ALMA SCIENCE REQUIREMENTS

Robert Brown
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1998-08-08: First version
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Summary

U.S.: In the U.S. the scientific capabilities required in the ALMA were refined in community science workshops sponsored by the NRAO throughout the decade of the 1980s and confirmed by the September 1995 ALMA Science Workshop held in Tucson, AZ. Five reports were written following the Tucson Workshop that summarize the science goals in the following categories:

1. Cosmology and Extragalactic
2. Star Formation and Stellar Evolution
3. Galactic Molecular Clouds and Astrochemistry
4. Solar System
5. Sun and Stellar

These reports are available on the ALMA www pages. While these different scientific areas emphasize different capabilities, they all require precision imaging over the millimeter and sub-millimeter wavelength bands and over resolutions from arcseconds to less than a tenth of an arcsecond.

Europe: In Europe the scientific requirements for the LSA were similarly discussed and summarized in documents:

1. Science at high Z or the youth of the Universe
2. Planetary Formation or the youth of the Solar System

The arguments were summarized at a 1995 meeting in Garching, at which the motivation was written. The LSA science requirements were issued, and in the 1998 *April LSA/MMA Feasibility Study* options for combining the arrays were explored. At a meeting in 1999 February in Tucson, the science requirements were joined.

The two projects merged into the ALMA project in 1999 June, resulting in a merger of the similar science needs. The capabilities of the merged array were discussed at the 1999 October Workshop "Science with the Atacama Large Millimeter Array." The proceedings of this conference will be published. In the meantime, unedited versions of the contributions to the Proceedings of that conference may be obtained at the ALMA Conference raw material dropbox. The science requirements and the technical specifications that derive from this material are summarized in Table 2.1.

Table 2.1 ALMA Science Flowdown to Technical Specifications

Science Requirement and Examples	Technical Requirements Needed to Achieve
1. High Fidelity Imaging • Imaging spatial structure within galactic disks; • Imaging chemical structure within molecular clouds; • Imaging protostars in star formation regions	• Reconfigurable Array • Robust Instantaneous uv-coverage, $N_{ant} > 60$ • Precision Pointing, 6% of the HPBW • Antenna Surface Accuracy RMS = 20 microns • Primary Beam Deviations < 7% • Total Power and Interferometric Capability • Precise (1%) Amplitude Calibration • Precise Instrumental Phase Calibration (<10 degrees rms) • Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry
2. Precise Imaging at 0."1 Resolution • Ability to discriminate galaxies in deep images; • Imaging protoplanets orbiting protostars; • Imaging nuclear kinematics	• Interferometric baselines longer than 3 km • Precise Instrumental Phase Calibration (<10 degrees rms) • Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry
3. Routine Sub-milliJansky Continuum Sensitivity • To enable imaging of the dust continuum emission from cosmologically-distant galaxies; • To enable imaging of protostars and protoplanets throughout the Milky Way • To enable astrometric observations of solar system minor planets and Kuiper-belt objects	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover <5K, and aperture blockage <3% • Antennas of aperture efficiency > 75% • Wide correlated IF bandwidth, 16 GHz • Dual polarization receivers • Array collecting area, $ND^2 > 7000\ m^2$
4. Routine Milli-Kelvin Spectral Sensitivity • Spectroscopic probes of protostellar kinematics • Spectroscopic chemical analysis of protostars, protoplanetary systems and galactic nuclei • Spectroscopic studies of galactic disks and spiral structure kinematics	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover < 5 K, aperture blockage <3% • Antennas with aperture efficiency > 0.75 • Wide correlated IF bandwidth, 16 GHz • Dual polarization receivers • Array collecting area, $ND^2 > 7000\ m^2$ • Array collecting length, ND > 700 m

