Atacama
Large
Millimeter
Array

ALMA Scientific Requirements

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1 Scope and Description

This document is meant to describe and specify 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 It draws from a long list of historical documents describing the desired scientific emphasis of ALMA (and the MMA and LSA) (see, e.g., Owen \etal 1983; Barrett \etal 1983; Wootten \& Schwab 1988; Shaver 1995; Brown \etal 1995; ESO Proposal 1999; Brown \etal 2000; Wootten 2001; Vanden Bout \etal 2003), and a number of technical memos and documents (many of them in the formal MMA and ALMA memo series). It is the defining document for the high level science requirements for ALMA. The implications of these requirements on the instrumental hardware, software, and operations (including calibration) plan is 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. For example, the antenna size and its pointing and surface accuracy specifications are the result of iterations between the scientists and the engineers and antenna vendors. Nevertheless, it was still felt useful to collect all of the requirements and supporting arguments into a single document.

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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 Product Tree	2002-11-01	SYSE-80.03.00.00-001L-LIS
[AD2]	ALMA Project Plan v1.0	2003-07-29	ALMA-10.04.00.00-001-A-PLA

Table 2

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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	2003-04-23	ALMA-80.02.00.00-004-B-LIS
[RD2]	ALMA Project Book	2002-02-20	Version 5.5
[RD3]	ASAC Report Sept 2001	2001-09-11	SCID-90.01.00.00-006-A-REP

Table 3

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;

1.1 Purpose

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 throughout the Universe;
2. Trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies deeply into the epoch of reionization;
3. Reveal the kinematics of obscured galactic nuclei and Quasi-Stellar Objects (QSOs) on spatial scales smaller than 300 light years;
4. Image gas rich, heavily obscured regions that are spawning protostars, protoplanetary disks and protoplanets, as well as remnant debris disks;
5. Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;
6. Obtain unobscured, subarcsecond images of cometary nuclei, and thousands of asteroids, Centaurs, and Kuiper Belt Objects (KBOs) 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.

Comment: This should be 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's scientific impact at any time will be determined by the quality of its instrument 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 imaging capability better in clarity of detail than 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 Keck Telescopes, the Very Large Telescope (VLT) and Gemini, to the HST, and its successor instrument, the James Webb Space Telescope, and to the Space InfraRed Telescope Facility (SIRTF), instruments which image light from stars and collections of stars such as galaxies.

1.2 General Requirements

We can write down a few generic high level requirements derived from the full suite of desired scientific experiments:

1. ALMA will cover all available millimeter and submillimeter atmospheric windows;
2. ALMA will be able to observe in both narrow (``spectral line'') and wide (``continuum'') bandwidth modes;
3. ALMA will maximize the sensitivity;
4. ALMA will maximize the flexibility of the spectral line capability;
5. ALMA will maximize the imaging capability, at both large and small angular resolutions;
6. ALMA will be able to collect full polarization data.

But in order to be very useful we must turn these somewhat vague requirements into more concrete numbers. Let us start to do this by first examining a few particularly important scientific experiments.

2 Primary Scientific Requirements

Comment: 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 primary science requirements are:

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 gaps created by planets undergoing formation in the disks.
3. The ability to provide precise images at an angular resolution of 0.1 arcseconds. 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 galaxies at high redshift, 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 starburst 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 five major terms: the atmospheric transparency, the surface accuracy of the antenna, the noise performance of the detectors, the bandwidth available, and the total collecting area. This is explained in much more detail in Appendix A. ALMA's Chajnantor site minimizes the contribution of the atmosphere compared to what is possible with current millimeter arrays. The surface accuracies of current millimeter arrays are quite good, but we expect to improve on that so that the wavelengths at which the reflectors have reasonable surface accuracy is matched to the wavelengths at which reasonable atmospheric transparency is measured at Chajnantor. The noise level of the detectors cannot be reduced by much more than a factor of two, because these receivers are approaching the fundamental quantum limit. An important factor of $\sqrt{2}$ will be gained by the requirement that ALMA support front end instrumentation capable of measuring both states of polarization. No gain from bandwidth differences is realized, since this is a spectral line detection. 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 at least 7000 m^2 of collecting area. A much more detailed derivation of this requirement is presented in Appendix B.

