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

[1]The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.

Scientific Justification for the ALMA Developments

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 accommodated 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 development for THz frequencies. In this document we provide scientific motivation for a suite of key science goals driving possible development projects.

I. ALMA Band 1: 31.3–45.0 GHz

ALMA's lowest frequency Band 1 offers many unique scientific opportunities. As well as being a vital adjunct to the main ALMA science programs at higher frequencies, Band 1 would also bring to ALMA an observational community largely distinct from that at (sub)millimeter frequencies. Its observing programs can be carried out even in poor Chajnantor weather. Compared with the upgraded VLA (EVLA), ALMA will be 17 times faster for wide-field imaging due to its higher aperture efficiency, better site and larger primary beams. The key science arguments for Band 1 are as follows.

1. High-resolution SZ imaging of cluster gas at all redshifts

The Sunyaev-Zeldovich (SZ) effect, in which the cosmic background (CMB) photons are scattered by hot gas in clusters, is independent of redshift and an excellent tracer of cluster mass and physics, especially in combination with new X-ray data provided by Chandra and XMM/Newton. Dedicated SZ surveys from the South Pole and space will be done over the next few years at lower spatial resolutions of a few arcmin, but ALMA is unique in its ability to map the small-scale structure in cluster gas on tens of arcsec scales. Many hundreds of clusters will be detected by these surveys out to high redshifts, and will be available for ALMA follow-up. South Pole surveys, of course, produce targets suitable for detailed scrutiny with ALMA. The ALMA close-packed array with Band 1 is ideal for this purpose since it contains many short baselines and reaches tens of μK sensitivity in only a few hours.

ALMA will also be important in imaging the very small-scale CMB anisotropies, which occur in the power spectrum at multipoles of $\sim$10,000. At these scales, theoretical models predict strong CMB fluctuations due to local reionization by early bursts of star formation and due to the effects of massive black hole formation. ALMA is the only planned instrument capable of probing the CMB power spectrum on these scales and testing these poorly understood physical processes in the early universe.

2. Mapping the cold ISM at intermediate and high redshift

The reservoirs of gas from which galaxies form may be quite cool, even at moderate redshift z. Most high redshift CO searches to date have focussed on the J=4–3, 5–4 or 6–5 lines shifted to millimeter wavelengths. Because the CO levels with $J \geq 3$ require densities and temperatures well in excess of what is normally found in average giant molecular clouds, these data preferentially trace the gas associated with dense, actively star-forming regions. The low-lying CO 1–0 and 2–1 lines are the only way to trace very cool gas and measure the kinematics and redshifts of this gas. Band 1 provides an ideal means to probe this gas in the CO 1–0 line in the redshift range z=1.6–2.7 and in the 2–1 line at z=4.1–6.3. It also allows HCN and HCO^+ 1–0 lines to be observed in emission or absorption for $1<z<1.8$.

Of course, high lying lines of CO also lie in this band, witness the detection of the J=3-2 line towards J1148+52 with the VLA.

3 Excellent probe of very dense dust disks

Protostars can be surrounded by accretion disks of gas and dust, the birthplaces of planets. Cool disk dust emits thermal radiation in proportion to its opacity, which is in turn related to the grain size distribution and composition. Since Band 1 samples longer wavelengths, it samples larger grains and provides longer lever arm for the interpretation of disk Spectral Energy Distributions (SEDs).

4 Chemistry of heavy organic species, carbon-chains, anions

The 7mm band contains many of the strongest emission from heavy organic species such as glycine, prebiotic molecules which may play a role in the inception of life. Strongest emission from carbon chain molecules, including the recently identified anions, occurs in the 7mm band for moderate density and temperature. Are the band edges appropriately defined for the most interesting molecules? A transition of paramagnetic SO lies just below the low end; a strong transition of HC3N just above 4 GHz. Both may be observed by the EVLA but emission from both may be extended.

II. ALMA Band 2: 67–90 GHz

1 Redshifted lines

Note that the lower frequency end of ALMA Band 3, nominally 90 GHz, was extended downward to 84 GHz to partially compensate for the lack of Band 2 in the construction suite of receivers. Band 2 will cover the low-excitation CO 1–0 and 2–1 lines in the redshift ranges z=0.28–0.72 and 1.6–2.4, respectively.

