large number of assumptions. (1) Planets/asteroids/moons are resolved on long baselines (or even in short baselines at high frequencies), and the accuracy of the planetary models limit the overall flux accuracy. (2) Quasars are time-variable and good models do not exist for high frequency. (3) Line emission and absorption (e.g., Neptune, Titan) needs a well-understood atmospheric model. (4) The accuracy of the flux calibration is also be limited by the primary beam shape and pointing accuracy.

Several developments for improving the amplitude calibration could be considered:

1. Better primary calibrator (planetary) models
   This is a research topic, and does not involve new instrumental development. Software development for implementing the new models may be needed.
2. More frequent flux monitoring of the secondary calibrators (probably not the best solution: lower priority). This also does not involve new hardware development, but requires more CSV (or "observatory calibration" time). Constructing an easy-to-use database may require a small-scale software development.
3. Atmospheric monitoring and modeling in order to correct for the atmospheric variation between the primary (secondary) calibrator and the target source. Better modeling may also require the addition of more weather stations, and an improve connection between the models and the parameters monitored.
4. Noise source calibration strategies and the associated hardware.

55 – Better Passband Calibration

For observations that require high spectral resolution, one runs into the problem of low signal-to-noise in the traditional use of an astronomical source for bandpass calibration. For wide-band observations, the knowledge of the calibrator spectral indices can be a limiting factor. Thus an immediate improvement may be possible by compiling a better calibrator database that contains a list of compact sources with known spectral indices. Characterization of the long-term variation and stability of the bandpass will also be beneficial. In addition, the bandpass calibration requires longer integration time for the ACA 7m array, which has smaller collecting area (currently, the 7m array uses ~ 10min for bandpass calibration, as a rule of thumb). One way to overcome this problem is to inject (early in the data stream) a common noise source that is well characterized to all correlations, which will possibly mitigate this problem. A similar method has been implemented and tested at the CARMA array. For the 7m array, another possibility is to implement the combined array mode, which cross correlates the 7m and the 12m arrays.

ALMA Memo 505 “Bandpass Calibration for ALMA” A. Bacmann (ESO) and S. Guilloteau (IRAM/ESO)
CARMA Memo Series 55 “Bandpass Calibration and Stability” Melvyn Wright

56 – Better Polarization Calibration and Purity

The role of magnetic field in various astrophysical phenomena is often not clearly understood. This is in part due to the limited sensitivities and polarization capabilities of the current instruments. ALMA will probe deeper into the strength and the alignment of the magnetic fields, and although the capabilities are limited, polarization observations are offered in the cycle 2 call for proposals.

Polarization information from dust particles, Zeeman splitting, Goldreich-Kylafis effect, Masers, YSOs, etc, can provide extremely valuable insights into the strength and the orientation of the magnetic field entangled with the interstellar medium. This kind of measurement allows us to investigate, for example, the role of magnetic fields in star forming GMCs (the rapid or slow star formation scenario), starburst winds, nucleus of dusty active galaxies, and the Galactic Center.

Polarization calibration is currently done using an astronomical source, and already achieving ~0.1% accuracy on-axis which is satisfying the ALMA spec. Characterization of the polarization calibration accuracy at the 3dB edge of the primary beam is ongoing. One way to improve the calibration accuracy is to use an artificial noise source with well-characterized polarization properties. However, the polarization accuracy of the current noise source is unknown and improvements to its characteristics (including stability) may be necessary. Another way forward is to improve the performance of the wire grids (bands 7, 9, 10) and OMT (for other bands), or install an external wire grid common to all frequency bands.

Possibilities for further developments are

1. Properly evaluate the characteristics of the AOS artificial noise source. Initial studies are needed, and evaluate if better components are deemed to improve the characteristics. CASA development may be needed.
2. Component developments of better wire grids (B7,9,10) and OMT (other bands) will be needed. In such cases the initial research and development will be done at the lab. It is important to understand how the precision of the laboratory measurements translates into the polarization calibration.
3. Applying the off-axis D-term to the map (CASA development)

