Atacama
Large
Millimeter
Array

ALMA Scientific
Specifications and Requirements

ALMA-90.00.00.00-001-A- SPE

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Prepared By:		
Name(s) and Signature(s)	**Organization**	**Date**
Alwyn Wootten, Thomas Wilson	ALMA	2005-05-26
Signed By:		
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Change Record

Version	Date	Affected Section(s)	Change Request #	Reason/Initiation/Remarks
A	2003-09-17	ALL	Draft A	Initial version by B. Butler, S. Guilloteau, E. van Dishoeck and A. Wootten.
A	2004-02-19	ALL	Draft B	Updated version, incorporating comments of D'Addario and Sramek
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A	2004-10-05	ALL	Draft E	Updated version, addressing comments of CCB meeting of 2004-Sep-30
A	2005-03-23	ALL	Draft F	Updated version, addressing comments of SE meeting of 2004-Oct-26
A	2005-05-25	Many	Draft G	Comments received after CCB meeting of April '05 Addressed.

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1. Scope and Description

This document describes and specifies the scientific requirements for ALMA. It draws from a long list of historical documents describing the desired scientific emphasis of ALMA (and the MMA and LSA) (see, e.g., [RD2 through RD9]), and a number of technical memos and documents (many of them in the formal MMA and ALMA memo series). It serves as a replacement for the Project Book Chapter 2. It amplifies the defining document for the high level science requirements for ALMA, the Project Plan. The implications of these requirements on the instrumental hardware, software, and operations (including calibration) plan are to be laid out in separate documents.

As with every astronomical telescope project, the scientific requirements are the result of a long and complicated trade-off between scientific dreams and technical and budgetary reality. For ALMA, much of this trade-off has taken place years ago. This document collects all of the top level scientific requirements and supporting arguments into a single document. In its original form, this document was written by Bryan Butler.

Comment [haw1]: When text of PPv2.0 becomes available, check wording.

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1.1 Applicable documents

The following documents are included as part of this document to the extent specified herein. If not explicitly stated differently, the latest issue of the document is valid.

Reference	*Document title*	*Date*	*Document ID*
[AD1]	ALMA Project Plan v2.0	2003-07-29	ALMA-10.04.00.00-001-A-PLA

Table 1

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1.2 Reference documents

The following documents contain additional information and are referenced in this document.

Reference	*Document title*	*Date*	*Document ID*
[RD1]	List of acronyms and glossary for the ALMA project	--	ALMA-80.02.00.00-004-A-LIS
[RD2]	ALMA Project Book	2002-02-20	Version 5.5, 'ALMA Requirements and Specifications'
[RD3]	Science with a Millimeter Array	1983	Various, MMA Memo 2
[RD4]	Report of Subcommittee on Millimeter and Submillimeter-Wavelength Astronomy to the NSF Astronomy Advisory Committee	1983	Barrett, A.H., Lada, C. J., Palmer, P., Snyder, L. E., & Welch, W. J., MMA Memo 9
[RD5]	Science with a Millimeter Array: MMA Design Study, Volume I	1988	Wootten, A., & Schwab, F. R. (Eds.) MMA Scientific Memo 3, 1986

[RD6]	Science with Large Millimeter Arrays	1995	Shaver, P. (Ed.) ESO Astrophysics Symposia, Springer
[RD7]	Reports of MMA Working Group Meetings in Tucson	1995	Brown, R., Reports of MMA Working Group Meetings in Tucson
[RD8]	Science with ALMA	1999	http://www.eso.org/projects/alma/science/alma-science.pdf
[RD9]	Science with the Atacama Large Millimeter Array (ALMA)	1999-10-08	Astronomical Society of the Pacific Conference Series Volume 235, A. Wootten, Editor
[RD10]	Water Vapour Radiometer Technical Requirements	2003-09-21	FEND-40.07.00.00-001-A-SPE
[RD11]	ASAC Report Sept 2001	2001-09-11	SCID-90.01.00.00-006-A-REP
[RD12]	Technical specification of the Millimeter Array	1998	Brown, R.L. 1998, Proc. SPIE, 3357, 231
[RD13]	Report of the Antenna Size Committee Meeting	1999	Butler, B., Brown, R., Blitz, R., Welch, J., Carlstrom, J., Woody, D., & Churchwell, E., MMA Memo 243
[RD14]	ALMA Sensitivity, Supra-THz Windows and 20 km baselines	1999	Butler, B., & Wootten, A., ALMA Memo 276
[RD15]	DSB versus SSB and Bandwith/Sensitivity Tradeoff	2002	Guilloteau, S. ALMA Memo 393
[RD16]	Front End Sub-System Technical Specification	2004	ALMA-40.00.00.00-015-A-SPE
[RD17]	Total Power Observing with the ALMA Antennas	2000-03-01	Welch, W. ALMA Memo No. 454
[RD18]	A face-on view of the first galactic quadrant in molecular clouds	1989	Solomon, P.M., & Rivolo, A. R., ApJ, 339, 919
[RD19]	Morphology of the interstellar cooling lines detected by COBE	1994	Bennett, C.L., and 11 others, ApJ, 434, 587
[RD20]	Preliminary spectral observations of the Galaxy with a 7 deg beam by the Cosmic Background Explorer (COBE)	1991	Wright, E.L., and 21 others, ApJ, 381, 200
[RD21]	Warm molecular gas in the primeval galaxy IRAS 10214 + 4724	1992	Solomon, P.M., Downes, D., & Radford, S. J. E., ApJ, 398, L29
[RD22]	*Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*	1972	Weinberg, S., New York: Wiley
[RD23]	Cosmic Background Radiation and the Milky Way's Carbon, Oxygen and CO Cooling Transitions	2003	Liszt, H., private communication.
[RD24]	Analytical Fit to the Luminosity Distance for Flat Cosmologies with a Cosmological Constant	1999	Pen, U.-L. ApJSS, 120, 49
[RD25]	The Molecular Interstellar Medium in Ultraluminous Infrared Galaxies	1997	Solomon, P.M., Downes, D., Radford, S. J. E., & Barrett, J. W., ApJ, 478, 144
[RD26]	Array Configuration of the Large Millimeter and Submillimeter Array (LMSA)	1996	Morita, K.-I. URSI General Assembly, Lille, France
[RD27]	Hour Angle Ranges for Configuration Optimization	1998	Holdaway, M., ALMA Memo 201
[RD28]	ALMA+ACA Simulation Results	2001	Pety, J., Gueth, F. and Guilloteau, S.. ALMA Memo No. 387
[RD29]	Impact of ACA on the Wide-Field Imaging Capabilities of ALMA	2001	Pety, J., Gueth, F. and Guilloteau, S.. A LMA Memo No. 398
[RD30]	Radio-interferometric imaging of very large objects: implications for array design	1993	Cornwell, T.J., Holdaway, M. A., & Uson, J. M., A&A, 271, 697
[RD31]	Effects of Atmospheric Emission Fluctuations and	2004	Holdaway, M. ALMA Memo No 490 .