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. Additional capabilities can 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.

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 a few times 10 kHz. Imaging the terrestrial planet regions in nearby debris disks requires few milliarcsecond resolution. A more detailed derivation of this is provided in Appendix C.

Gaps created by giant planets in their early stages of formation (``proto-Jupiters'') in protoplanetary disks are expected to be of order 1 AU in width. Combined with the distance of the nearest star forming regions (60-140 pc), this implies that ALMA needs to provide 10milliarcsecond resolution or better. This can be obtained by combining high frequency (650 GHz and above) observations with array configurations approximately 10 km in physical dimension.

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 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 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.

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, 40 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. High fidelity imaging also requires the ability to perform calibrations to “freeze” the atmospheric turbulence which distorts the radiation coming from celestial sources.

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. 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 7000 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. 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.

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.

3.1 Frequency

ALMA should be able to observe in all atmospheric windows between 30 and 950 GHz.

1. In order to achieve this technically, the receiving system will be separated into 10 bands: band 1 = 31.3-45 GHz; band 2 = 67-90 GHz; band 3 = 84-116 GHz; band 4 = 125-168 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 = 787-950 GHz. [SCI-90.00.00.00-00010-00]

2. In the long run, SSB receivers promise the best sensitivity and should be an ultimate goal of ALMA front end design (Ref: RD3 ASAC September 2001 Report, Appendix B). [SCI-90.00.00.00-00011-00]

3. It shall be possible to tune ALMA completely across the observable windows, i.e., reach a spectral line transition at any arbitrary frequency. [SCI-90.00.00.00-00020-00]

4. It shall be possible to configure the correlator to achieve sufficient resolution to resolve thermal linewidths (~0.05 km/s). [SCI-90.00.00.00-00030-00]

5. It shall be possible to retune ALMA to a new frequency within a band in a time not greater than 100 milliseconds. [SCI-90.00.00.00-00040-00]

6. It shall be possible to retune ALMA to a new frequency in a different band that is currently ``warm'' in a time not greater than 1.5 seconds. [SCI-90.00.00.00-00050-00]

7. It shall be possible to retune ALMA to a new frequency in a different band in a time not greater than 1 minute. [SCI-90.00.00.00-00060-00]

8. The required spectral dynamic range is 10000:1 for a few experiments, more generally 1000:1. [SCI-90.00.00.00-00070-00]

3.2 Sensitivity

1. ALMA shall routinely obtain sub-millijansky point source sensitivity at all observing frequencies, within a few minutes of integration time. [SCI-90.00.00.00-00080-00]
2. ALMA shall be sited at the Llano de Chajnantor, to take advantage of the extremely dry conditions (transparent atmosphere) there.[SCI-90.00.00.00-0090-00]
3. ALMA shall be comprised of 64 12-m antennas.[SCI-90.00.00.00-0100-00]
4. The antennas shall have surfaces with rms deviation from the ideal of 25 µm or less. [SCI-90.00.00.00-0110-00]
5. The antennas shall have forward gain of at least 0.95 to minimize spillover. [SCI-90.00.00.00-0120-00]
6. The ALMA feed systems shall be tapered to 13 dB at the edge of the antenna, to reduce spillover. [SCI-90.00.00.00-0130-00]
7. The antennas shall have less than 3% geometric blockage. [SCI-90.00.00.00-0140-00]
8. The antennas shall have aperture efficiency of 75% at 30 GHz. [SCI-90.00.00.00-0150-00]
9. The ALMA receivers shall be close to quantum limited, with SSB receiver temperatures of: $\boldsymbol{\alpha} \mathbf{h}\nu / k + 4$ K, where $\boldsymbol{\alpha} = 6$ for bands 1-6; $\boldsymbol{\alpha} = 8$ for bands 7 and 8, and $\boldsymbol{\alpha} = 12$ for bands 9 and 10. [SCI-90.00.00.00-0160-00]
10. The ALMA data sampling and transmission system shall have IF bandwidth of 8 GHz per polarization in continuum mode. [SCI-90.00.00.00-0170-00]
11. The full 8 GHz IF bandwidth per polarization per antenna must be processed by the correlator. [SCI-90.00.00.00-0180-00]
12. Correlator and electronics losses shall be 0.09 or less. [SCI-90.00.00.00-0190-00]

