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ORIGINAL ARTICLE

# The Atacama Large Millimeter/Submillimeter Array: overview & status

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**Abstract** The Atacama Large Millimeter/Submillimeter Array (ALMA) is an international millimeter-wavelength radio telescope under construction in the Atacama Desert of northern Chile. ALMA will be situated on a high-altitude site at 5000 m elevation which provides excellent atmospheric transmission over the instrument wavelength range of 0.3 to 3 mm. ALMA will be comprised of two key observing components—a main array of up to sixty-four 12-m diameter antennas arranged in a multiple configurations ranging in size from 0.15 to ∼18 km, and a set of four 12-m and twelve 7-m antennas operating in a compact array ∼50 m in diameter (known as the Atacama Compact Array, or ACA), providing both interferometric and total-power astronomical information. High-sensitivity dual-polarization 8 GHz-bandwidth spectral-line and continuum measurements between all antennas will be available from two flexible digital correlators.

At the shortest planned wavelength and largest configuration, the angular resolution of ALMA will be 0.005″. The instrument will use superconducting (SIS) mixers to provide the lowest possible receiver noise contribution, and special-purpose water vapor radiometers to assist in calibration of atmospheric phase distortions. A complex optical fiber network will transmit the digitized astronomical signals from the antennas to the correlators in the Array Operations Site Technical Building, and post-correlation to the lower-altitude Operations Support Facility where the array will be controlled, and initial construction and maintenance of the instrument will occur. ALMA Regional Centers in the US, Europe, Japan and Chile will provide the scientific portals for the use of ALMA; early science observations are expected in 2010, with full operations in 2012.

**Keywords** Radioastronomy · Array · Millimeter · Submillimeter

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## 1 Introduction

ALMA has been designed to provide sensitive spectra and images in the wavelength range from 0.3 to 3 mm of atomic & molecular gas, nonthermal electrons and thermal dust in our Solar System, the Galaxy, nearby galaxies and high-redshift universe. These data will provide new and unique insights into the formation of galaxies, stars, planets and the chemical precursors necessary for life itself. ALMA will complement 8–10 meter optical/near-IR telescopes such as the Very Large Telescope, Gemini, Subaru and to the Hubble Space Telescope and its successor, the James Webb Space Telescope, with its ability to image dust enshrouded or cold molecular material.

Three exciting new observing capabilities have been used to define the primary technical specifications of ALMA: (1) the ability to detect spectral line emission from rotational spectral lines of the carbon monoxide molecule, atomic and ionized carbon in a galaxy with the properties of the Milky Way at a redshift of $z = 3$ in less than 24 hours of measurement; (2) to image the kinematics of gas in protostars and protoplanetary disks around young solar type stars out to a distance of 500 light years (this represents the distance to the nearby well-known clouds in Ophiuchus, Taurus or Corona Australis); and (3) to provide high-fidelity precise images at an angular resolution better than 0.1″.

ALMA's flexible design will support:

- Imaging the broadband emission from dust in evolving galaxies at epochs of formation as early as $z = 10$.
- Tracing the chemical composition of star-forming gas in galaxies throughout the history of the universe through measurements of molecular and atomic spectral lines.
- Measuring the motions of obscured galactic nuclei and Quasi-Stellar Objects on spatial scales finer than 300 light years.
- Imaging gas-rich heavily obscured regions that are collapsing to form protostars, protoplanets and pre-planetary disks.
- Measuring the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing.
- Producing sub-arcsecond images of cometary nuclei, hundreds of asteroids, Centaur and Kuiper belt objects together with images of planets and their moons.
- Observations of active solar regions to investigate particle acceleration on the suns surface.

## 2 Overview

ALMA is a partnership between Europe, Japan and North America in cooperation with the Republic of Chile. In Europe it is funded by the European Southern Observatory (ESO), in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan, and in North America by the US National Science Foundation (NSF), in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are carried out on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI). ALMA project development is coordinated by the Joint ALMA Office (JAO), based in Santiago Chile.

ALMA will be built on the Chajnantor altiplano in the Atacama Desert of northern Chile (see Figs. 1–2) at an elevation of slightly over 5000 m. The site is administered by the Chilean Ministry of National Assets and set aside by Presidential decree as a protected region for science. Measurements made since 1995 of the atmospheric trans-

