The Atacama Large Millimeter/Submillimeter Array[1] Development Program

Activity White Paper for Astro2010 Program Prioritization Panel

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and

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[2]The National Radio Astronomy Observatory, operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

[3]http://www.cv.nrao.edu/naasc/admin.shtml

[4]see membership at http://www.almaobservatory.org

Overview

ALMA will be in full operation by 2013; its results will begin transforming astronomy in 2011. Having invested ∼\$1.3B to realize the biggest advance ever in groundbased astronomy, it is vital to plan to keep the facility upgraded to maintain and expand its capabilities. When ALMA commences a program of Early Science, it will already eclipse any other millimeter/submillimeter array in its sensitivity and resolution by nearly two orders of magnitude. ALMA will operate from 3mm to 0.3mm across a decade of nearly complete frequency access broken only by the atmospheric limitations of its spectacular site. The ALMA Operations Plan envisaged an ongoing program of development and upgrade. ALMA's design (Wootten and Thompson 2009) allows for expansion of the 50 antennas in the 12m Array to a complement of 64. ALMA's wavelength coverage may be extended to cover 1cm to 200 μm, or a factor of 50 and an increase of more than 50% from its first light capability. With a modest investment of less than 1% of capital cost per year divided among the three funding entities ALMA will lead astronomical research through the 2010 decade and beyond. Several programs which spearhead a development plan have been identified by the scientific community.

• Four new receiver bands (italics, Table 2), most already accomodated in the ALMA design, increase its frequency span by more than 50%, an important asset to an instrument whose sensitivity allows it to address the questions of how the first stars and galaxies in the Universe were born, to measure the abundances of the first metals and to chronicle the development of isotopic diversity among the elements. Improvements to existing receivers can also increase observing efficiency in discrete bands.

• Additional antennas, included within the project scope and so provided for in its plan, from correlator capacity to configuration design, could increase the speed with which ALMA explores the cosmos. Both antenna contracts contain clauses by which the production line might be extended by an additional 7 antennas; exercising both would increase speed by ∼30%. No other improvements (*e. g.* improving signal digitization accuracy) can so significantly increase throughput across ALMA's frequency span.

• Very long baseline capability can tie other antennas' collecting area in with ALMA's to create a global telescope capable or delineating detail as fine as ten microarcseconds, allowing imaging of the black hole at the center of our galaxy.

Many of these programmatic items take advantage of recent technical advances, an example of which could be refurbishing the 3mm band with MMIC amplifiers. Others, such as building sensitive receivers at the highest frequencies will require development during the coming decade as detailed in a white paper on technology developmend for THz frequencies. In this document we provide scientific motivation for a suite of key science goals driving possible development projects, along with technical details.

1. Scientific Goals

In the total electromagnetic spectrum of the Universe, there are three major peaks. One, the biggest, is the 2mm peak from the 3K blackbody radiation relic of the Big Bang. That peak occurs in the millimeter wavelength range of the spectrum, as expected for any black body radiating at such a low temperature. The third strongest peak occurs near one micron wavelength: this contains the accumulated light from all of the stars and planets in the Universe. The second strongest occurs at about 1.5 THz or 200 microns wavelength. 1.5 THz radiation cannot penetrate the atmosphere, as it is absorbed by water and other molecules in the atmosphere–this peak was identified through satellite observations. This spectral feature represents all of the cool (∼200 K) objects in the Universe–clouds of dust and gas as well as radiation from warmer sources that is absorbed and reradiated. Although THz radiation is not easily accessible from the ground, for local objects emission from its longer-wavelength components may be examined from high dry sites on which significant apertures may be deployed. Furthermore, at redshifts of ∼1 the wavelength of the peak migrates to wavelengths below 1.5 THz, providing ground-based telescopes access to this important window on galaxy assembly and evolution. ALMA, with excellent sensitivity and resolution at a high dry location will allow sensitive and detailed imaging in the range 31-1500 GHz (wavelength ∼1 cm to 200 μm). Thus ALMA will observe within the regimes of the strongest two radiation peaks, to the extent that Earth's atmosphere allows. ALMA will image the cool thermal radiation which comprises most of the photons in the Universe, photons emitted by stars and planets during their formation processes, as well as warmer radiation from the distant Universe which is shifted into its range by the expansion of the Universe.