	Gain Fluctuations on Continuum Total Power Observations with ALMA		
[RD32]	ALMA Software Science Requirements and Use Cases	2004-7-29	ALMA-70.10.00.00-002-A-SPE
[RD33]	Atmospheric Transparency at Chajnantor: 1973-2003		Otárola A., Holdaway M., Nyman L-Å., Radford S.J.E., Butler B. J.

Table 2

1.3 Acronyms

A limited set of basic acronyms used in this document is given below.

ALMA	Atacama Large Millimeter/Submillimeter Array
FOCC	Fraction of occupied (*u,v*) cells in a particular time interval
IF	Intermediate Frequency
LCDM	Lambda Cold Dark Matter (a cosmology currently in favor)
PWV	Precipitable Water Vapor
WVR	Water Vapor Radiometer

1.4 Verb Convention

"Shall" is used whenever a specification expresses a provision that is binding. The verbs "should" and "may" express non-mandatory provisions.
"Will" is used to express a declaration of purpose on the part of the design activity.

1.5 Requirements Numbering

The requirements within the present document are numbered according to the following code:

[SCI-90.00.00.00-XXXXX-YY]

Where:

SCI-90.00.00.00 identifies the 'Science Sub-System' as based on [AD1];

XXXXX is a consecutive number 00010, 00020, … (the nine intermediate numbers remaining available for future revisions of this document);

YY describes the requirement revision. It starts with 00 and is incremented by one with every requirement revision;

Requirements are referenced by number in the text where the science under discussion mandates them. They are collected in a table at the end of the document for reference.

1.6 Purpose[1]

Comment [haw2]: When text of PPv2.0 becomes available, check wording.

ALMA should provide astronomers with a general purpose telescope which they can use to study at a range of angular resolutions millimeter and submillimeter wavelength emission from all kinds of astronomical sources. ALMA will be an appropriate successor to the present generation of millimeter wave interferometric arrays and will allow astronomers to:

1. Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z=10;
2. Trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies throughout the history of the Universe;
3. Reveal the kinematics of obscured galactic nuclei and Quasi-Stellar Objects on spatial scales smaller than 300 light years [SCI-90.00.00.00-00380-00];
4. Image gas rich, heavily obscured regions that are spawning protostars, protoplanets and pre-planetary disks;
5. Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;
6. Obtain unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper Belt Objects in the solar system along with images of the planets and their satellites;
7. Image solar active regions and investigate the physics of particle acceleration on the surface of the sun [SCI-90.00.00.00-0360-00].

Comment [haw3]: This was updated after exchange with A. Benz.

No instrument, other than ALMA, existing or planned, has the combination of angular resolution, sensitivity and frequency coverage necessary to address adequately these science objectives.

ALMA is conceived and designed to be a long-lived user observatory. Its scientific impact at any time will be determined by the quality of its instruments and the creativity and industry of its scientist users.

ALMA will have the capability to extend the high resolution imaging techniques of radio astronomy to millimeter and submillimeter wavelengths to achieve an astronomical

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[1] From Project Plan v2.0

imaging capability equal in clarity of detail to the imaging capability of the Hubble Space Telescope (HST) and large ground based telescopes. It will do so at wavelengths where the richness of the sky is provided by thermal emission from the cool gas and dust from which stars and all cosmic objects form. In this sense, ALMA is the appropriate scientific complement to the Very Large Telescope (VLT) and Gemini, to the HST, and its successor instrument, the James Webb Space Telescope, instruments which image light from stars and collections of stars such as galaxies.