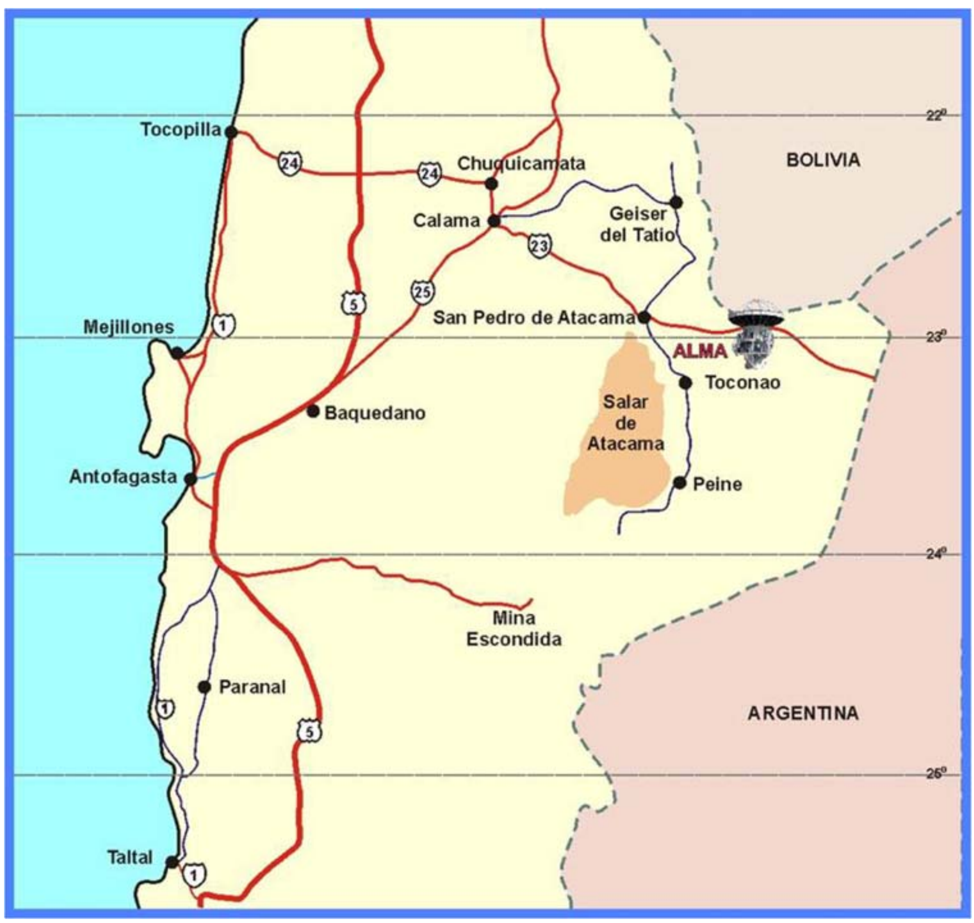


Fig. 1 Location of the ALMA array site near San Pedro de Atacama, northern Chile

**Fig. 2** The ALMA site at 5000 m (*photo: S. Radford*)

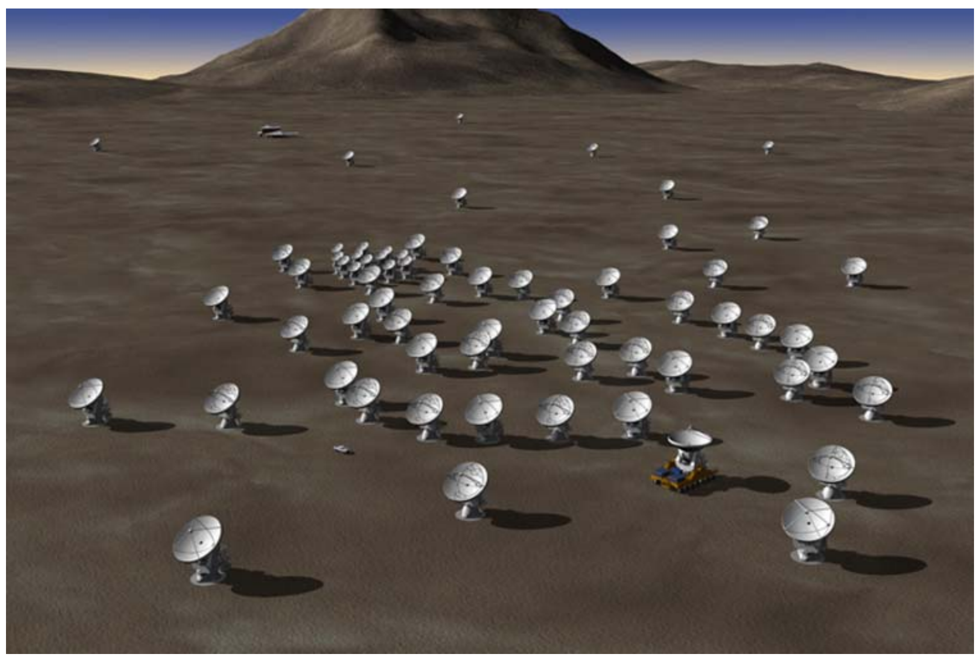

**Fig. 3** Simulation of ALMA main array plus ACA on the Chajnantor site

parency and stability confirm that the site has superior conditions for millimeter and submillimeter-wavelength astronomy.