60 Flexibility

Lead author: Leonardo Testi

61 – Subarrays

The subarray capability is a means of obtaining simultaneous observations of different targets or at different frequencies. The number of subarrays available for ALMA is limited. Increasing the number of subarrays would open a number of interesting options for simultaneous observations. The sensitivity and image fidelity drops much faster than the gain in time by simultaneous observations. There are however interesting use cases of subarraying. A few potentially interesting cases could be to observe the Sun (e.g., providing simultaneous imaging of more than one FOV) or maser sources (if detailed, high-fidelity imaging is not required) with a very limited set of antennas and use most of the array for another program. Another use case would be simultaneous multi-frequency observations of highly variable sources (but these would need to be sufficiently bright). Finally an interesting application could be the use of a subset of the array elements as a phased array for pulsar observing or to participate in a VLBI session while the rest of the system continues standard observing. There could also be interesting technical and/or calibration use cases for additional subarrays. The cost of adding subarrays is relatively modest (assuming that no impact is expected on software and operations).

There is currently an NA approved project aimed to reinstate the full subarraying capabilities that were reduced as part of the rebaselining. The outlook at the moment is to be able to use 2 subarrays for ACA operations (total power and interferometry) and up to four subarrays with the main array.

62 – Increase in Data Rates

As it has been investigated in a number of ALMA memos, the current data rate is a limiting factor for the scientific throughput of the array. Data rates limit the spectral resolution of the observations, for example, and directly impact the use of archival observations for spectral line research (since the fall-back position is to limit the data rate by reducing the spectral resolution of spectral windows that do not contain the proposed main lines). These limitations will become more severe with long baselines operations and in some fast dump rate observing modes (like on-the-fly single dish and interferometry mosaicing) or high spectra resolution modes. This may become an even more critical limitation in the future if the system is upgraded to process wider bandwidths. It will be extremely important to perform a detailed study on the possibility of increasing the average and maximum data rates from the observatory and its implications for the software and archive systems.

70 Usability

Lead author: Alwyn Wootten

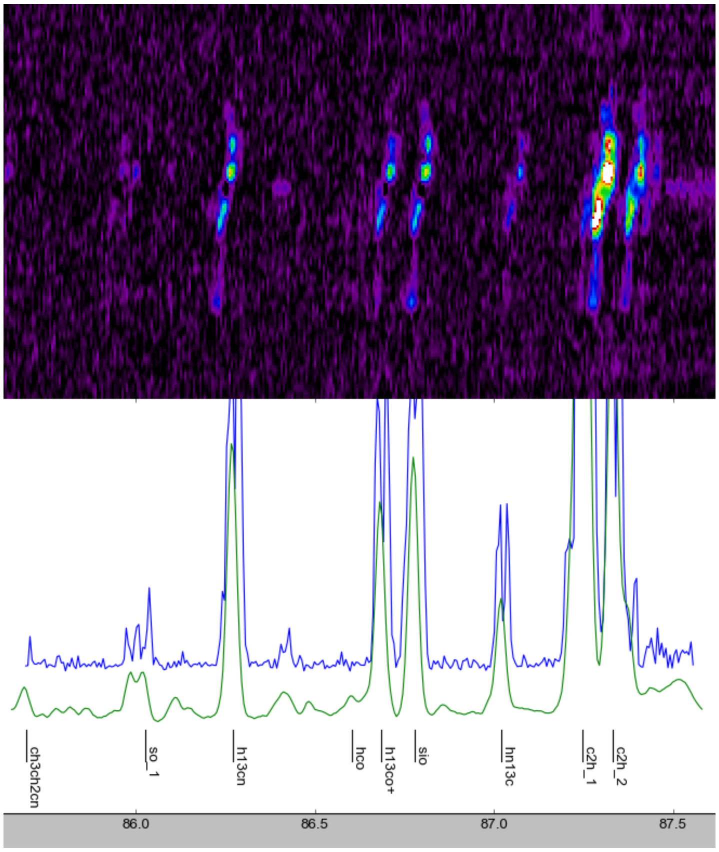
ALMA need provide the tools to find data of interest in an enriched, and forever expanding, data and software archive. These tools can either be operated remotely, if the size of the dataset is too overwhelming (but perhaps at the cost of limited interactivity or less flexible computing), or locally on a users "desktop". For more control, the user may use CASA packages and toolkits for analysis and modeling (pipelines), to explore the robustness of science results. Ideally these toolkits can be expanded on by the astronomer to create new analysis tools for the a wider audience.