1.7 General Requirements

One can write down a few generic high level requirements derived from the full suite of desired scientific experiments ([RD4],[RD5]):

1. ALMA shall cover all available millimeter and submillimeter atmospheric windows [SCI-90.00.00.00-0020-00];
2. ALMA shall be able to observe in both narrow (``spectral line") and wide (``continuum") bandwidth modes [SCI-90.00.00.00-0030-00];
3. ALMA shall maximize sensitivity over its frequency bands [SCI-90.00.00.00-0110-00, SCI-90.00.00.00-0120-00, SCI-90.00.00.00-0130-00, SCI-90.00.00.00-0140-00, SCI-90.00.00.00-0150-00, SCI-90.00.00.00-00040-00, SCI-90.00.00.00-00160-00, SCI-90.00.00.00-0200-00];
4. ALMA shall maximize the flexibility of spectral line capability [SCI-90.00.00.00-00030-00, SCI-90.00.00.00-0040-00, SCI-90.00.00.00-0050-00, SCI-90.00.00.00-0060-00];
5. ALMA shall maximize imaging capability, both as an interferometer and as a collection of single antennas, at both large and small angular resolutions [SCI-90.00.00.00-0220-00, SCI-90.00.00.00-0230-00;
6. ALMA shall be able to measure all polarization cross-products simultaneously [SCI-90.00.00.00-0310-00].

In the following text, these somewhat vague requirements are expanded into more concrete numbers. First, examine the highest level scientific experiments.

2. Level-1 Scientific Requirements[2]

Comment [haw4]: Check Project Plan wording; add [C II] and anything else which is there but not here.

The primary science requirement for ALMA is the flexibility to support the breadth of scientific investigation to be proposed by its creative scientist-users over the decades long lifetime of the instrument. However, three science requirements stand out in all the science planning for ALMA done in both Europe and in North America. These three Level-1 primary science requirements are the following:

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[2] Text from ALMA Project Plan v2.0

1. The ability to detect spectral line emission from CO or C II in a normal galaxy like the Milky Way at a redshift of z=3, in less than 24 hours of observation.
2. The ability to image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star forming clouds in Ophiuchus or Corona Australis), enabling one to study their physical, chemical and magnetic field structures and to detect the tidal gaps created by planets undergoing formation in the disks.
3. The ability to provide precise images at an angular resolution of 0.”1. Here the term precise image means representing within the noise level the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

These requirements have driven the concept of ALMA to its current technical specifications. In the following sections, a simplified flowdown of science requirements into technical specifications is presented.

2.1 Detecting the Milky Way at z=3

For high redshift galaxies, the translation of the science requirement into a performance specification can be made by comparison with the results obtained by current millimeter arrays, which have collecting areas between 500 and 1000 m^2. These arrays can detect CO emission from the brightest galaxies, amplified by gravitational lensing, in one to two days of observation. Emission from normal, unlensed objects will typically be 20-30 times fainter.

The sensitivity of ALMA for a given integration time is essentially controlled by three major terms: the atmospheric transparency, the noise performance of the detectors, and the total collecting area. Compared to current millimeter arrays the contribution of the atmosphere will be minimized by locating ALMA at the Chajnantor altiplano in the Atacama Desert of northern Chile at an elevation slightly over 5000m [SCI-90.00.00.00.00-060-00]. The noise level of the detectors cannot be reduced by much more than a factor of two, because these receivers are approaching fundamental quantum limits [SCI-90.00.00.00-0160-00]. An important factor of √2 will be gained by the requirement that ALMA support front end instrumentation capable of measuring both states of polarization [SCI-90.00.00.00-0310-00]. The remaining factor of 7-10 can only be gained by increasing the collecting area by a similar amount. Hence the ALMA goal is to achieve 7238 m^2 of collecting area [SCI-90.00.00.00-0100-00], from the following arguments ([RD12-16]). ALMA sensitivity calculations are detailed in [RD14]; these result in a number of requirements as listed in §1.7.3 above.

Comment [haw5]: Went from five factors to three in Jun04 PP.

The spectral lines of scientific interest as diagnostics of the gas content and dynamics of a galaxy early in the history of the universe have frequencies that are fixed in the rest frame of the galaxy, but we observe these lines at a frequency that depends on the redshift of the particular galaxy. Since galaxies are found at every redshift (i.e., age), the goal of the ALMA Project is to provide the capability to observe in all atmospheric windows from 30-950 GHz so that galaxies of all ages may be studied. Initially, the Project will support observations in the four highest-priority bands [SCI-90.00.00.00-0100-00, SCI-90.00.00.00-0020-00]. Additional capabilities may be added in the operational phase of ALMA. Since the redshift of the galaxies will initially be essentially unknown, the instantaneous bandwidths of the receivers should also be as large as possible [SCI-90.00.00.00-0170-00, SCI-90.00.00.00-0180-00] with rapid tuning [SCI-90.00.00.00-00040-00, SCI-90.00.00.00-00060-00].

The requirement on the total collecting area of ALMA in order to be able to detect spectral line emission from a Milky Way type galaxy to z=3 will now be derived.

At cosmological redshifts the 10 kpc disk of the Milky Way is much smaller than the primary beams of reasonably sized millimeter antennas, so the ALMA collecting area, proportional to the product ND^2, is the parameter one needs to optimize, where N is the number of antennas of diameter D in the array.