Extragalactic Science ALMA's enormous collecting area and superb site empower it with unparalleled sensitivity, a singular instrument for the exploration of the most distant parts of the Universe. Fortuitously, at the redshifts $6<z<15$ at which the first stars created the first metals, the strong forbidden lines of the most abundant of those first elements migrate through the ALMA bands. Oxygen and carbon are the most abundant metals produced by these first stars and fortunately both have lines detectable in this redshift range. The 157 micron [C II] line is among the brightest lines in the Universe, carrying ∼1% of the luminosity of the Milky Way and is the strongest line detected in *e. g.* the distant galaxy J1148 at z=6.4. [C II] emission at the strength of the line in Arp 220 could be detected in several hours by ALMA at z∼10, for which it lies in the 1.6mm band (if the complement of six available ALMA 162-211 GHz receivers were augmented to include all antennas). Other carbon carriers will also be detectable by ALMA, including [C I], CO, CH and CH^+. Strong atomic oxygen lines occur at 63 and 145 ([O I]) and 52 and 88 ([O III]) microns; these lines may be detected in several hour integration times to redshifts which reach the near edge of cosmic reionization. Together with OH and H_2O lines detectable at moderate redshift, these lines chronicle the production of metals over the course of the history of their creation. The metals also form dust, of course. Thermal dust emission provides an essentially distance-independent means of measuring galaxies to z$\sim$10 owing to the inverse K correction.

ALMA's resolution will allow it to produce detailed images of diverse emission lines as the first protogalactic structures evolve and the first stars enrich the Universe. ALMA will measure redshifts and can produce spatially and spectroscopically resolved images to reveal the kinematic, thermal and mass character of these structures. Star-forming gas emits strongly in lines of CO and other molecules (Solomon & vanden Bout 2005). Observations of CO monitor the kinematics of molecular gas; multiline studies provide excitation and mass estimates. Observations of HCN and HCO^+ trace dense gas intimately associated with star formation. Lower frequency coverage (31-45 & 67-90 GHz) reaches lower rotational transitions of CO, HCN and HCO^+ from modest redshifts to define gas excitation, low for tracers of very dense gas such as HCN and HCO^+ (Bussman *et al.* 2008).

The neutral gas also cools through emission in the fine structure lines. Comparison of line data reveal the state of the gas in regions spanning the gamut between cold dense star forming regions and higher ionization regions traced by atomic ions. Obtaining high spatial resolution on these lines in the far infrared (FIR) is hampered by limited collecting area aloft; as the lines redshift through the ALMA bands that problem is resolved. Extension of ALMA's frequency coverage through the submillimeter to the limits of the atmosphere and the instrument allows full use of ALMA's collecting area for imaging FIR emission brought into its range.

Primordial clouds of H_2 gas produced the first stars at 6<z<15. This molecular gas cooled via the lines of H_2 and HD until supernovae produced the metals which could more effectively cool the now-enriched gas. The H_2 S(0) 28 μm line enters the highest frequency proposed ALMA band, 1.3-1.5 THz, for z>5.5; the HD line for z>0.7. It is difficult to know what flux might be emitted by H_2, but if it is equal to that seen by Spitzer in the nearby Universe, ALMA could detect the line, opening up the dark side of reionization to study (Appleton *et al.* 2009).