71 – Better Pipeline Calibration and Imaging Heuristics

The Calibration and Imaging Pipeline is under active development, with calibration heuristics approaching levels suitable for initial deployment. Imaging heuristics will be improved substantially during development. It is envisioned that as pipeline heuristics improve, reprocessing of archived data is essential and will be supported. The content of the archive will therefore improve as heuristics improve. While eventually, for instance, all of the spectral lines in an ALMA data cube will be imaged and archived, in the pre-pipeline era only the lines specifically requested in a proposal Science Goals will be imaged, archived and delivered to the investigator. It is anticipated that pipeline improvements to perfect imaging and calibration and to add new observing modes will be ongoing throughout the lifetime of the observatory. Experience with observatories such as *Spitzer* and *Herschel* shows that external effort and expertise can be very synergistic to the internal pipeline development. The role of Analysis Pipelines should not be underestimated. Ideally there would be a method to feed their results back into the archive, for example, detection of unidentifed lines.

72 – Automatic Analysis and Enriching the Archive

Each dataset may be characterized by its spectral content. Chief among these are the names of the spectral lines targeted by the PI. But ALMA's sensitivity and spectral grasp normally allow the inclusion of many other lines in the dataset, awaiting serendipitous discovery: a typical dataset for a bright source will contains tens to hundreds of lines that have not been specifically targeted in an observation but just happen to be detected. An automated program may hunt through the archival cubes, discovering other lines, and identifying them from a comparison to a catalogue such as that provided by Splatalogue. For the sub-cube containing the spectral line, image statistics could be calculated and attached to the line name. Small images of derived quantities such as spectral line peak profile parameters, moment images and other characterizing products could all be stored in the archive to provide fast access to information on the content of the data product cube. More complex (and interesting) descriptions of the dataset can be envisioned; for example a PCA-like data product pointing out which lines have similar distributions, an automatic source extractor and catalog, kinematic data products, etc. Thus the richness of the archival datasets can be made available easily. The key elements of this automated program are that it provides easy, organized, immediate access to the science data in the cubes, as well as tools for discovering and mining science from the data and efficient access to the science in archival data for data reuse.



Automatic line identification in an extragalactic datacube. The data are ALMA observations of NGC 253. The p-v diagram spectrum is shown in blue. The results of a cross-correlation algorithm based on the p-v diagram correspond to the green trace. High cross-correlation corresponds to identifiable spectral features, correspondingly labeled (from ADMIT toolbox).

To accomplish this, one might envision a post-reduction pipeline or toolkit that would create a detailed data overview including spectral search, line identification, moment maps, spectra, overlap integrals, and other images and browsable tables. These data overviews would be served from the ALMA archive. To explore these overview products software would be provided from the science portal or other repository. We envision this to be a python-based toolkit distributed with CASA for the user to examine, re-compute, and expand on the detailed data overview, or perhaps a client-server system. This would be the same toolkit that produced the archive data, but users can now improve on their results from their own workstation if data size allows this. Similar data products might be spread through the archive, related to different observing proposals. The post reduction pipeline toolkit should provide the structured environment needed to bring together archival datasets from multiple projects, analyzing and comparing them in uniform ways. In case of python, the astronomical community has already organized itself (e.g. astropy), and with a CASA interface in python an environment can be created to cover the whole range from basic analysis to sophisticated data mining. This Analysis Toolkit should also engender new analysis ideas by astronomers, which could later be adopted by the ALMA pipeline version. Thus not only data, but also software would be donated back to the archive. It is accurate to say that the richness of ALMA datasets opens a new dimension in the realm of archival value that radio astronomy needs to exploit to realize the full potential of the instrument. Projects and studies along these lines have been funded in NA (e.g., ADMIT) and EU.