HCO^+, HCN, HNC, N_2H^+ and the H_2CO resonance lines all lie within ALMA Band 2. These molecules are important indicators of the star formation environment in galaxies. The HCN 1-0 survey of Gao & Solomon (2004a,b) found a remarkable, tight linear correlation between $L^{'}$(HCN1-0) and L_{IR} over three orders of magnitude in L_{IR}. Linear correlations are also observed in other dense gas tracers including HNC J=1-0 and HCO^+ J=1-0. These particular lines may be observed in the present Band 3 out to redshifts of z∼.05. ALMA's sensitivity would allow measurement of these important high density tracers through Band 2, or out to z∼0.3.

2 Molecular resonance lines, deuterated molecules

The resonance lines of abundant molecules lie in the upper part of this band: HCO^+, HCN, HNC, N_2H^+ and the H_2CO resonance line lies near 72 GHz, at the lower end of the band. ALMA Band 2 also contains the lowest J=1–0 transition of many deuterated isotopomers of these molecules, making it possible to study the extreme deuterium fractionation processes found in the coldest gas.

Deuterated species in cold clouds are important diagnostics of the temperature evolution of the region. As ion-molecule chemistry can concentrate deuterium in molecules in cold regions by factors of up to a hundred thousand, deuterated species act as important diagnostics for the role of that chemistry. Resonance lines of the deuterium isotopomers of the abundant lines in the upper frequency portion of the band lie between 67 and 86 GHz. Lines of DCO^+, DCN, DNC, N_2D^+, NH_2D, NHD_2, HDO, and CH_2D^+ are available.

III. ALMA Band 5: 163–211 GHz

ALMA Band 5 covers the range 163–211 GHz (1.8–1.3 mm), which includes the strong atmospheric water absorption line at 183 GHz and its wings. Under excellent conditions at Chajnantor, the opacity in this line may go below unity, allowing observations of the line outside the atmosphere. Band 5 will be important for red-shifted [C II] lines in the range z=8-11. Moreover, it covers the H_2O 183 GHz and the $H_2^{18}O$ 203 GHz line. The 183 GHz line is a strong maser, but can also probe extended thermal H_2O emission under exceptional conditions. The 203 GHz line offers a unique possibility to image an optically thin isotopic water line from the ground at high angular resolution. Such studies would be important complements to H_2O studies carried out with the Herschel Space Observatory at lower angular resolution in the same timeframe. It is a crucial band to measure redshifted CO, [C II] and dust in critical redshift ranges. It also provides important opportunities for astrochemistry.

1. Photometric redshifts and [C II] of the most distant galaxies

In the Band 5 frequency range, the flux densities of high redshift galaxies of a given luminosity do not vary strongly with redshift. With the expected sensitivity, a $4 \times 10^{12} L_\odot$ galaxy located anywhere between $z = 1 - 10$ will be detected with $S/N = 10$ in ~ 1 hour in the thermal dust continuum. Bands 4 and 5 are particularly important for the determination of the spectral energy distribution of the highest redshift systems. At $z \sim 10$, the adjacent higher frequency Bands 6 and 7 probe only the peak of the dust spectrum, whereas at the lower frequencies covered by Band 3, the emission decreases too steeply to be detectable. To determine the photometric redshift, and eventually also the dust mass and temperature, the turnover frequency of the submillimeter emission needs to be measured, for which ALMA Bands 4 and 5 are uniquely suited.

Another significant use of Band 5 includes the search for the redshifted [C II] 158 μm emission line in sources with z ∼8-10, the principal cooling line of neutral atomic gas. It is thought that this range includes the epochs during which the earliest stars were enriching the interstellar medium with the heavier elements. As the medium became enriched, metal enrichment and the fine structure lines enabled primordial structures to cool more efficiently, changing the character of the early Universe. ALMA has the sensitivity to detect this line even at very high redshifts.

2. Evolution of normal galaxies up to $z \approx 1$

In normal field galaxies like the Milky Way, most of the molecular gas is in cold ($T \approx 10 - 20$ K) low density gas, in which only the lowest CO J=1–0 and 2–1 lines are significantly excited; observations of local galaxies show that even the J=3–2 line is up to a factor of 10 weaker. Band 3 contains redshifted CO 1–0 and 2–1 lines in the ranges z=0.0–0.4 and z=1.0–1.8, but the crucial range z=0.4–1.0, during which a strong evolution in star formation is known to have occurred from optical observations, is not covered. Bands 4 and 5 offer the opportunity to probe the mass, distribution, and kinematics of cold gas in disk galaxies in the critical $z = 0.4 - 0.8$ range (see Fig. 2).