As protogalaxies and protoclusters emerge they imprint the cosmic microwave background with a snapshot of their emerging structure through the Sunyaev-Zeldovich (SZ) effect. ALMA's excellent imaging quality will reveal detailed structure which traces the pattern of scattering by hot electrons in the nascent cluster. An optimal use of ALMA imaging will be to measure this fine structure in clusters identified by, for example, the southern hemisphere SPT and ACT experiments, now discovering new large samples of SZ clusters complementary to northern hemisphere clusters imaged by the GBT, EVLA and soon the LMT. Cooling spectral line radiation from these objects will be measured to determine redshifts and kinematics. As a catalog of primordial clusters is assembled, number counts will detail the growth of these structures with the evolution of the early Universe, allowing constraints on the early history of dark energy and dark matter. SZ imaging with ALMA would be accomplished with the lowest frequency windows, 31-45 GHz and 67-90 GHz, construction of which awaits ALMA Development funding.

As the heavy elements seeded the Universe, followed by their isotopologues, so too apparently grew the population of black holes. The growth of the first galactic mass black hole, is likely to be something that is invisible in radio synchrotron emission (*e. g.* from SKA observations) owing to CMB-quenching and invisible to JWST owing to extinction. One topical question is how the tight relationship between the mass of the stellar bulge component of a galaxy, and the central supermassive black hole was established. High-resolution observations of the obscured cores of feeding AGN at high redshift, incorporating dynamical information from ALMA spectral line data, provide a direct insight into this question. In terms of discovery potential, maximizing both sensitivity and frequency response for ALMA, the EVLA and the GBT are critical.

A primary science goal, ALMA can detect a galaxy like the Milky Way in [C II] in a few hours at z=3. It would be difficult to discover such a galaxy with ALMA alone. Complementary wide field surveys from large ground-based telescopes such as the Green Bank Telescope (GBT), the Large Millimeter Telescope (LMT) or Cornell-Caltech Atacama Telescope (CCAT) in conjunction with shorter wavelength studies from Spitzer, Herschel, WISE, Sloan-III, DOE Dark Energy Survey (DES), Pan-STARRS and LSST projects should guide ALMA targeting. As interesting galaxies extend across the full range of redshifts the ability to compare different samples on a like-for-like line-for-line basis requires rather complete frequency coverage. This is one reason why the first receivers planned for ALMA cover a contiguous spectral region.

The primary future needs for ALMA in the area of distant extragalactic astrophysics are sensitivity and bandwidth. Increased collecting area benefits all frequencies but is particularly important for weak spectral line signals from the early universe, as observing time shrinks as the square of the increase in collecting area. Completion of the receiver complement, in particular 31-90 GHz, 163-211 GHz and 1.3-1.5 THz extends ALMA's coverage, importantly at the extrema of its current frequency coverage. With all bands implemented, the range is extended by 50%, probing the fine structure lines which enter the upper range as well as the molecular lines which shift to lower frequencies.

Nearby Galaxies Accompanying the black holes, jets must have also made their first appearance. Acceleration of high energy electrons in radio galaxies imaged with the VLA/VLBA and at high energy have detailed interactions between jets and the surrounding ISM and IGM. ALMA's resolution and imaging capabilities should extend studies of relativistic synchrotron and free-free emission to southern sources, and from cooler, keV shocked gas. The mix of sensitivity and mm-wave performance will open a new window on these high-energy processes. One of the most exciting prospects would be to use ALMA as an element of a very long baseline array, which should allow imaging of the Sgr A* black hole at $\lambda \sim$1mm and reveal its inner structure (*c. f.* Event Horizon Telescope submission).

VLBI observations of Sgr A* offer the prospect of tracing the orbit of hot material at the last stable orbit before fueling the black hole at the Galactic Center. This work can only be carried out at wavelengths shorter than about 1mm: at longer wavelengths, interstellar scintillation blurs out the necessary size scales ($\sim$10 micro-arcsec). As a direct probe of the details of strong gravity, the equipping of ALMA with inter-element phasing, and VLBI clocks and recording equipment would add a powerful node to a breakthrough array comprising ARO, CARMA, eSMA and LMT, synergistic at 31-90 GHz with the VLBA, EVLA and GBT.