73 – Visualization

The volume of data produced by modern astronomical instruments can be enormous. The process described above can begin to parse the dataset into individual components, each destined for analysis. Proper analysis of these data products begins with visualization of their content. The visualization stage is an important element to bridging the gap between the raw images and the scientific result. That visualization may be limited by available hardware, or by fundamentals of the software architecture. Given potential image data sizes of 50 GB to 1 TB (ALMA Memo 501), the current visualization solutions (e.g., the CASA Viewer, kvis, ds9, etc.) will be performance-limited by the hardware used to explore the data and many are fundamentally design-limited in their software architecture. One appealing way to visualize the data would involve dedicated servers running software optimized for the purpose. To address the need for exploring large data sets, an attractive approach is one where the visualization of the data is mediated through the ALMA science portal, and the computation required for visualizing the data takes place on dedicated servers using optimized software. Scientists may examine data anytime, any place, on any platform, in concert with one another simultaneously discovering hidden aspects of the data. Adaptive mesh imaging (e.g. voronoid tesselations) to deal with large data or VR (Oculus, Google Glass) environments could also address needs not met otherwise.

This suggests the development of a modular, plug-in architecture for a new viewer application, fusing the full feature set of the CASA viewer with a high performance independent viewer, capable of upgrade with fewer overheads. Using a web-based server located, for instance, at the archive site would enable fast visualization without the need to move large datasets over the net. NA has funded development along these lines. The software we contemplate would foster development of community plug-ins, increasing the depth of the available viewing options. Some form of interoperability with the aforementioned toolkit would seem an important feature to provide interactive components to this toolkit to empower the user during the re-analysis stages.

74 – Cube Analysis Tools

Astronomical imaging provides two-dimensional views of emission projected on the celestial sphere. ALMA's independently tunable spectral windows can provide a suite of image cubes each of which contains velocity information as its third dimension. Comparison of adjacent pixels and velocity channels allows software to identify structures within the data that may not be apparent when viewed in two-dimensional subsets of the data. Emission regions could be characterized by their chemistry --- identification of certain sets of lines that follow similar traces of position and velocity for instance. A viewer/analyzer could also predict, via excitation and radiative transfer software, the complete spectra of a suite of molecules for comparison to the data in order to characterize the physical conditions in the parcel of gas imaged. This argues for integration between the visualization and analysis tools, where each can utilize functions in the other. These tools need be flexible enough for an astronomer to write additional modules that will benefit others.

80 Reliability and Efficiency

Lead author: Stuartt Corder

81 – Remote Power Recovery

Even in circumstances when power generation is extremely reliable, occasional partial or complete power interruptions are likely to affect the array. Even a relatively short power interruption can result in weeks of lost time if cryostats warm up, particularly in the extended configurations which typically occur during the Winter months coupled with possible snow conditions. Temperature cycling of cryostats can also produce failures related to thermal stress and reduce the reliability of the system, and therefore it is best avoided. The payoff in terms of reduced system downtime and increased reliability can be very significant.

Remote start capabilities can provide the ability to recover power to the array elements in the event of a short power interruption (less than 2 hours). Most critically, the cryostats of the healthy array elements will keep vacuum and be capable of cool down in less than 24 hours (warming up causes gas particles that were trapped on cold surfaces by cryo-pumping to be released, degrading the vacuum of the dewar). Power outages of over two hours, due to the dependence on UPS systems, are likely to cause extended recovery efforts, although refinements could allow for intelligent detection and potential response to power events thus allowing a slightly extended lifetime for rapid remote recovery. These refinements, and potential reduction in the time to recover the compressor post power outage, may result in less lost time due to power events.

The basic remote start capability is currently being implemented. The potential impact of further upgrades is unclear and will depend on the combined performance of the initial implementation of the remote power recovery and work to enhance the stability and robustness of the entire power network. It is expected that in 2015 it will become clear how frequent failures are and how often these potential extensions would impact operations.

82 – Upgrade of Power Delivery System

ALMA generates power through turbines operating at 3,000 m of altitude. The power is sent to the 5,000 m plateau through high-voltage underground cables and distributed to the antennas and correlator through a network of underground cables, switches, and step-down transformers. Reliable power is crucial for the long-term health and stability of the observatory. Significant power failures mean destabilization of the receiver cryogenics and the controlled environment of the correlator, with the consequent increase in component failures. Furthermore, transients during power failure, or caused by bringing back the power, may damage electronic components. The operation of restarting the observatory after a major power failure is long and complex, and requires a very significant investment of time (a week or longer).