If one wishes to detect spectral line emission in a galaxy that is similar to the Milky Way but at redshifts up to z=3 then the most obvious line candidate to observe is CO. The total CO luminosity of the Milky Way in the 1-0 transition has been estimated by [RD18]. This luminosity agrees roughly with the CO luminosities seen in the higher transitions by COBE ([RD19] [RD20]. Note that COBE also measured emission from neutral and ionized carbon (CI and CII) and ionized nitrogen (NII). Given the luminosity of the CO 1-0 transition, we can calculate the expected received flux density in any transition as (see [RD21]):

$$S_{CO} = 3.08 \times 10^{-8} \frac{L'_{CO}\, \nu_{rest}^2\, (1+z)}{\Delta v_{rest}\, d_L^2} \quad ,$$

S_{CO} is the flux density in Jy, L'_{CO} is the CO luminosity in K km/s pc^2, ν_{rest} is the rest frequency of the transition in GHz, d_L is the "luminosity distance" in Mpc, and Δv_{rest} is the rest line width in km/s. The luminosity distance can be written ([RD22]):

$$d_L = \frac{c}{H_o\, q_o^2}\ \left[z q_o + (q_o - 1)\left(-1 + \sqrt{2 q_o z + 1}\right)\right] \quad .$$

This obtains for H_0 = 75 km/s/Mpc, q_0 = 0.5 so that for z=3, d_L = 16 Mpc. For a LCDM cosmology the luminosity distance will be larger, as calculated below. Adopt $L'_{CO} = 5 \times 10^8$ K km/s pc^{-2} for the 1-0 transition, which is slightly larger than that in [RD18] (where $L'_{CO} = 3.7 \times 10^8$ K km/s pc^{-2}), but is consistent with the COBE results. One then modifies the luminosity as a function of transition and redshift according to a model which accounts for the proper radiative transfer given the higher background temperature at higher z, and assuming that 90% of the CO is in clouds similar to our galactic dark clouds and 10% is in regions similar to strong photodissociation regions [RD23]. In the Milky Way, most of the CO emission arises in clouds of several tens of Kelvin kinetic temperature. In more distant Milky Way look-alikes, the gas will be somewhat warmer owing to the relatively higher background temperature. Beyond z~5, transitions above J=5 strengthen while those below J=5 weaken somewhat. For the Milky Way at z=3, the J=3-2 and J=4-3 lines will fall within Band 3, the J=8-7 and J=9-8 lines will fall within Band 6, and the [C II] will fall within Band 8. One assumes H_0 = 75 km/s/Mpc, q_0 = 0.5 (note that under this assumption, the above equation for the luminosity distance is exactly equivalent to that in [RD24], if Ω_0 is assumed to be equal to 1.0), and that the intrinsic width of the lines is Δv = 300 km/s [RD25]. One can then calculate, given any array collecting area, the maximum z to which any of the transitions of CO (we calculate up to the 8-7 transition) can be detected by that array. One demands a 5σ detection in a 75 km/s channel in 12 hours of integration (24 hours of telescope time might yield 16 hours of usable on-source time). With these requirements, the following relationship between collecting area and maximum detectable z_{max} is derived:

$$z_{max} \sim \frac{N D^2}{3100\,\mathrm{m}^2} \quad .$$

Thus, to reach z=3, an ND^2 of 9300 m^2 is required. This is satisfied with an array of 65 12-m antennas. If one assumes a Lambda-Cold Dark Matter cosmology, the calculation for luminosity distance is more complex; taking H_0 = 71 km/s/Mpc, Ω_{tot}=1.0 and Λ = 0.7 one calculates d_L = 26 Mpc; one can only reach a 4σ detection in a 75 km/s channel in a full day's integration.

Of course, larger values of ND^2 are always desirable, as they would allow one to resolve the line flux density into more pixels (higher angular or spectral resolution) or image to higher S/N more quickly.

Note finally that lines of CI (Bands 3 and 6), and redshifted lines of NII (Band 7) and CII (Band 8) will also be observable and will provide important probes of the IMF and the Lyman continuum luminosity from the most luminous stars in early galaxies. The latter is the primary cooling line for the Milky Way; COBE found its emission widespread. ALMA should detect this line in a few hours of integration. The intensity of the line is relatively insensitive to the carbon abundance; because the emission is widespread the brightness temperature of the line is actually lower than that of CO although its total flux is higher.

2.2 Protoplanetary Disks

A similar sensitivity argument can also be made for the studies of protoplanetary disks: going from the 0.5 arcsecond angular resolution obtained in the best images with current millimeter arrays to the 0.1 arcsecond resolution comparable with that of optical telescopes requires a factor of 25 improvement in sensitivity, similar to that mentioned above. In addition, proper study of the kinematics requires spectroscopy with velocity resolutions finer than 0.05 km/s, or about 10 kHz at 3mm wavelength.

Gaps created by giant planets in their early stages of formation (“proto-Jupiters”) in protoplanetary disks are expected to subtend about 1 AU in width. Combined with the distance of the nearest star forming regions (60-140 pc), this suggests that ALMA needs to provide 10milliarcsecond resolution or better [SCI-90.00.00.00-00220-00]. This can be obtained by combining high frequency (650 GHz and above) observations with array configurations reaching 18.5 km in longest physical dimension [SCI-90.00.00.00-00250-00].

The sensitivity of ALMA highlighted above will allow, for the first time, the opportunity to investigate the structure of the magnetic field both in the larger protostellar regions and in the small protoplanetary disks, by observing polarized emission from dust. The spatially resolved kinematics[3] of a rotating, infalling protostellar envelope provides insight into the hydrodynamics of star formation, whereas the morphology of the magnetic field probes the magnetodynamics. The combination of the two will allow

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[3] The most interesting narrow lines are those which have self-absorption which indicates infall ("infall asymmetry"). In that case the minimum number of channels across the line needed to model the line properly increases, from perhaps 2 resolution elements = 1 sigma for a simple gaussian line to something like 4 resolution elements = 1 sigma for a line with a dip or a red shoulder. If one applies these criteria to an extreme case (low frequency, heavy molecule, low temperature), then one should consider e.g. an HC_3N line at 100 GHz, in a cold, slowly contracting starless core with a central temperature of 8 K. The thermal velocity dispersion would be 0.036 km/s and so the spectral resolution should be about 0.018 km/s to resolve a gaussian line or 0.01 km/s to resolve a self-absorbed gaussian line [SCI-90.00.00.00-00030-00]. The baseline correlator provides a resolution of 0.011 km/s, meeting this need.

astronomers to discover the physical process by which magnetic fields accelerate or impede the process of star and disk formation. The requirement to support these observations emphasizes again the firm requirement for the ALMA receiving system to have full simultaneous polarization capability. The formation of stars and planets also causes changes in the density, temperature and chemistry in the envelopes and disks. Wide frequency coverage is essential to probe these different conditions.