The ALMA antennas each have a primary reflecting surface 12 meters in diameter with a parabolic cross-section. The materials used in their construction have been selected to allow the antennas to maintain their performance when fully exposed to the thermal variations and wind gusts imposed by the site environment. Each antenna is fully steerable, and more than 85 percent of the celestial sphere is above the horizon at the Chajnantor site (Fig. 3). The antennas can be moved (reconfigured) among 186 prepared antenna locations (see Fig. 4) to provide a range of spatial resolutions in the final astronomical images. Each station has a concrete foundation to support the antenna and provision for electrical power and fiber-optic based data communications. The antennas are moved by a pair of specially-designed rubber-tired antenna transporters currently under construction. ALMA will be delivered with a range of antenna configurations forming arrays as small as 150 meters in diameter (for the study of large or low surface brightness objects) and as large as 18.5 km in diameter (for the study of small, high surface brightness objects). The ACA's four 12 m and twelve 7 m antennas will be located in a more compact configuration ∼50-m in diameter to allow sensitive wide-field imaging and total power measurements. Three

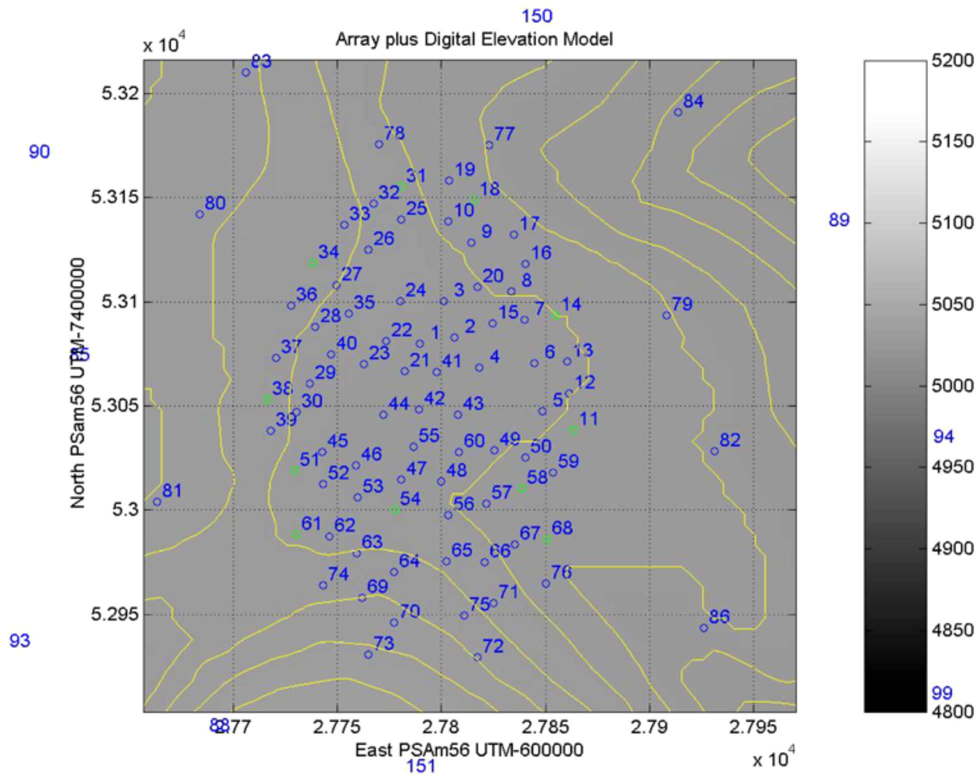


**Fig. 4** The antenna locations in the center of the main array

**Fig. 5** The Alcatel (*left*) and Vertex (*right*) antenna prototypes, built at the VLA site in New Mexico

different manufacturers are involved in producing antennas for ALMA: in Europe, XXXXX; in the US, Vertex RSI, and Mitsubishi Electric Company in Japan. During 2002–2005 these companies built prototype antennas at the NRAO VLA site in New Mexico (see Fig. 5) to explore the designs and engineering required to meet the demanding ALMA antenna technical specifications.