3. Astrochemistry and galactic studies

The Band 5 wavelength range is known to be very rich in spectral lines in star-forming regions and in circumstellar envelopes of AGB stars, and is expected to be a key band for probing the chemistry of circumstellar disks. It contains the $J = 2 - 1$ transition of many simple linear molecules composed of 2 to 4 atoms of cosmically abundant elements, the fundamental transition of H_2S, important lines of H_2O, and lines of many linear carbon chain molecules C_nH as well as large organic molecules. In circumstellar envelopes, the conditions are such that the excitation of these heavy molecules peaks in Bands 4 and 5, so that this will be the prime band to search for rare molecules.

IV. ALMA Band 11: 1255–1565 GHz

The superterahertz band has not been included in the ALMA project, for which receivers were mandated for atmospheric windows for which transparency exceeded 0.5. Nonetheless, observations in the band from the Chajnantor site have been obtained with the APEX telescope, a copy of an ALMA prototype antenna; transparency may reach 35% in good conditions. While it would be premature to begin development of this band at present, we mention some high points of a science case for the construction of the band.

1. [C II] and [N II] emission from nearby galaxies

The brightest emission line in the spectrum of most galaxies is the 157μm [C II] line. Although the [C II] line does not enter the band for redshifts below about z$\sim$0.2, its strength provides an important diagnostic of atomic gas in galaxies. At present, the line must be observed from above the atmosphere, a locations where collecting area is limited. The line is a prime target for the Herschel spacecraft. ALMA's sensitivity and resolution would provide important keys to understanding the gas giving rise to the line.

Although somewhat weaker, the 205 μm N II] line occurs in this window. It is among the brightest emission lines in galaxies, tracing higher excitation conditions than the [C II] line. The line has been observed in galactic sources from single antennas on high Chilean sites.

2. Emission from distant galaxies. While a few important bright lines lie within the STHz window, one important aspect of it is that as bright lines are redshifted, this window covers the lowest redshifts at which we might see these lines in distant galaxies. **2. Critical molecular lines.**

Table 1. Summary of Important Atomic and Molecular Transitions at THz Frequencies

Line	Transition	Frequency (THz)[a]	Approximate Co. Chajnantor	Transmission Antarctica[a] (%)
$[OI]$	$^3P_1 \rightarrow ^2 P_2$	4.74	...	...
$[OI]$	$^3P_0 \rightarrow ^2 P_1$	2.06	2	18
$[OIII]$	$^3P_2 \rightarrow ^2 P_1$	5.79	??	38
$[OIII]$	$^3P_1 \rightarrow ^2 P_0$	3.393	9	60
$[CII]$	$^2P_{32} \rightarrow ^2 P_{12}$	1.901	1.5	20
$[NII]$	$^3P_2 \rightarrow ^2 P_1$	2.459	...	...
$[NII]$	$^3P_1 \rightarrow ^2 P_0$	1.461	32	??
$[SiI]$	$^3P_2 \rightarrow ^2 P_1$	4.38	5.6	35
$[SiI]$	$^3P_1 \rightarrow ^2 P_0$	2.31	2.7	27
$[SI]$	$^3P_0 \rightarrow ^2 P_1$	5.323	...	...
H_3^+	$1_{0,1} \rightarrow 0_{0,0}$	1.37^b	36	??
HD	$1 \rightarrow 0$	2.68	...	..
LiH	$3 \rightarrow 2$	1.329	30	??
H_3O^+	$4_3 \rightarrow 3_3$	4.31	10	??
OH	$^2\Pi_{12}J = 3/2^- \rightarrow 1/2^*$	1.83	11	40
CH	$^2\Pi_{32}J = 3/2^- \rightarrow ^2 \Pi_{12}1/2^*$	2.01	14	59
CH_2	$2_{2,0} \rightarrow 3_{1,4}$	4.93	18	..
CO	$17 \rightarrow 16$	1.96	15	..
SiH	$^2\Pi_{1/2}J = 5/2 \rightarrow 3/2$	1.11	...	...
FeH	$^4\Delta_i, J = 9/2 \rightarrow 7/2$	1.41	...	...
MgH	$N = 3 \rightarrow 2$	1.03	30	...