Mapping molecular clouds in nearby galaxies requires sensitivity and the full resolution of the array. Imaging compact HII regions and super stellar clusters in the process of formation would benefit from good atmospheric decorrelation correction performance on the longest baselines. Good imaging, particularly at high resolution, demands many baselines. As the number of baselines increases roughly as the antenna number squared, additional antennas, in addition to providing additional sensitivity, dramatically improve imaging at high resolution.

To map nearby galaxies, which extend over tens of arcmins, using mosaicking with the current baseline ALMA would require many hours, so that to match *e. g.* the STINGS/SINGS projects would require of order a year of observing time. Outfitting ALMA with the additional antennas provided for by its design would provide a ∼30% increase in observing speed at all bands. For specific lines, the development of multi-beam receivers would allow the full range of dynamics and environments to be captured in nearby galaxies more rapidly, as proposed for development by the CARMA group.

The addition of VLB capability, in addition to sensitivity and bandwidth upgrades, arm ALMA with the capability of measuring the black hole at our galaxy's center. Imaging of gas and dust in nearby galaxies is improved by sensitivity increases and by increasing throughput.

The Galaxy and Star and Planet Formation in Molecular Cores and Disks A second top-level science goal requires "The ability to image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc, enabling one to study their physical, chemical and magnetic field structures and to detect the gaps created by planets undergoing formation in the disks". This requirement drives angular resolution, since a disc of radius equal to Jupiter's orbit, for example, subtends only 0.03 arcsec at 150 pc. To meet this requirement, ALMA's resolution will be finer than this. To measure the chemical properties of the disk, one needs a wide bandwidth, capable of simultaneously measuring emission lines from many different atomic or molecular species. To measure magnetic fields, the system must be able to measure the resulting polarized components of the incoming waves. Polarization is typically only a few per cent, demanding high sensitivity and very accurate calibration with the optics design of the Front Ends. Development of dedicated polarimeter equipment such as rotating wire grids in the optical path just outside the vacumm windows would greatly improve polarization accuracy and could be done at relatively modest cost. Injection of signals of known polarization could also improve calibration. A mentioned above, both sensitivity and imaging capability are improved for very high resolution images most effectively by adding antennas to the array.

The innermost, and therefore hottest, regions of protoplanetary disks, with brightness temperatures of ∼300 K could be detectable on significantly longer baselines than 10 km. The availability of additional antennas, perhaps on modest VLB baselines analogous with the Pie Town antenna for the VLA, would provide a potentially valuable insight into the inner disk rocky planet formation zone. The innermost regions of the youngest protoplanetary disks, in which the optical depth might exceed unity even at 100 GHz, can be probed by observations at optically thinner lower frequencies, such as those covered by the 31-45 and 67-90 GHz bands. These science goals are complementary with the EVLA and GBT. Gains in speed to image interesting regions could be achieved most cost-effectively by implementing additional antennas which improve both sensitivity and imaging fidelity. The availability of longer baselines would allow even more precise imaging of masers in strongly excited regions–of particular interest is the widespread 183 GHz water maser (lying in skeletally equipped band 5), for which the clarity of the ALMA site offers unique scientific advantages.

As mentioned above, cool components of the local Universe emit most of their radiation around 1.5 THz. A new 1.3-1.5 THz band would enable more accurate measurements of the total luminosity of protostellar cores and nearby galaxies. In addition, this band could provide follow-up capability to line emission detected using Herschel-HIFI.

Important development goals for galactic and star/planet formation science include the addition of VLB capability and completion of the suite of receivers for ALMA.

The Solar System Observations longward of 200 μm can illuminate the character of planet formation and evolution. Advantages of this spectral region include low opacity, availability of extremely high resolution to reach planet formation scales, the ability to perform precision astrometry and to achieve high sensitivity to thermal emission (Wootten *et al.* 2009).