Several upgrades are being explored regarding the power system. The speed at which the power can be returned following an outage could be improved by including automatic starting of the start-up generator, which is required to restart the turbine power system. External monitoring of the turbines is also a potential way to improve reliability, perhaps providing a means to address problems before they become outright power failures. The need for such improvements will depend sensitively on the performance and understanding of the power system. Significant experience is being gained with the operation of the system and these gains have resulted in some solved problems, suggesting that the steady state performance is yet to be reached. Once steady state is reached a cost assessment would be required to handle residual problems and determine if there is a clear need for upgrades.

83 –Cryogenic Cooling Improvements

The cryogenic coolers of the ALMA front ends can in principle be upgraded with more modern equipment that could allow for operational cost savings (for example lower power consumption), increased reliability, and/or higher cooling power. There is an ongoing European study that is investigating the possible operational gains that could be achieved by upgrading the front-end cryostats.

84 –Remote Inspection for Weather Recovery

One of the greatest challenges to array recovery after weather events is the requirement to physically inspect each antenna. After the antennas have been shut down or stowed in the event of a weather emergency they need to be inspected for condensation, snow blockage, etc, before moving them away from the survival position. Detailed inspection is mandated in the warranty conditions and, as experience develops, some of it may not be ultimately necessary. Nonetheless there is a level of inspection that is reasonable and unavoidable. Because the antennas will eventually be spread over the entire plateau and transportation between them following weather events will be likely slow if at all possible, there is a clear need for a remote inspection system. This will become necessary once extended configurations (~separations of a few km or more) are scheduled during periods of probable weather events (June-August). Such scenario is planned starting in 2016, and remote inspection capabilities are thought to be critical for the long-term health of the observatory.

Remote inspection requires the use of a distributed camera network, possibly mounted at several critical locations in, on, and around the antennas. At a bare minimum remote inspection will require, high definition, steerable cameras mounted on the weather station masts (seven in total), and additional cameras on varying locations along the arms and around the central cluster to allow visibility to each antenna from two sides. These cameras would need to be weather proof with quality zoom performance. If critical areas of the antennas and power infrastructure cannot be reliably secured from moisture and/or effectively imaged from remote stations, antenna mounted cameras may be needed. Additionally one or more cameras would be placed in every antenna, but these cameras could be of lower quality. It is advantageous to also install microphones in key portions of the antenna, for example close to the drives and the cold heads. They are inexpensive and low bandwidth, yet they can be used to quickly pinpoint problems such as a degrading drive. Automatic software can also be used to detect human voices or vehicles near far out antennas that may need additional security.

Detailed costing and benefit of this approach will depend on data currently being collected regarding the performance of the antennas in adverse weather conditions and the speed at which visual inspections can currently be done. Efforts to improve the latter are being made and tested, which will enable a definitive cost-benefit analysis for this improvement. Regardless of the outcome, antennas will continue to require visual inspection following adverse weather until the end of the antenna warranty period.

Appendix A: Multi-beam Receivers

1. Optics

There are several challenges for multi-beam optics in order to satisfy the current ALMA specifications:

1-1. Cross-polarization < -23 dBc
1-2. Defocus and distortion of off-axis beams
1-3. Small diameter of the cryostat window

In order to provide polarization separation capabilities, one of the two components must be used: wire grid or an OMT. Since a multipixel array horn aperture plane could potentially be quite large, the required wire grids are also expected to be too large, which makes the fabrication difficult and increases the cost. Using an OMT is a better solution, but the XsP performance of the receiver will be problematic. For example, the XsP in the current ALMA band 10 design is low because of the fact that the wire grid is blocking the cross-polarization of the feed horns. If an OMT is used, such as in band 4, there will be two new terms in the total XsP equation: XsP OMT and XsP horn.

$$XsP = XsP_{horn} + XsP_{OMT} + XsP_{mirrors} + XsP_{IRfilters/window}$$

This will increase the total system XsP, which will require the use of very good feed horns (a new design may be necessary). Moreover, there are currently no OMTs that are demonstrated at frequencies approaching 1 THz or beyond.

Another problem for a multi-pixel design is the small size of the cryostat window and the IR filter opening. The aperture is designed to avoid the truncation of a single beam. Avoiding the truncation of the off-axis beams will therefore be challenging. A possible solution might be the use of individual mirrors for each beam to slightly change the beam direction. This could allow all the beams to pass close to the center of the window. Proper illumination of the secondary would then be challenging.