One can now derive the requirement on the total collecting area of ALMA in order to be able to image protoplanetary disks.

Consider an observation of the gas distribution and kinematics in a protoplanetary disk by observation of CO. A velocity resolution of 1 km/s (or slightly better) might be desired. A spatial resolution of 0.1 arcseconds or so might be desired, implying a maximum baseline length on the order of 4 km. Assume 12 hours of on-source time (same as the high-z case above).

One needs to achieve a brightness temperature sensitivity of $\Delta T \sim 1$ K - sufficient to image marginally optically thick lines in cool (10's of K) protoplanetary disks[SCI-90.00.00.00-00011-00].

Using the brightness temperature sensitivity numbers from [RD14] (divided by $\sqrt{720}$ to account for 720 minutes in 12 hours), one can see that the required ND^2 is roughly what one gets from 64 12-m antennas (for the 1-0 and 2-1 transitions of CO, around 110 and 230 GHz).

2.3 Precise Images

High fidelity imaging requires a sufficient number of baselines, in order to cover adequately the *uv* plane (i.e., the time/frequency domain plane in which the data are sampled). Detailed studies of the imaging performance of aperture synthesis arrays have shown that imaging performance implies a minimum number of antennas, several dozen or more, and accurate measurements of the shortest baselines, as well as of the large scale emission measured by total power from the antennas. Such accurate measurements can only be obtained with high quality antennas, with superior pointing precision. The relative positions of the antennas must be determined accurately so the geometrical delay can be correctly calculated [SCI-90.00.00.00-00280-00]. Residual delays due to incorrect antenna locations will result in phase errors which change across the observing band and differential phase errors between two different sources on the sky (for example, a calibrator and target source). High fidelity imaging also requires the ability to perform calibrations to “freeze” the atmospheric turbulence which distorts the radiation coming from celestial sources. ALMA will incorporate two techniques to effect this "freeze" of the turbulent atmospheric screen: fast switching of the antenna between target object and nearby calibrator both spatially and in frequency [SCI-90.00.00.00-0050], and monitoring of a water vapor line along a direction near to the observation by a water vapor radiometer (WVR) [SCI-90.00.00.00-0290-00]. Precise images require accurate calibration [SCI-90.00.00.00-00300-00, SCI-90.00.00.00-00350-00].

In this section the requirements on ALMA to provide precise imaging are summarized. A large number of MMA and ALMA memos present and discuss simulations of the imaging capabilities and properties of ALMA.

2.4.1 (*u*,*v*) coverage

The key criterion that we must consider for imaging is the ability of the instrument to achieve good coverage of the (*u*,*v*)-plane. Morita [RD26] and others have emphasized that excellent imaging, limited by dynamic range, can be achieved when 50% of the (*u*,*v*)-cells are filled. Morita calls this quantity FOCC, the ``fraction of occupied cells." It is calculated by simulating the observed (*u*,*v*) points in a particular configuration and gridding them onto the Fourier plane with a cell size equal to the antenna diameter. The fractional area of the gridded (*u*,*v*)-plane out to the diameter of the longest array baselines that is filled by observations is the quantity FOCC. Clearly, FOCC is a function of hour angle; it asympotically approaches a value of one.

Holdaway ([RD27]) presents a detailed analysis of the variation of FOCC depending on an array configuration and hour angle coverage. To achieve FOCC ≥0.5 using an array of given collecting length (ND) will require observations made out to the hour angle limits shown in Table 3.

Table 3 Hour Angle Limits to Achieve FOCC=0.5 for an Array of N Antennas of Diameter D(m) in a Configuration with Maximum Baseline of 3000m

ND	*h*
300	6.9
400	3.9
500	2.5
600	1.7
700	1.3
800	1.0

Obviously, observations taken at large hour angles will be given low weight in the imaging owing to the increase in system temperature at low elevation. To avoid corrupting the image with such low weight points, the observer should restrict observations to hour angles such that the lowest weight points are reduced from those on the meridian by no more than √2. One would wish to retain the opportunity to do such imaging in the submillimeter spectral windows: in median meteorological conditions on the Chajnantor site, one needs to observe out to a limiting hour angle range of no more than approximately h=2.0.

With this restriction, Table3shows that the specification for the ``collecting length'' ND for the ALMA needs to be approximately ND ≥ 560. The full ALMA instrument (64 12-m, hence ND=768) satisfies this specification. Even considering four antennas being used for single-dish observations (see below), and, *e.g.* two antennas out of order for maintenance, ALMA will still provide ND=696, hence allowing FOCC larger than 0.5 to be obtain in less than 2 hours observing time. These parameters also ensure ALMA will constitute an excellent survey instrument, capable of forming excellent high resolution images in a short period of time.