Observations of solar system objects would benefit from a variety of developments. Simultaneous multifrequency imaging whether achieved through subarrays or simultaneous multi-band capability, would allow maximizing throughput for observations of time-varying events, revealing outgassing and chemical processing in comets; varying asteroidal thermal emission, active solar region evolution and imaging of planetary winds. A 10km baseline at 350 microns corresponds to an angular scale of about 7 milliarcsec, or a linear scale of 50 km at 10 AU, the scale of the ice fountains of Enceladus. Direct molecular spectroscopic capability is difficult to achieve from small space probes, and no such capability is currently deployed. Longer baselines could detail revealing structures in moon outgassing, from the volcanoes of Io to Enceladus' ice fountains long after the demise of spacecraft orbiting nearby. Perhaps the most interesting solar system molecule is water. The high dry ALMA site provides access to the low excitation 183 GHz line in sparsely equipped Band 5, for which the atmosphere can be relatively transparent. Water and its isotopes may be imaged in detail with ALMA, revealing the water cycle on Mars, the origin of external water sources from Earth to the giant planets and the primordial composition of comets, which are principally water bodies.

Key development goals for small body studies include provision of VLB capability to enable astrometry down to tens of microarcseconds, the sensitivity to image on finer scales brought by additional antennas, as well as the availability of a complete suite of frequencies, especially 31-45 and 67-90 GHz, 163-211 GHz (for water) and 1.3-1.5 THz for thermal emission.

2. Technical Overview

ALMA consists of two parts. There is the array of up to 64 antennas of diameter 12 m and baselines extending from 15 m to ∼15 km, which here we refer to as the "12-m array". Although the scientific requirement is for 64 antennas, to realize its scientific goals, the contracts in place will provide at least 50 antennas. In addition to the 12-m array, ALMA contains the Alma Compact Array (ACA) which consists of four 12 m antennas plus twelve 7 m antennas (Iguchi 2009) with baselines extending from 8.75 m to ∼50 m. The ACA normally functions as an independent entity, acquiring short spacing data for projects requiring it. A summary of ALMA specifications and sensitivities can be found in Table 1 and Table 2.

Table 1. Summary of ALMA Specifications

Parameter	12m Spec	7m Spec
Number of Antennas	54 to 68	12
Antenna Diameter	12 m	7 m
Antenna primary focal ratio (f/D)	0.4	0.37
Geometrical Blockage	<3%	<5%
Antenna Surface Precision	< 25 μm rms	< 20 μm rms
Antenna Pointing Accuracy	< 0."6 rms	< 0."6 rms
Total Collecting Area	6600-7700 m^2	462 m^2
Antenna primary beam	17" x λ^a (mm)	30" x λ (mm)
Max (finest) Angular Resolution	0.015" x λ (mm)	5" x λ (mm)
Configuration Extent	150 m to 14 km	41 m
Correlator Bandwidth	16 GHz per baseline	same
Spectral Channels	4096 per IF	same
Number of 2 GHz-wide IFs	8	same

[a] λ indicates wavelength

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. 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[5] 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.

The most severe imaging errors are induced by turbulence in the Earth's atmosphere. In order to achieve the high resolution and deep sensitivity re-

[5]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)

Table 2. Summary of ALMA Receivers

Band[a]	Frequency (GHz)	T^b_{SSB} (K)	Configuration of Receiver	Continuum[c] ΔS (mJy[c])	Spectral Line[d] ΔS (mJy)	Beam[e] (arcsec)
1	**31 - 45**	*17*	HEMT	0.03 (0.023)	8.5	0.12
2	**67 - 90**	*30*	HEMT	0.04 (0.032)	8.5	0.06
3	84 - 116	41	2SB	0.040 (0.03)	7.0	0.038
4	125 - 163	51	2SB	0.06 (.046)	7.1	0.030
5	**163 - 211**	*65*	2SB	0.075 (0.059)	4.9	0.021
6	211 - 275	83	2SB	0.10 (0.075)	10.2	0.018
7	275 - 373	147	2SB	0.18 (0.14)	16.3	0.012
8	385 - 500	196	2SB	0.28 (0.02)	22.6	0.010
9	602 - 720	175[f]	DSB	0.62 (0.49)	62.1	0.006
10	787 - 950	230[f]	DSB	1.1 (0.84)	56	0.005
11	**1255 - 1565**	*375*[f]	DSB	*11 (9)*	*450*	0.005