[a] Cerro Chajnantor (CCAT) transmission for 0.2mm PWV as shown in plot. Antarctic numbers for 0.1mm PWV from Townes and Melnick, PASP 102, 357 (1990). [b] Molecular Frequencies from http://www.splatalogue.net or CDMS

V. Additional Antennas

In the ALMA Scientific Specifications and Requirements (ALMA-90.00.00.00-001-A- SPE) requirement SCI-90.00.00.00-100-00 states that ALMA shall be comprised of 64 12-m antennas. In that document, this number of antennas is derived from the Level One Science Requirements as set forth in Annex B of the Bilateral Agreement. Each of the two bilateral partners signed a contract in 2005 each for the construction of 25 to 32 12m antennas. Following the rebaselining of ALMA, current plans call for the delivery of 25 12m antennas from each of the two contracts. Options for construction of additional antennas at fixed cost expire in summer 2009. In the interim, NINS (Japan) has joined ALMA, signing a contract for an additional four 12m antennas as well as twelve 7m antennas, to be sited in an Atacama Compact Array (ACA) and tasked with providing the wider field data needed to ensure that ALMA imaging meets its challenging goals. In this short paper we address the need for additional 12m antennas to be purchased under the options in the bilateral contracts.

Additional antennas restore capability to ALMA in two fundamental areas: (1) the sensitivity of the array is increased, and (2) the imaging capability of the array is improved. These two areas have been discussed by the ALMA Science IPT (1,2), the ALMA Scientific Advisory Committee (3,4,5) and by a committee appointed by the US National Research Council (6). Since most of these reports (1 and 3-6) were issued, the enhancement of ALMA by the addition of the ACA has improved the first of these areas somewhat. For a 50-antenna array, the 64-element correlator in only used at 64% capacity. A means of patching ACA antennas, when available, into the correlator has been implemented to the 64-input limit of its capacity. The additional collecting area provided by the 16 ACA antennas is the equivalent of an increase in collecting area of about 15%, or nearly eight 12m antennas (2). The entire complement of 66 antennas cannot be patched into the 64 station correlator. It is forseen that this mode will be most useful for increasing calibration accuracy of the smaller ACA antennas (2). Studies of the demands on the ACA for providing short spacing data to ALMA suggest that very little time will be available for the ACA to provide additional collecting area in this manner(2).

Furthermore, all antennas are unlikely to be available at one timein reference (6) it was assumed that a 50 antenna array would require the construction of 54 12m antennas, rather than of the 50 currently contracted. Most of the pre-rebaselining 64-antenna array calculations assumed a 60 antenna operational array, taking into account the fact that antenna availability would seldom reach 100%. Taking maintenance parameters from (7) one can show that at most 49 of 50 antennas are likely to be available for observations at any given time. ALMA plans to strive for an availability of 95% (number of antennas ready for observing at a given time as a fraction of the total number owned). For 50 antennas, this is 47.5. We estimate 47-49 12m antennas from the bilateral array could be available. We calculate that the collecting area of a combined array would be 90-94% that of a sixty 12m antenna ALMA; a given integration could take 19%-13% longer than with the full specified complement of operational antennas. Observations of time-sensitive events such as gamma ray bursts, supernova explosions or comet passages gains substantially from lessened integration time; surveys may be completed to a deeper level in a more timely manner. Given the ACA availability very little extra sensitivity may be realized for non-calibration observations.

The imaging capability of the array is improved by the addition of the ACA antennas in the case of low resolution images (2), but not for very high resolution images (1,6), as needed to satisfy the second and third elements of the Level One ALMA Science Goals. Imaging time-sensitive objects at fairly high resolution is improved by the addition of additional baselines made possible with additional antennas. For very high resolution images, 0.1 or better at 850 microns, baselines on the order of 2km are needed; baselines which can only be provided by configurations of the 12m Array. For high resolution images, fewer than 50 antennas may be available in the operational ALMA. Two conclusions of the NRC committee were that (a) the Level One goal of high-contrast imaging of protostellar disks is difficult to meet with an array of 50 operational antennas and (b) that image fidelity would be degraded by a factor of two with such an array. These conclusions are supported by study (1), which showed that imaging capability dropped rapidly as number of antennas dropped below 56. As the contracted complement of 12m antennas for ALMA is 50, the operationally available number of antennas could be 46-48, impacting ALMAs ability to provide excellent high resolution images.