2. Superconductor-based mixer or semiconductor-based RF amplifier

In radio astronomy, SIS mixers have been used because of the quantum-limited low noise performance. The problem of the current heterodyne receiver using the SIS mixer is that the size of the front-end system is too large to put multiple receivers on the 4-K stage of the ALMA cartridge. The ALMA receiver needs a sideband-separating mixer which consists of a number of cryogenic IF components such as a 90-degree hybrid, an isolator, and a low noise amplifier with wideband and low power consumption.

On the other hand, technologies of semiconductor-based RF amplifier, recently, are rapidly growing. RF amplifiers make the receiver system on the 4-K stage very simple because we can install the IF components at the other stages. Moreover, the semiconductor-based amplifier allows the operating temperature to be around 20 K. This reduces the thermal load to the refrigerator. By improving the fabrication process, Heterojunction bipolar transistor (HBT) and High electron mobility transistor (HEMT) in several currently available models exceed f_t(cut-off frequency) and f_{max}(maximum frequency) of 500 GHz. Using InP HEMT, comparable performance of low noise amplifier up to G-band (140-220 GHz) with SIS mixers was reported [Lorene A. Samoska, ISSTT, 2011]. For excellent and stable performance, finding the right manufacturer or a collaborator is needed.

3. Local oscillator power

For the multi-beam SIS receiver, the LO power required to drive each beam is proportional to the number of beams. If using a solid-state LO source for all beams, the power has to be efficiently divided and distributed to each device, because it is difficult to amplify signal that is higher than 200 GHz. Table 1 summarizes the required LO power per beam and the maximum number of pixels driven by the currently-used LO power P_{LO} in ALMA. The estimation reveals the number of operable receiver by the LO power is only 1 beam for frequencies higher than 500 GHz. Improvement of multiplier output power and increase of upper frequency limit of a power amplifier are needed. On the other hand, photomixing, quantum cascade laser (QCL) and Josephson oscillator technologies might be promising candidates as LO sources for the multi-beam receiver.

The photomixer can generate terahertz wave that corresponds to the difference of the frequency of two (short wavelength) lasers. The power of the lasers can be amplified using an Erbium-doped fiber amplifier (EDFA), which provides signal to each photomixer with enough power and low loss. Astronomical observation has been demonstrated at 1.05 THz for a single pixel receiver [I. C. Mayorga, et al., IEEE, 2012]. While this approach is promising, we will need to develop a more stable system for the interferometry in the future.

Radio emission by the QCL is based on the inter-subband transitions in the conduction band of the semiconductor hetero-structures. The important features are; powerful output power (over 100 mW), stable frequency, narrow linewidth, and in CW mode, which meet the conditions as an LO oscillator source for heterodyne receivers. One technical challenge which we need to solve for a multibeam receiver is developing the QCL with lower cut-off frequency. According to the paper by B. S. Williams [Nature photonics, 2007], the lowest output frequency remains at 0.85 THz at an operating temperature of 40 K by applying magnetic field.

Element		Frequency Band					
		150 GHz		500 GHz		900 GHz	
		2SB	2SB-BM	2SB	2SB-BM	DSB	BM
Junctions	(uW)	0.10		0.13		0.3	
Mixer chip	(dB)	-0.5		-0.5		-2.0	
Quasioptical Coupling		0		0		-3	
Coupler		-17	-3	-17	-3	-13	-3
3dB coupler (2SB)		-3		-3		0	
Waveguide		-6		-6		-2	
Subtotal	(mW)	44.2	0.9	57.5	1.1	29.7	3.0
Available LO power P_{LO}	(uW)	630		100		30	
Number of elements		14	714	1	87	1	10

Table 1 Required LO power for each frequency and mixer configuration
2SB: Sideband separating mixer, BM: Balanced mixer, DSB: Double sideband mixer

Josephson junction oscillator also directly generates submillimeter power by applying voltage (0.4836 THz/mV). This means that no low frequency power source is needed. In addition, it would be easy to integrate the oscillator with a superconducting mixer V. P. Kochelets, et al [SPIE, 2010] and it is also possible to individually supply LO power to the mixer. In order to apply this technique to a multi-beam receiver for ALMA, this system stability and the linewidth needs to be improved

4. Thermal Loads

Thermal loads in the ALMA cartridge on 4, 15, and 110-K stages are limited to within 41, 162, 850 mW. Table 2 summarizes the estimated thermal loads for each band. The largest heat load on 4-K stage is the low noise amplifiers (LNAs), and no more pixels can be added. The most important task is to reduce the power consumption of the LNA, and/or to move the LNA to the other stages. In this estimation, excluding the heat load from wirings, if the power consumed in the LNA is less than 1 mW, more than 10 LNAs can be added.