[a] All bands provide two polarizations; Bands 1, 2, 5 & 11 are not included in the construction scope of ALMA, although six receivers for Band 5 will be provided through non-construction funding. [b] Requirement for 80% of the radio frequency band. [c] Bandwidth = 8 GHz, two polarizations. 50 antennas assumed with 64-antenna sensitivity in parentheses; 1σ for 60s integration given for nominal atmospheric conditions. One Jansky (Jy) = 10^-26 W m^{-2} Hz^{-1}. [d] Bandwidth = 1 km s^{-1} (equivalent Doppler spread at line frequency), two polarizations, 50 antennas. [e] Highest resolution. [f] DSB receiver noise temperature is given for Bands 9, 10 & 11. There are no specifications for Band 11; those given are illustrative only.

quired by the scientific goals, ALMA is being built at an altitude of 5000m in the Llano Chajnantor area about 50km east of San Pedro de Atacama in the eastern part of Region II in Chile. At this altitude, the average barometric pressure is only 55 percent of the value at sea level, ultraviolet radiation is about 170% of that at sea level and there is significant flux caused by secondary cosmic rays. The jet stream scrapes the Andes over the site, lending it a breezy character with annual 50th percentile winds of 10.4 m/s. The median annual temperature is -2.5^{o}C with a range of 20C above and below this. The antennas are exposed to these environmental extremes and have been challenging to build. The APEX telescope (Gusten *et al.* 2006), a modified version of the Vertex design for the ALMA prototype (Mangum *et al.* 2006), has operated on the site since 2005, proving the antenna design suitable for its environmental challenges. The surface accuracy of this telescope, of the two prototype antennas, and of the delivered production antennas, is about 17μm under nominal conditions, substantially better than the specification of 25μm. Such an accurate surface allows operation at higher frequency than originally planned–antenna costs are an important component of the budget, a fact which tempered specifications for the antennas.

The site affords both the long baselines and phase stability needed for exquisite resolution (see Table 2) and excellent transparency. Atmospheric testing was carried out at the site by multinational teams between 1994 and 2006. The testing campaigns also aimed at measuring site qualities needed for excellent submillimeter imaging: transparency and phase stability. Transparency at 225 GHz was monitored over the period (Radford *et al.* 2002); the 50th percentile zenith optical depth at this frequency is 0.061, which using atmospheric modeling, corresponds to a column of precipitable water vapor of a little more than 1 mm. With the low water column inferred from atmospheric modeling of these data and a more limited set taken at higher frequencies, observations are possible at the atmospheric windows covered by the two highest frequency receivers (602-950 GHz) for roughly half of the time. Even the super THz windows at 1.035 and 1.3 to 1.5 THz have been measured from Chajnantor (Peterson *et al.* 2003) showing transmission of up to 30% for about 10% of time. In fact, the APEX telescope has successfully observed in the upper window (Wiedner 2007) and a new receiver for these frequencies was recently installed there. The exciting science possible in these windows, ALMA's accurate antennas and the stable transparent site suggest that ALMA be instrumented for scientific observations in the atmospheric windows at 1.3-1.5 THz.