The above requirements are derived for a 3000m configuration. The more extended the ALMA configuration, the more hour angle coverage or the more antennas one requires to obtain a high FOCC. This rapidly makes it impossible to get FOCC ≥0.5. Even after optimizing extended configurations and combining them with compact or intermediate ones, the FOCC cannot be made uniform over the whole Fourier plan. This is a trade-off that has to be made between the FOCC and the angular resolution of the observations.

2.4.2 Short Spacings

Whatever the hour angle coverage or combination of multiple observations, ALMA--as for any array--will not be able to measure interferometrically the smallest spatial frequencies, below approximately the antenna diameter. The filtering of the short-spacings information, hence of the most extended structures, can introduce major artifacts in the resulting images. This will affect all observations of sources more extended than ~2/3 of the primary beam. For such observations, a key requirement is therefore the ability to observe in total-power mode with the ALMA antennas, and thereby derive the short-spacings information[SCI-90.00.00.00-0230-00].

The optimal combination and relative weighting of the short-spacings and interferometric observations requires the signal-to-noise be equivalent in both datasets -- which is a somewhat relaxed criterion as compared to matching the sensitivities. Although the exact numbers would depend on the source structure, simulations from [RD28, RD29] have shown that this can be achieved by spending a factor of 16 more observing time on the total power than on the interferometric observations. This can in practice be obtained by using 4 antennas, which can then be optimized for total power measurements (nutating secondary), each one observing 4 times more than ALMA. This would allow measuring the short-spacings for 25% of the projects observed by the interferometer. These data, combined with the interferometric data, then provide the final ALMA image. For these images to meet the standards in [AD1], the ALMA antennas must point to 0.6 arcseconds [RD30], the primary beam must be accurately measured [RD30], and total power mapping must be accomplished quickly relative to atmospheric fluctuations [RD31][SCI-90.00.00.00-00240-00, SCI-90.00.00.00-00260-00, SCI-90.00.00.00-00270-00]

Even after combination of the ALMA and total power data, there is still a “gap” in the weight distribution in the (*u,v*) plane, in a ring located at approximately half the antenna diameter (*i.e.* 6m). Depending on the amount of smooth extended structures in the source brightness distribution, this may induce significant artifacts. The addition of data from a compact array of *e.g.* 12 7-m antennas allows one to obtain reliable images in all circumstances [RD29]. Not only the imaging process is more robust, but the results are also more immune to pointing and primary beam errors.

2.4 Other Implications

The combination of these three major requirements calls for a reconfigurable array covering baselines from a few meters up to several kilometers, observing over the full millimeter and submillimeter atmospheric windows. In addition to this large spatial dynamic range, ALMA science requires high image dynamic range [SCI-90.00.00.00-00070-00]. The maximum size of the individual antennas is driven by the required pointing and surface precision: a choice of 12 meter diameter antennas offers an excellent technological compromise. To provide no less than 7238 m^2 of total collecting area, 64 antennas are needed, which is a large enough number to guarantee excellent imaging performance.

Finally, to allow cancellation of atmospheric disturbances, the antennas must be equipped with water vapor radiometers to measure atmospheric pathlength variations and correct the image distortions such phase variations create. This is a technique identical in its purpose and application to adaptive optics as used for ground-based telescopes operating at visual and infrared wavelengths. In addition, ALMA is designed to be able to detect calibration sources such as quasars in a time short enough to minimize the atmospheric phase fluctuations so that the needed correction may be as small as possible. Detecting weak sources requires wide instantaneous bandwidth for all the front end receivers to maximize the continuum sensitivity.

The final major scientific requirement affects the diverse community that will use and benefit from the scientific capabilities that ALMA brings to extend their research endeavors: ALMA should be "easy to use" by novices and experts alike [sci-90.00.00.00-00400-00]. Astronomers certainly should not need to be experts in aperture synthesis to use ALMA. Automated image processing will be developed and applied to most ALMA data, with only the more intricate experiments requiring expert intervention [SCI-90.00.00.00-00410-00, SCI-90.00.00.00-00420-00]. Flexible (dynamic) scheduling is essential for ALMA, and this defines the overall science operations concept [SCI-90.00.00.00-0210-00].

3 Detailed Requirements

In this section we list specifically and in some more detail the requirements necessary to undertake the scientific investigations which ALMA should enable. In the following Table:

- Unless otherwise noted, "total power" refers to measurements made in both autocorrelation mode and measurements made using the analogue total power detectors of Intermediate Frequency (IF) 2 GHz bandwidth.
- Unless otherwise noted, requirements on permitted errors refer to r.m.s. errors.
- Unless otherwise noted, requirements apply to operation at all permitted observing frequencies with antennas in any array configuration.

Table 4. Detailed Requirements for ALMA

Requirement Category	Specification	Number [SCI-90.00.00.00-nnn-00]
1. Frequency	ALMA should be able to observe in all atmospheric windows between 31.3 and 950 GHz.	
1.1 Bands	In order to achieve this technically, the receiving system shall be separated into 10 bands, of which four shall be built during ALMA construction: band 1 = 31.3-45 GHz; band 2 = 67-90 GHz; band 3 = 84-116 GHz; band 4 = 125-163 GHz; band 5 = 163-211 GHz; band 6 = 211-275 GHz; band 7 = 275-373 GHz; band 8 = 385-500 GHz; band 9 = 602-720 GHz; band 10 = 787950 GHz. Ref [RD2] Table 1.1, CRE81.	10
1.2 Tunability	It shall be possible to tune ALMA completely across the observable windows, i.e., reach a spectral line transition at any arbitrary observable frequency.	20
1.3 Spectral resolution	It shall be possible to configure the correlator to achieve sufficient resolution (0.01 km/s) at 100 GHz to *resolve* thermal line widths.	30
1.4 Intraband tuning	It shall be possible to retune ALMA to a second frequency within a band from a first in the same band in a time not greater than 1.5	40