One of the approaches to reduce thermal loads on 4-K stage is to use a single stage as a preamplifier of IF signal. Since it would be difficult to control the gain for the single stage amplifier, two or three stage LNA to equalize the frequency dependence of gain should be put on the 110 K stage. In our estimation of the noise budget, the preamplifier with gain of more than 10 dB and noise temperature of less than 5 K on the 4 K stage, and the LNA with gain of more than 20 dB and the noise temperature of less than 20 K on the 110 K stage are necessary to keep the current cartridge performance.

The research and development on ultra-low power consumption and ultra-low noise LNA using semiconductor-based technologies is moving ahead and feasibilities of such LNA development for the multi-beam receiver have been shown. Chalmers University of Technology in Sweden has already demonstrated an InP-HEMT amplifier with power consumption of below 5 mW for three stages and noise temperature of 1 K [J. Schleeh, et al, IEEE, 2012]. California Institute of Technology has established and accumulated technologies as regard to development of cryogenic LNA. Recently they showed results of noise measurements of 1-20-GHz LNAs [Ahmed H. Akgiray, et al, IEEE, 2013].

Source of heat load	Band 4			Band 8			Band 10		
	4 K	15 K	110 K	4 K	15 K	110 K	4 K	15 K	110 K
Wiring Heat Load	3.1	16.6	32	3.1	10.2	17.3	6.4	21	28
LO waveguide	0.2	21	90	0.4	24	94			298
IF coax	1.1	44.5	132	1.4	27	102	0.5	22	70
HEMT amplifiers	8 x 4			8 x 4			17 x 2		
Multiplier			20			100			200
Summary (mW)	36.2	82.1	174	36.9	61.2	313.3	41	43	596
Dewar ICD (mW)	41	162	850	41	162	850	41	162	850

Table 2 Thermal loads in the ALMA cartridge

In addition to the semiconductor-based technologies, research on a superconducting amplifier is going forward. Recently, superconducting travelling wave parametric amplifier was demonstrated, which has features of quantum-limited low noise, low power consumption, wide-bandwidth with several gigahertz and high dynamic range [B.H. Eom, et al, Nature Physics, 2012]. This amplifier uses the nonlinearity of kinetic inductance of superconducting thin film. This makes it easier to integrate with a superconducting mixer. They also mention that the concept of this amplifier design can potentially be used for frequencies up to terahertz. On the other hand, operating temperature at 80 mK in the paper should be higher for the practical application such as ALMA.

5. Integration of devices and receivers

In the ALMA cartridge, a horn antenna, mixer blocks and other components occupy large area of 4-K stage. This is one of the critical issues which makes it difficult to increase the number of beams. In order to put more devices, the size of these components must be smaller. To this end, system optimization between devices and building of on-chip technologies would be needed, and then devices should be integrated.

One of the problems is the 50-Ω interface. For example, IF signals from the superconducting mixer unit are generally output to the 50-Ω transmission line and then input to LNA through SMA connectors. However, output impedance of the superconducting mixer is not always 50 Ω. In addition, input impedance and noise optimum impedance of the LNA are quite different and not 50 Ω. An isolator is usually used to match between them, but should be removed for integration. Therefore, an optimized design which is not limited by the 50-Ω interface would be needed.

An on-chip RF circuit takes advantages of the compact, low interconection and transition loss, and easy handing. Recently, an increasing number of studies on waveguide technology based on microwave and lightwave circuits, and application to submillimeter-wave exists. For instance, a substrate integrated waveguide (SIW) and photonic crystal waveguide are becoming available for (sub-)millimeter wave circuits. The SIW makes it possible to propagate the waves in the same propagation mode as a rectangular waveguide (M. Bozzi, 2009). Photonic crystal waveguide, which is basically lightwave technology, has no metallic loss. The device size and structure can be fabricated by applying microelectromechanical system (MEMS) technologies [A. L. Bingham, 2008). Even a corrugated horn array can be fabricated on Silicon [J. W. Brittona, 2010]. These technologies help receiver to integrate and reduce the size.