While the phase characteristics of the Chajnantor site are very good, some mechanism for atmospheric correction must be employed to use the longest baselines. Phase errors induced by variations in the atmospheric path length result from water vapor and from variations in the density of the dry component of the atmosphere. For ALMA, variations in the water vapor are monitored by measurement of the intensity of the radiation from the atmosphere in the 183.31 GHz water line (Hills 2001). Each 12 m antenna is equipped with an additional receiver and feed for this measurement. The width of the beam at 183 GHz is $\sim$33 arcsec. The receiver uses an uncooled Schottky-diode mixer as a double-sideband input stage, and the input is rapidly switched to measure the difference in noise temperature between the sky and a cold load[6]. The receiver passband covers approximately 175-191 GHz and contains four filters that provide measures of the peak value and width of the line (Hills 2007). These data are combined with other weather information to calibrate an atmospheric model that provides corrections to the observed visibility phases about once per second. The water line data are insensitive to the dry component of the atmosphere, which can be monitored by moving to a nearby calibration source at intervals of about five minutes. This provides a calibration of the instrumental and dry atmospheric phase components. This area is one of active research and development is needed for phase correction to reach its full potential (*c. f.* White Paper 'Adaptive Optics for Radio Interferometers by Woody *et al.*).

ALMA will have two correlators, one (ALMA Correlator) serving 64 elements comprised of either antennas of the main array of 12-m antennas or an array combined of these antennas with elements of the ACA antenna complement, or a second independent correlator (ACA Correlator) which serves the 16 elements of the ACA. To the observer, the two correlators offer nearly identical functionality and operate in a parallel fashion. The ALMA Correlator offers a great deal of flexibility; it is described in Escoffier et al (2007) and the ACA Correlator is described in Iguchi (2009).

[6]At the time of writing the testing phase of the atmospheric correction system is in progress, and the choices of techniques and parameters are not yet final.

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3. Technology Drivers

For implementation of additional antennas or for the planned bands, there are no key technology drivers. For 1.3 - 1.5 THz, sensitive wideband heterodyne detectors need to be developed (*c. f.* Kerr et al, **In Support of Instrument Technology Development for THz Astronomy** white paper submitted to the RMS and EOS panels). NbN and NbTiN are currently used for SIS mixers operating in the THz regime, but mixer performance is limited by the superconducting energy gaps of 9K and 15K, which constrain good performance to $\sim \nu <$700GHz and $\sim \nu <$1000GHz, respectively. New material systems are required for the development of SIS mixers in quantity operating beyond the limits of the current niobium-based technology. Promising new devices must be developed to realize a goal of near quantum-limited performance. Local oscillator sources capable of reaching THz frequencies need to be supported. Lastly, receiver technology can be improved in terms of sensitivity and in requirement for local oscillator power. These benefit array receivers also. Although array receivers for ALMA appear to be a distant development dream, all of these factors move astronomy closer to the day when array receivers on interferometers can take advantage of the investment made in collecting area.

Atmospheric phase correction and calibration accuracy are developments that will benefit almost all users, but especially those making images of faint targets at high-resolution. Developments that may be required include additional atmospheric monitoring tools, new calibration software, better site-specific weather/phase prediction tools etc. An increase in efficiency of the array by better phase correction, and a significant reduction in the number of tracks that have to be terminated because of deteriorating weather would benefit all science.

4. Project Organization

ALMA is a joint scientific venture between Europe, North America and East Asia, with participation by the Republic of Chile. ALMA operations will serve these communities in a way that distributes the burdens and benefits in a mutually agreeable way. The organizational structure for ALMA Operations is derived from the organization of the project for the construction phase.

The Joint ALMA Observatory is funded by the agencies ESO, NSF/NRC and NINS/AS, staffed by the Executives (the designated administrative organizations: AUI/NRAO, ESO, and NINS/NAOJ), and overseen by the ALMA Board, composed of representatives of the Parties (i.e. the funding agencies, the Executives, and the user communities). The primary function of the Joint ALMA Observatory is the operations and maintenance of the array at the AOS and the OSF near San Pedro de Atacama in Chile. The Joint ALMA Observatory also maintains the Santiago Central Office (SCO) to facilitate administrative and operational tasks that need not be done at the OSF, as well as to provide offices for the ALMA scientific staff during work periods scheduled for personal scientific research.