	seconds. Switching between two frequencies less than 25MHz apart (e.g. to cancel primary-secondary standing waves of this frequency) shall take no more than 10 ms. Note that this applies to switching within (rather than between) bands.	
1.5 Interband tuning, second band ready	It shall be possible to retune ALMA to a new frequency in a different band that is currently on standby (``warm'') in a time not greater than 1.5 seconds; there shall be two standby bands in addition to the band currently employed for array observations	50
1.6 Interband tuning, second band unready	It shall be possible to retune ALMA to a new frequency in a different band in a time not greater than 1 minute.	60
1.7 Dynamic range	The required spectral dynamic range is 10000:1 and the required image dynamic range, for point sources, is 50000::1, peak to rms.	70
2. Sensitivity	ALMA shall maximize sensitivity over its frequency bands	
2.1 Flux sensitivity	ALMA shall routinely obtain sub-millijansky point source sensitivity at all observing frequencies, within ten minutes of integration time, under median atmospheric conditions (τ=0.082, [RD33]).	80
2.2 Site	ALMA shall be sited at the Llano de Chajnantor, to take advantage of the extremely dry and phase-stable conditions there, which derive from the transparent and stable atmosphere over the site.	90
2.3 Antenna complement	ALMA shall be comprised of 64 12-m antennas (see Appendices).	100
2.4 Antenna surface	The antennas shall have surfaces with rms deviation from the ideal of 25 μm or less [RD14].	110
2.5 Antenna forward efficiency	The antennas shall have forward efficiency of at least 0.95 to minimize spillover [RD14].	120
2.6 Antenna edge taper	The ALMA feed systems shall be tapered to -13 dB at the edge of the antenna, to reduce spillover while still allowing high aperture efficiency. [RD14].	130
2.7 Antenna blockage	The antennas shall have less than 3% geometric blockage [RD14].	140
2.8 Antenna aperture efficiency	The antennas shall have aperture efficiency of 75% at 31.3 GHz [RD14].	150
2.9 ALMA Receivers	The ALMA receivers shall be close to quantum limited, with SSB receiver temperatures of: $\boldsymbol{\alpha} \mathbf{h} \nu / k + 4$ K over the central 80% of the band, where $\boldsymbol{\alpha} = 6$ for bands 1-6; $\boldsymbol{\alpha} = 8$ for bands 7 and 8, and $\boldsymbol{\alpha} = 10$ for bands 9 and 10; for the outer 20% of the band $\boldsymbol{\alpha} = 10$ for bands 1-6; $\boldsymbol{\alpha} = 12$ for bands 7 and 8, and $\boldsymbol{\alpha} = 15$ for bands 9 and 10.	160
2.10 IF bandwidth	The ALMA data sampling and transmission system shall have IF bandwidth of 8 GHz per polarization in continuum mode.	170
2.11 Processed IF	The full 8 GHz IF bandwidth per polarization per antenna must be processed by the entire signal chain, from the front end element	180

	(mixer) through to the correlator.	
2.12 Correlator losses	Correlator losses shall not exceed those expected for two bit correlation after a filter, or 13.3%.	190
2.13 Data accuracy	Data storage and processing must not result in a significant loss in sensitivity (from, e.g., not storing enough bits per number).	200
2.14 Dynamic scheduling	ALMA shall be dynamically scheduled, with the next project to be observed being determined by a combination of the current set of available projects ranked by scientific priority, their demands on conditions, and the actual current conditions.	210
3. Imaging	ALMA shall maximize imaging capability, both as an interferometer and as a collection of single antennas, at both large and small angular resolutions.	
3.1 High fidelity	ALMA shall provide high fidelity imaging at spatial scales from of order degrees to λ/D~10 milliarcseconds. More precisely, images shall be thermally limited at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.	220
3.2 Total Power	Both total power and interferometric data must be collected. All antennas must be capable of collecting total power data, and at least 4 antennas must be equipped with nutating subreflectors in order to do atmospheric emission cancellation.	230
3.3 Integration Time, correlation	It shall be possible to record subsets limited only by the data rate of the available correlations at intervals of 1 msec for autocorrelations only, and 16 msec when cross correlations are included.	240
3.35 Integration Time, total power continuum	For on-the-fly observations (0.5 degree/s) at 950 GHz, the beam crossing time is 3.3ms. Oversampling the Nyquist rate to keep loss of signal-to-noise ratio below 1% requires analogue total power continuum sampling of 0.5msec or faster.	245
3.4 Configuration	The ALMA antennas shall be relocatable, so that a variety of spatial scales of interest can be imaged, from a compact configuration including 64 antennas within a diameter of 150 m to a spread out configuration of maximum baseline 18.5 km.	250
3.5 Pointing	The ALMA antennas shall point to 0.6 arcseconds rms radial with the aid of reference pointing [RD 29].	260
3.6 Primary Beam	The primary beams of the ALMA antennas shall be measurable and repeatable to an accuracy of 6% in power out to the 10% point at all operating wavelengths.	270
3.7 Antenna Location	The phase center position of the ALMA antenna locations shall be determined to a radial accuracy of 65 µm, stable over a fortnight.	280
3.8 Phase Correction	The corrected visibility phase fluctuations shall not exceed 1 radian (57 degrees) at 950 GHz on time periods shorter than 10 seconds (phase noise). A WVR system provides the ability to correct	290

Comment [haw6]: Reliability spec?