The science capabilities of ALMA, while transformational, are limited by the current 50 antenna scope of the bilateral array. High resolution imaging is most at risk as confirmed by a number of studies. An additional 4-6 12m antennas added to the current 50 antenna complement of the 12m Array would: Increase sensitivity for the combined array by 5-7% , and for the 12m Array by 8-13%, decreasing integration time by 17-27% (2) Increase high resolution imaging quality by as much as a factor of two in image fidelity (1,6)

References (1) Image Quality as a Function of the Number of Antennas in ALMA. M.A. Holdaway (2005) (2) On the Scientic Benets of Cross Correlating the 12m Array and the ACA Daisuke Iono, Shigehisa Takakuwa, Ryohei Kawabe and B. Vila Vilaro (ALMA-J O?ce) (2007) (3) ASAC Report September 2004 (4) ASAC Report February 2005 (5) ASAC Report October 2004 (6) 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) (7) Array Operations Plan, Version D.

VI. Very Long Baseline Interferometry

Please see attached materials for the Event Horizon Telescope. Inclusion of ALMA in this long baseline high frequency array should enable resolved images of the galactic center black hole, and of that in M87.

VII. Additional Projects

1. Sideband-separating mixers for Bands 9 and 10

The ALMA installations for the receivers in Bands 9 and 10 are double sideband. For interferometry, the sidebands may be separated but for total power observations separation of the sidebands is more complex, requiring a process analogous to the 'CLEAN' image restoration in interferometry or other processes which have the effect of increasing noise. A single sideband system would remove this confusion. It would also improve the system temperature significantly by rejection of the atmospheric noise contribution in an unwanted sideband.

Observing time in the high frequency bands will be scarce, as good conditions occur about 25% of time at Chajnantor. Implementing this development could increase sensitivity by a factor of $\sqrt{2}$ (c.f. ALMA Memo Series for details).

2. Upgrade for Band 3

The 3mm band is the ALMA workhorse band, usable for primary science under most conditions and for calibration purposes with higher frequency bands. Although its early frequency range was set to 90-116 GHz, the low frequency end was extended to 84 GHz after it was realized that construction funding would not support construction of Band 2 (67-90 GHz). The SIS mixer design could be modified to employ a low-noise High Electron Mobility Transistor (HEMT) device, which would improve performance. If an improvement in receiver temperature of 10% were achieved, observing times could be reduced by about 30%.

In the current design, both sidebands are recovered, with a 4 GHz bandwidth in both. This design does not allow recovery of the main CO isotopomers in one setting. A HEMT implementation using an 8 GHz bandwidth could be used in an upgrade of the receiver; this would allow recovery of both isotopes with one setting.

3. Balanced mixer for Band 6

Although the 1.3mm band had originally been planned to cover a bandwidth of 8 GHz in either sideband, meeting the demanding ALMA specifications resulted in cutting this back to 4 GHz in both sidebands over an intermediate frequency range of 6-10 GHz (this is 4-8 GHz in other bands). This upgrade would optimize spectral line coverage. This band is important for line work because the associated dust will remain optically thin much further in toward the core of a protostar or AGN than it will at higher frequencies.

4. Backend equalizers

In the current design, when one switches between bands for phase transfer or other purposes, the attenuation also needs to be changed in the signal path. If instead one employs equalizers this problem is circumvented. Using equalizers in the ALMA BackEnd could improve phase transfer between bands, which ultimately will improve image fidelity as well as instrumental stability. This should result in an improvement in sensitivity for most ALMA bands of about 3-4%.

5. Maintain support for IS mixer foundries

Although the ALMA mixers are very good they have not yet reached the fundamental quantum noise limit. Current materials used at the higher frequencies are far from ideal as they operate above the fundamental band gap frequency for those materials. Continued research and development is necessary to push the technology to its fundamental limits or to develop new materials. Support for the foundries in North America which develop the technology is insecure. Some ALMA development funds should go toward continued support for these foundries, which supply mixers for all North American observatories.

6. Upgrade to data rate

The current standard data rate for ALMA is 6 MB/s, with a peak of 60 MB/s. However, the correlator can output data at a rate of 1 GB/s. To use the correlator at its full data rate would allow observers to obtain higher resolution data across the whole bandwidth that receivers produce at the highest spatial resolution.