The ALMA Directors Office (ADO) is the focal point for operations management of the Joint ALMA Observatory. The ADO will be composed of the primary personnel: The ALMA Director (currently Thijs de Graauw), Head of the Department of Administration (currently Russell Smeback), Head of the Department of Science Operations (currently Lars-Ake Nyman) and Head of the Department of Technical Services (currently Richard Prestage). The ALMA Director leads the Joint ALMA Observatory and reports to the ALMA Board. The ALMA Board appoints the ALMA Director, and the remaining key personnel in concurrence with the ALMA Director.

In response to the ALMA Director's requirements, the Executives hire the necessary staff to perform ADO activities. All ADO staff that have functional duties that do not require a daily presence at the OSF are co-located in Santiago de Chile at the Central Office. Each member of the ADO is employed by one of the Executives.

Currently, ALMA construction is proceeding toward inauguration in 2012. Fourteen antennas are currently located at the OSF, of which two have been accepted by the project, have been outfitted with ALMA equipment and are undergoing further integration and verification under direction of the Joint ALMA Office. Some elements of ALMA have been transferred to the Operations team (buildings and transporters) which has been functioning since 2007.

5. Proposed Development and Operations Schedule

The ALMA Operations plan was first approved by the ALMA Board in 2005. After further revision, it was reviewed by both an NSF committee and by an international panel in 2007, which resulted in further improvements to the plan. ALMA Operations Plan Version D was adopted by the ALMA Board in October 2007.

Funding for ALMA Operations is provided by the funding agencies. The North American funding agencies provide 37.5% of the total, a sum which is matched by the European funding agency. East Asian funding agencies provide the remaining 25% of ALMA Operations funding.

Within North America, 92.75% of ALMA Operations funding is provided by the National Science Foundation, and 7.25% is provided by the National Research Council of Canada. The following table illustrates the development funding proposed from the United States for the 2010-2020 decade. Operations funding from 2015-2020 is projected to be constant in inflation-adjusted dollars. funding profile from the operations plan, NSF share, escalated to then-year USD: Continuing technical upgrades and development of new capabilities will be required to maintain ALMA as the state-of-the-art facility for millimeter/submillimeter astronomy over the course of its projected life of 30+ years. In particular, the rapid progress of electronic technology should make new hardware components and subsystems offering improved performance and higher reliability available for insertion into ALMA throughout the project lifetime. Equally important, advances in software and computing will offer improved performance and reliability that translate into more capability and reduced costs of operation. The tri-lateral project has recognized that continued hardware and software development are essential to keep ALMA up-to-date with the rapidly advances in these areas, thereby keeping ALMA at the forefront of astronomical research for its projected 30+ year lifetime.

Table 3. Summary of ALMA Development Federal Funding Profile

Fiscal Year	Proposed Development Funding
FY2010:	\$ 30k
FY2011:	\$ 476k
FY2012:	\$1124k
FY2013:	\$1995k
FY2014:	\$3533k
FY2015:	\$5129k

The ALMA Board agreed that:

1. ALMA is working on a science-driven long-range development plan. The planning started in 2008 with regionalized processes to provide community input to a set of science priorities for ALMA and associated developments. This planning is currently in process–the ALMA Scientific

Advisory Committee (ASAC) delivered a set of prioritized science-driven development projects in 2009 March. The Executives and JAO will work together to further estimate initial costs.

2. The Board, with input from the ASAC, will review the proposed development plan and provide policy guidance to generate a scientific vision with both long-term and short-term projects. An approved plan should be in existence by 2009. This will allow each agency to have access to a detailed long-range development plan that justifies their commitment to ALMA development. Once a project is in place, it is managed regionally in coordination with the JAO.

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