Science Requirement and Examples	Technical Requirements Needed to Achieve
5. Wideband Frequency Coverage • Spectroscopic imaging of redshifted lines from cosmologically-distant galaxies • To enable comparative astrochemical studies of protostars, protoplanets and molecular clouds • To enable quantitative astrophysics of gas temperature, density and excitation	• Receiver bandwidths matched to the width of the atmospheric windows • Tunable local oscillator matched to the bandwidth of the receivers • Cryogenic capacity > 1 W at 4 K
6. Wide Field Imaging, Mosaicking • Imaging galactic disks • Imaging the astrophysical context of star formation regions • Imaging surveys of large angular regions • Searches for dusty and luminous protogalaxies • Searches for minor planets in the solar system • Solar astrophysics	• Compact array configuration, filling factor > 0.5 • Instantaneous uv-coverage that fills more than half the uv-cells, $N_{ant} > 60$ • Precision pointing, 6% of HPBW • Antenna surface accuracy 20 microns • Total power <u>and</u> interferometric capability • Precise amplitude calibration, 1% • Precise Instrumental Phase Calibration (<10 degrees rms) • Correlator dump time 10 msec • Capability to handle data rates > 100 Mbyte/sec
7. Submillimeter Receiving System • Measurement of the spectral energy distribution of high redshift galaxies • Chemical spectroscopy using CI and atomic hydrides • Determination of the CII and NII abundance in galaxies as a function of cosmological epoch	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover < 5 K, aperture blockage <3% • Antennas with aperture efficiency > 0.75 • Precise Instrumental Phase Calibration (<10 degrees rms) • Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry
8. Full Polarization Capability • Measurement of the magnetic field direction from polarized emission of dust • Measurement of the magnetic field strength from molecular Zeeman-effect observations • Measurement of the magnetic field structure in solar active regions	• Measure all Stokes parameters simultaneously • Cross correlate to determine Stokes V • Calibration of linear gains to <1%
9. System Flexibility • To enable VLBI observations • To enable pulsar observations • For differential astrometry • For solar astronomy	• Ability to phase the array for VLBI • Sum port on the correlator for external processing • Sub-arraying, 4 subarrays simultaneously • Optics designed for solar observations

II. General Requirements

1. Frequency Coverage

ALMA needs eventually to cover all the available atmospheric windows between about 30 and 900 GHz. An initial implementation of the four frequency bands of highest scientific priority was specified by the ALMA Science Advisory Committee. These requirements are summarized in the Frequency Bands whitepaper. This requires an outstanding site as discussed in the "Recommended Site for the Millimeter Array" document.

2. Spectral Line and Continuum

The ALMA must operate as both a sensitive spectral line and continuum array. This implies using the widest continuum bandwidth practical from the point of view of the IF and the correlator. This appears now to be 8 GHz per IF; however, a 4 GHz per IF bandwidth may be accommodated should the wider bandwidth compromise receiver performance. A flexible correlator as described in the MMA Correlator Whitepaper will process a total of 16 GHz from each antenna. See also Chapter 10 of this Project Book and the ALMA Correlator Home Page.

3. Sensitivity

The array must maximize both point source and surface brightness sensitivity. For antennas with the same overall properties, this requires maximizing the different quantities, nD^2 (for point source sensitivity), nD (for surface brightness sensitivity in a sparsely filled array) and $n^{1/2}$ (for a tightly packed array or total power mode). See MMA Memo 177, MMA Memo 243, MMA Memo 273.

4. High Resolution

Given the expected brightness and size of sources considered in the science documents, this implies array configurations capable of providing precision, high fidelity imaging at 0.''1 angular resolution. Such configurations will have an extent of 4 km. In addition, a very extended configuration of 12 km diameter is needed for imaging at ~10 milli-arcseconds. This requirement demands the ALMA be adequately phase stable both internally and in the presence of atmospheric phase fluctuations. This will be discussed further in Section 3.

5. Large Source Imaging

On the other end of the angular scale, a further requirement exists for imaging objects both close to and bigger than the primary beam. This requirement has several implications. First, 3)+ 4) + 5) require that the array be reconfigurable into configurations optimized for the resolution and sensitivity required by each experiment. Second, the array must be able to make large mosaicked images (multiple pointings) to image regions on the order or larger than the primary beam. Third, the array must have a sensitive, stable total power system so that spatial frequencies smaller than are available in interferometer mode can be measured. Since the primary beams at the highest frequencies for antennas of 12 m diameter are < 10 arcseconds, modes 2 and 3 should be very common, perhaps being the vast majority of all observations with the array. A goal of the array is to produce images of similar size and resolution to those produced from optical telescopes, to facilitate direct comparison. Such a goal entails mosaicking.

6. High Fidelity Imaging

Especially in the modes discussed in 5), a significant fraction of the experiments and some the most important require high fidelity imaging. That is, the signal-to-noise must be high enough and the uv-coverage complete enough that even for complex sources errors in pointing and calibration will not degrade the scientific usefulness of the experiment.

Such problems require 1) excellent pointing, 2) high quality amplitude calibration and 3) accurate phase calibration; these topics will be discussed quantitatively in Section III.