Table 2. Summary of ALMA Bands and Science Targets

Band	Frequency Range (GHz)	Principal drivers
1	31.3–45.0	Sunyaev-Zeldovich imaging clusters, high-z cold CO, free-free/synchrotron/dust
2	67.0–90.0	Deuterated molecules 1–0, high-z cold CO
3	84.0–116	CO 1–0, bulk of low-exc. lines, high-z CO, SiO 86 GHz maser
4	125–163	CO $z \approx 1$, high-z dust SED, [C II] $z = 10 - 14$, astrochemistry
5	163–211	H_2O 183 GHz, $H_2^{18}O$ 208 GHz, [C II] $z = 8 - 10$
6	211–275	CO 2–1, bulk of med-exc. lines, dust SED, high-z CO + dust search, [C II] $z = 6 - 8$
7	275–373	CO 3–2, bulk of med-exc. lines, dust maps, polarization, [C II] $z = 4 - 6$, H_2D^+
8	385–500	[C I] 492 GHz, HDO 464 GHz, CO 4–3, [C II] $z = 2.8 - 4$
9	602–720	CO 6–5, high-exc. lines, dust SED, [C II] $z = 1.0 - 1.4$
10	787–950	[C I] 810 GHz, CO 7–6, dust SED, [C II] $z \approx 1$
11	1255–1565	[N II], dust SED, [C II] $z \approx .2$

[a] Bands 3, 4, 6, 7, 8, 9 and 10 are included in the ALMA baseline project, as are 6 receivers for Band 5.

Table 3. Redshifts for ALMA Bands for Important Atomic and Molecular Transitions at THz Frequencies

Line	Transition	Frequency (THz)[b]	B10 z		B11 z		Xmission [a] Co. Chaj.
MgH	$N = 3 \rightarrow 2$	1.03	0.31	0.08	-0.18	-0.34	30
SiH	$^2\Pi_{1/2} J = 5/2 \rightarrow 3/2$	1.11	0.41	0.17	-0.12	-0.29	...
LiH	$3 \rightarrow 2$	1.329	0.69	0.40	0.06	-0.15	30
H_2D^+	$1_{0,1} \rightarrow 0_{0,0}$	1.37	0.74	0.44	0.09	-0.12	36
FeH	$^4\Delta_i, J = 9/2 \rightarrow 7/2$	1.41	0.79	0.48	0.12	-0.10	...
$[NII]$	$^3P_1 \rightarrow^2 P_0$	1.461	0.86	0.54	0.16	-0.07	32
OH	$^2\Pi_{12} J = 3/2^- \rightarrow 1/2^*$	1.83	1.33	0.93	0.46	0.17	11
$[CII]$	$^2P_{32} \rightarrow^2 P_{12}$	1.901	1.42	1.00	0.51	0.21	1.5
CO	$17 \rightarrow 16$	1.96	1.49	1.06	0.56	0.25	15
CH	$^2\Pi_{32} J = 3/2^- \rightarrow^2 \Pi_{12} 1/2^*$	2.01	1.55	1.12	0.60	0.28	14
$[OI]$	$^3P_0 \rightarrow^2 P_1$	2.06	1.62	1.17	0.64	0.32	2
$[SiI]$	$^3P_1 \rightarrow^2 P_0$	2.31	1.94	1.43	0.84	0.48	2.7
$[NII]$	$^3P_2 \rightarrow^2 P_1$	2.459	2.12	1.59	0.96	0.57	...
HD	$1 \rightarrow 0$	2.68	2.41	1.82	1.14	0.71	...
$[OIII]$	$^3P_1 \rightarrow^2 P_0$	3.393	3.31	2.57	1.70	1.17	9
H_3O^+	$4_3 \rightarrow 3_3$	4.31	4.48	3.54	2.43	1.75	10
$[SiI]$	$^3P_2 \rightarrow^2 P_1$	4.38	4.57	3.61	2.49	1.80	5.6
$[OI]$	$^3P_1 \rightarrow^2 P_2$	4.74	5.02	3.99	2.78	2.03	...
CH_2	$2_{2,0} \rightarrow 3_{1,4}$	4.93	5.26	4.19	2.93	2.15	18
$[SI]$	$^3P_0 \rightarrow^2 P_1$	5.323	5.76	4.60	3.24	2.40	...
$[OIII]$	$^3P_2 \rightarrow^2 P_1$	5.79	6.36	5.09	3.61	2.70	??

[a] Cerro Chajnantor (CCAT) transmission for 0.2mm PWV . [b] Molecular Frequencies from http://www.splatalogue.net or CDMS

Table 4. 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.