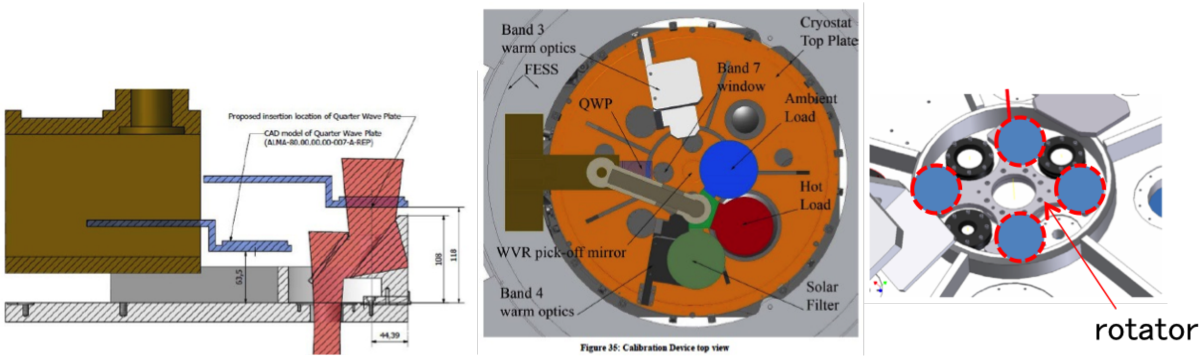
In summary, in order to construct the multi-beam receivers, significant modification to the current cartridge design is needed. Considerations not only from the engineering point of view but also from the research point of view are important. In terms of thermal loads, size and LO power, innovative improvements of component and device are needed. New technologies or adopting technologies developed in other fields will help. Discussion in different fields from radio astronomy, e.g. superconductor, semiconductor, MEMS, terahertz, telecommunication and photonics, will be important.

Appendix B: Under-illuminating Feed

Another factor that we need to consider is the sensitivity loss due to the insertion of lenses. The estimate is given in the following table (assuming a lens reflection of 1% and insertion loss of 2%). For example, the Tsys increases by 7% at band 7. Coupled with the sensitivity loss due to the under-illuminated feed, the sensitivity (AP_eff/T) will drop to 0.3*0.93 = 0.28.

Band	1	2	3	4	5	6	7	8	9	10
Tau0	0.01	0.0285	0.0261	0.03	0.0398	0.06	0.09	0.35	0.99	0.9
Trx no lens [K]	17	30	37	51	65	83	147	196	175	230
Eant	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
El [deg]	45	45	45	45	45	45	45	45	45	45
Tamb [K]	270	270	270	270	270	270	270	270	270	270
Tsys no lens [K]	53.4	77.0	83.9	102.1	123.8	157.0	256.2	579.4	1735.2	1713.8
lens eff	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Troom [K]	295	295	295	295	295	295	295	295	295	295
Trx with lens [K]	26.6	40.1	47.3	61.7	76.1	94.7	160.7	211.2	189.5	246.2
Tsys with lens [K]	64.3	88.7	95.8	114.5	136.9	171.1	273.5	607.1	1800.7	1778.2
Tsys(lens)/Tsys(noLens)	1.20	1.15	1.14	1.12	1.11	1.09	1.07	1.05	1.04	1.04

There are several ways to implement the lenses into the current ALMA receiving system; (1) using the quarter wave plate arm, (2) use the solar filter area of the ACD, (3) use a lens installer attached to a rotator. The advantage of (1) or (2) is that it only has a small impact on control. The disadvantage of (1) is that it can only be used for band 7. The disadvantage of (2) is that the solar filter will not be available. The advantage of (3) is that it can be used (for example) for four bands (e.g. bands 7,8,9,10), and the disadvantage is that it requires a new ICD to control, and additional costs to implement the stepping motors etc. A few examples of the Gaussian optics design are being considered.



[from left to right; (1) quarter wave plate arm, (2) solar filter area of the ACD, (3) lens installer attached to a rotator]