7. Polarization

Observations of both linear and circular polarization of lines and continuum emission are a significant part of the ALMA science program. At centimeter and longer wavelengths interferometers produce linear polarization by correlating the opposite circular polarizations from different antennas, that is R with L and L with R. However, it appears technically difficult to do this at millimeter wavelengths across the broad bands needed for with the ALMA. Thus it seems best to observe in the more natural linear polarization with the ALMA. This means we crosscorrelate to calculate the V stokes parameter; we get I, Q and U from linear combinations of the two linear correlations. This requires both linears be present all the time and that either their relative gains remain very stable and/or we have the necessary internal calibration signals to measure their changes. (see MMA Memo 208 , Cotton, 1998 and ASAC Report on Polarization).

8. Solar Observations

Requirements for observing the sun are discussed in the Sun and Stars science document and by Bastian et al, 1998.

9. VLBI

The highest resolution with the ALMA will be obtained from VLBI observations using the ALMA as a single element. The requirements for this are discussed by Claussen and Ulvestad, 1998.

10. Pulsar/High Speed

Pulsar observations will require a gating mode with the correlator as well as a sum port which can be attached to specialized external recording equipment. This latter capability should also be available for other high speed phenomena such as solar or stellar flares.

III. Implications

The requirements summarized above imply the need for the array capabilities summarized here.

1. Phase Stability

As the observing frequency increases into the submillimeter the electrical path length through the atmosphere and through the electronics must be increasingly stable in order to enable the ALMA to produce high fidelity images.

- <u>Internal Phase Stability</u>. The electronics systems must be stable enough that they do not degrade the imaging relative to those path length fluctuations caused by atmospheric effects. For example, at 900 GHz the instrumental phase must be less than 10 degrees. A system to monitor and compensate for electrical path length changes in the instrument is necessary.

- <u>Atmospheric Phase Stability.</u> Atmospheric path length changes must be measured and corrected to preserve the capability for high fidelity imaging. Techniques to be developed to accomplish this include fast switching of the array antennas and radiometric techniques for measuring and correcting atmospheric phase distortion.

- *Fast Switching.* In this mode the antennas are rapidly cycled between a nearby calibrator source and the program source before the atmosphere can change significantly. The method has proven to be effective (MMA Memo 139, MMA Memo 173); it requires the antennas to have the capability to move between source and calibrator that are separated by less than 2 degrees on the sky on a cycle time of less than 10 seconds.

- *Radiometric Phase Correction.* Since water vapor in the atmosphere is responsible for both temporal changes in the sky opacity and changes in the electrical path length (the phase), measurements of the changing sky brightness can be used to infer changes in the atmospheric phase distortion. The techniques require stable radiometry and are best employed using either the 22 GHz atmospheric water line or the 183 GHz water line. The expected efficacy of the techniques, and the precision required by the ALMA, are discussed in MMA Memo 210. This has been updated in an ASAC White Paper.

2. Amplitude Stability

The capability to measure and maintain amplitude stability of the ALMA at the level of one percent is needed to combine imaging information from one array configuration to another reliably and permit accurate comparison of line strengths to determine such physical parameters as the excitation temperature of interstellar clouds or material in galactic nuclei. This will require use of an external calibration system such as discussed in MMA Memo 225. The specifications can be found in an ASAC White Paper and in ALMA Memo 289.

3. Integration Times

The fastest integration time needed by the ALMA will be driven as much by the need to perform total power continuum observations and fast on-the-fly mosaicking as it will be by the need to measure time variability in astronomical sources. This issue is evaluated quantitatively in MMA Memo 192.

4. Contingency Scheduling

This is an operational issue. The ALMA will need to be scheduled to allow the most demanding submillimeter observations, and mosaicking observations in the most compact configuration, to be done in conditions of favorable transparency and low prevailing wind. To accomplish this the array will need to be scheduled in near real time.

5. Data Flow

This is another operational issue. The astronomer will benefit by the ability to see his or her data in near real time. Most observations requiring longer than a few hours will be scheduled such that they are made over several source transits so little or no data is taken at extreme hour angles where the low elevation will compromise the system noise. This provides the opportunity for the astronomer to refine his or her observational techniques as the observations are in progress. The design requirement is for real-time imaging and for the capability for those images to be transmitted from the Chile site to the astronomer in the U.S. or elsewhere in a timely way. This requirement and its implications are explored in MMA Memo #164.