Comment [HAW7]: At highest frequency the resolution is 4.6mas. However, the electronic specs will make it very difficult to achieve this—they will limit phase stability the best 5% of the time.

Comment [HAW8]: Analog? Interferometric. Makt explicit assumption that we mean both if not noted.

Comment [HAW9]: To agree with antenna spec.

Comment [HAW10]: Here we mean analog total power. Need to specify this as such. Ref ALMA-56.06.00.00-001-A-CRE for details.

Comment [HAW11]: State rms. Note that numbers are rms unless specifically said they are peak to peak.

Comment [HAW12]: Rms

Comment [HAW13]: In one second.

	atmospheric fluctuating delay to 10(1 + PWV) microns of path, rms, (where PWV is the water vapor along the line of sight in millimeters; see [FEND-40.07.00.00-00150-00 / T]; see [RD6]).	
3.9 Amplitude Fluctuations	The corrected visibility amplitude fluctuations on time scales of 1 second to 300 seconds must not exceed 3% at frequencies less than 300 GHz, 5% at higher frequencies, considering: A. antenna gain stability under changing wind and gravity conditions; B. ability to measure and correct for atmospheric opacity and emission fluctuations. C. Instrumental gain fluctuations	300
3.95 Amplitude Fluctuations	Sensitive total power continuum measurements, such as discussed in §2.2 above, require instrumental gain stability $\Delta G/G \leq 10^{-4}$ in 1 second [RD7], [RD8] if atmospheric emission variations and thermal noise rather than the instrumental gain stability are to limit sensitivity[4]. On longer timescales, stability $\Delta G/G \leq 3\cdot10^{-3}$ in 300 seconds (TBC) so that instrumental gain fluctuations are a small part of the visibility amplitude fluctuations constrained by Sci Req # 300.	305
4.0 Polarization	ALMA shall be able to measure all polarization cross-products simultaneously	
4.1 Signal measurement	It shall be possible to measure all polarization cross-products simultaneously.	310
4.2 Polarized flux error	The error in polarized flux for a source where the circularly and linearly polarized fluxes are zero shall be no more than 0.1% of the total intensity.[5]	320
4.3 Polarization position angle	It shall be possible to determine the position angle of linearly polarized flux density to 6°.	330
4.4 Relative polarization channel stability	Sensitive polarimetric interferometric observations require system stability in the independent polarization channels. To measure polarisation accurately in interferometric mode to 0.1% levels requires a differential gain stability between the two polarisation channels of better than 1×10^{-3} in 5 minutes, the typical time between which calibration of instrumental polarisation can be performed. This applies to all receiver systems.	345
5.0 Calibration	The final visibilities shall be on a calibrated flux density scale, accurate to within 3% at frequencies less than 300 GHz, and 5% at higher frequencies, relative to measurements at other bands. Absolute calibration shall be possible to 5% accuracy. Calibration repeatability shall be achieved to the same levels.	350
6.0 Other		
6.1 Solar	It shall be possible to observe the sun at all frequencies.	360
6.2 Phased Array	It shall be possible to phase up the array, with provision of an output	370

Comment [HAW14]: 1s short time scale but long timescale should be what—calibration cycle or ten minutes.

Comment [HAW15]: This assumes that a) opacity corrections are done on time scales from 1s to 300s using WVR data or other broadband radiometry data, and, b) system gain is calibrarted (approx) every 300s using a flux calibrator source. On longer timescales, the flux density of thecalibrator radio source, corrected for atmospheric opacity, will be determined using thr amplitude calibration device and possibly tipping scans. An allocation of amplitude variation should be made to antenna, atmospheric correction and instrument stability.

Comment [HAW16]: Just a comment about but what about atmospheric absorption. Go to flux density std. What spec for 300s? LD'A proposed 10-3. What is the right number. We'll probably get 10-3 in 1s in all antennas.

Comment [HAW17]: Accepting the footnote to Science Req # 305, only four antennas with nutators need meet the requirement stability $\Delta G/G \leq 10^{-4}$ in 1 second. All antennas must have stability $\Delta G/G \leq 3\cdot10^{-3}$ in 1 second. This will compromise total power continuum observations by approximately a factor of 7.

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[4] In practice, for an ALMA image incorporating both total power and interferometric data, four antennas providing stability at this level would suffice.

[5] Meeting the polarization requirements is particularly important in band 7 and could require a quarter-wave plate.

	sum port, either hardware or software.	
6.3 VLBI	It will be possible to use ALMA for VLBI, both with a single element, or with phased array (or subarray) output, at frequencies TBD although the electronics for realization of VLBI performance are not included in the ALMA construction plan. The accuracy of phasing up shall be TBD.	380
6.4 Subarrays	It shall be possible to have at least four subarrays where the observing frequency and antenna control in each is completely independent of the others.	390
7.0 Software		
7.1 Ease-of-use	ALMA shall be ``easy to use" by both novice and expert astronomers. (Ref [AD1], p 15.)	400
7.2 Software tools	ALMA shall provide tools for preparation of proposals, preparation of observations, and reduction of data.	410
7.3 Data Reduction	There shall be a standard data reduction performed for most projects successfully completed, resulting in a properly calibrated image cube (the ``pipeline"). This shall require minimal input from the astronomer in most cases.	420