    Comment: This was 0.05 but for two-bit correlation .1 seems more appropriate.
13. Data storage and processing must not result in a loss in sensitivity (from, e.g., not storing enough bits per number). [SCI-90.00.00.00-0200-00]
14. 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. [SCI-90.00.00.00-0210-00]

3.3 Imaging

1. ALMA shall provide high fidelity imaging at spatial scales from of order degrees to 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. [SCI-90.00.00.00-0220-00]

2. 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 wobbling subreflectors in order to do atmospheric emission cancellation. [SCI-90.00.00.00-0230-00]

3. It shall be possible to dump data at rates of 1 msec for total power, and 16 msec for visibilities. [SCI-90.00.00.00-0240-00]

4. The ALMA antennas shall be relocatable, so that a variety of spatial scales of interest can be imaged, from a compact configuration of maximum baseline 150 m to a spread out configuration of maximum effective baseline 15 km. [SCI-90.00.00.00-0250-00]

5. The ALMA antennas shall point to 0.6 arcseconds with the aid of reference pointing. [SCI-90.00.00.00-0260-00]

6. The primary beams of the ALMA antennas shall be measured to an accuracy of 6% in power out to the FWHM point. [SCI-90.00.00.00-0270-00]

7. The ALMA antenna station locations shall be determined to an accuracy of 65 μm. [SCI-90.00.00.00-0280-00]

8. The visibility phase fluctuations must not exceed 1 radian (57 degrees) at 950 GHz[SCI-90.00.00.00-0290-00], implying:

    A. antenna delay stability of 50 fs (non-repeatable component);

    B. electronics stability of 30 fs (fluctuating component);

    C. ability to correct atmospheric fluctuating delay to 33 (1.1 + PWV) fs, where PWV is in millimeters.

9. The visibility amplitude fluctuations must not exceed 1% at frequencies less than 300 GHz, 3% at higher frequencies[SCI-90.00.00.00-0300-00], implying:

A. antenna gain stability under changing wind and gravity conditions;
B. electronics gain stability;
C. ability to measure and correct for atmospheric opacity and emission fluctuations.

3.4 Polarization

1. It shall be possible to observe simultaneously in full Stokes polarizations. [SCI-90.00.00.00-0310-00]

2. It shall be possible to determine the linearly polarized flux density to 0.1% in amplitude. [SCI-90.00.00.00-0320-00]

3. It shall be possible to determine the linearly polarized flux density to 6° in position angle. [SCI-90.00.00.00-0330-00]

4. It shall be possible to do very precise polarization work in band 7, requiring a quarter-wave plate [SCI-90.00.00.00-0340-00].

3.5 Flux Density Scale

The final visibilities must be on a calibrated flux density scale, accurate to within 1% at frequencies less than 300 GHz, and 3% at higher frequencies [SCI-90.00.00.00-0350-00].

3.6 Miscellaneous

1. It shall be possible to observe the sun at all frequencies [SCI-90.00.00.00-0360-00].

2. It shall be possible to phase up the array, with provision of an output sum port, either hardware or software [SCI-90.00.00.00-0370-00].

3. It shall be possible to use ALMA for VLBI, both with a single element, or with phased array (or subarray) output[SCI-90.00.00.00-0380-00].

4. It shall be possible to observe in four subarrays simultaneously, where here a subarray is defined as a set of antennas tuned to a frequency within a different band [SCI-90.00.00.00-0390-00].

3.7 Software

Detailed scientific software requirements are defined by the Science Software Requirements group (*q.v.*).

1. ALMA shall be ``easy to use" by both novice and expert astronomers [SCI-90.00.00.00-0400-00].

2. ALMA shall provide tools for preparation of proposals, preparation of observations, and reduction of data [SCI-90.00.00.00-0410-00].

3. There shall be a standard data reduction performed most projects successfully completed, resulting in a properly calibrated image cube (the ``pipeline"). This shall require minimal input from the astronomer in most cases [SCI-90.00.00.00-0420-00].

4 Appendices

A. The appendices are in LaTeX and will appear in pdf format in an accompanying document.