Each antenna will be equipped with a receiving system (Front End) capable of detecting astronomical signals in six wavelength bands. Two of the receiver bands are to be provided by NAOJ; the design and infrastructure of ALMA will allow the installation of up to ten receiver bands, eventually covering all the millimeter/submillimeter atmospheric transmission windows from 9 mm to 0.3 mm. The ALMA

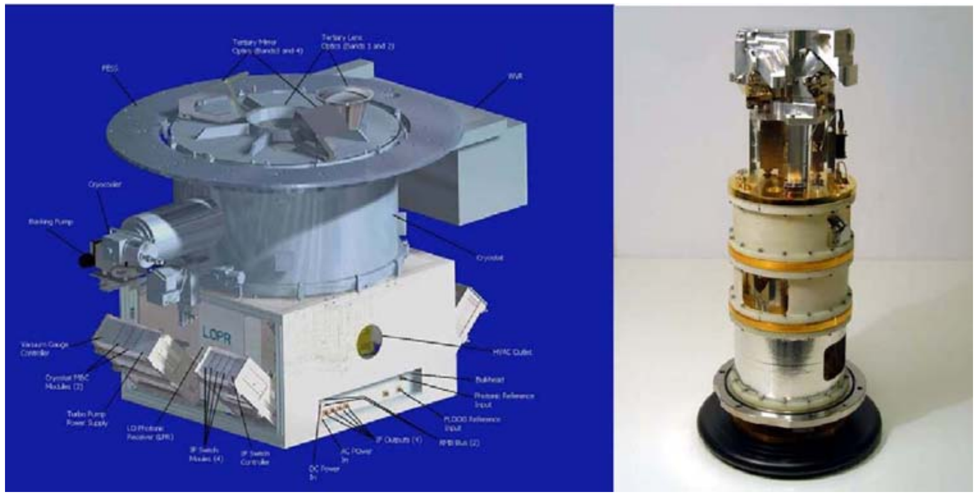


**Fig. 6** The Front End cryostat holding the antenna receivers (*left*), and a Band 9 cartridge (*right*)

receivers are coherent detectors, meaning they strictly preserve phase across the elements of the array. To achieve this, a common local oscillator signal is distributed to all antennas to convert the received astronomical signal to a much lower intermediate frequency that is transmitted to the high-site technical building, where it is correlated with the signals from all other antennas. Each frequency band receiver cartridge includes two receivers which operate in orthogonal linear polarizations, allowing the complete polarization state of received radiation signals to be measured. All receivers utilize superconducting mixers that operate at temperatures below 4 K. The receivers for each antenna are housed in a common cryogenic dewar located at the Cassegrain focus of each antenna (see Fig. 6).

Also mounted at the Cassegrain focus, but removed from the optical axis of the telescope, is a water vapor radiometer tuned to the 183 GHz line of terrestrial water emission. These devices will be used to correct for the atmospheric phase distortions caused by fluctuations in the amount of water vapor over the site, which would otherwise seriously limit the performance of the array over long baselines.

The received signals are amplified, digitized at the antenna and returned to the control building via fiber optics connections. In order to process the 16 GHz bandwidth IF, digital electronics subdivides that signal into eight 2 GHz sub-bands for transmission to the correlator. Timing signals and reference oscillators synchronize the operation of the antennas and the data collection. Buried power and fiber optic connections link each station to the Technical Building at the Array Operations Site (AOS-TB), which houses the array correlator and support electronics (including the LO system, fiber patch panel and computers) and contains an interim control room for array operations and hardware testing.

The astronomical signals are processed in the AOS-TB (Fig. 7) by a correlator: a special-purpose digital signal processor (see Fig. 8). It combines the digitized IF signals from all the antennas pair-wise and produces a set of complex correlation coefficients (fringe amplitude and phase) as a function of baseline and frequency. Images of the angular distribution of the radio emission from the astronomical source on the sky are created by Fourier inversion of these complex (phase and amplitude) data. For these recycling correlators the product of total bandwidth with number of channels is a constant. For a 2 GHz bandwidth, two polarizations, the correlator provides 128 spectral channels for each 2016 baseline correlation. The finest frequency resolution will be 31 kHz, or 0.1 $\mathrm{km\,s^{-1}}$ at 100 GHz.

To support the construction, maintenance and operation of ALMA, an Operations Support Facility (OSF) is under construction at 3000 m. The OSF provides a pleasant working environment for staff involved in a broad range of activities. Scientific operation of the array will be from a control room at the OSF via a high speed digital link to the AOS-TB. Infrastructure at the OSF will consist of the antenna service building, array control building, electronic laboratories, and office, administrative and residential facilities. The OSF is connected to the AOS by a road constructed to transport the antennas and the operations/maintenance staff.

The ALMA computing system has the task of scheduling observations on the array, controlling all the array instruments, including pointing the antennas, monitoring instrument performance, monitoring environmental parameters, managing the data flow through the electronics and presentation of these data to the correlator. The correlator output must be processed through an image pipeline, where it is calibrated and first-look images produced. Finally, the science data and all associated calibration data, monitor data, and derived data products are archived and made available for network transfer. In full operation, the standard output from ALMA will be calibrated images that have been processed in a standard set of reduction programs linked in

**Fig. 7** The center of the area planned for antenna stations; the AOS-TB is visible to the right

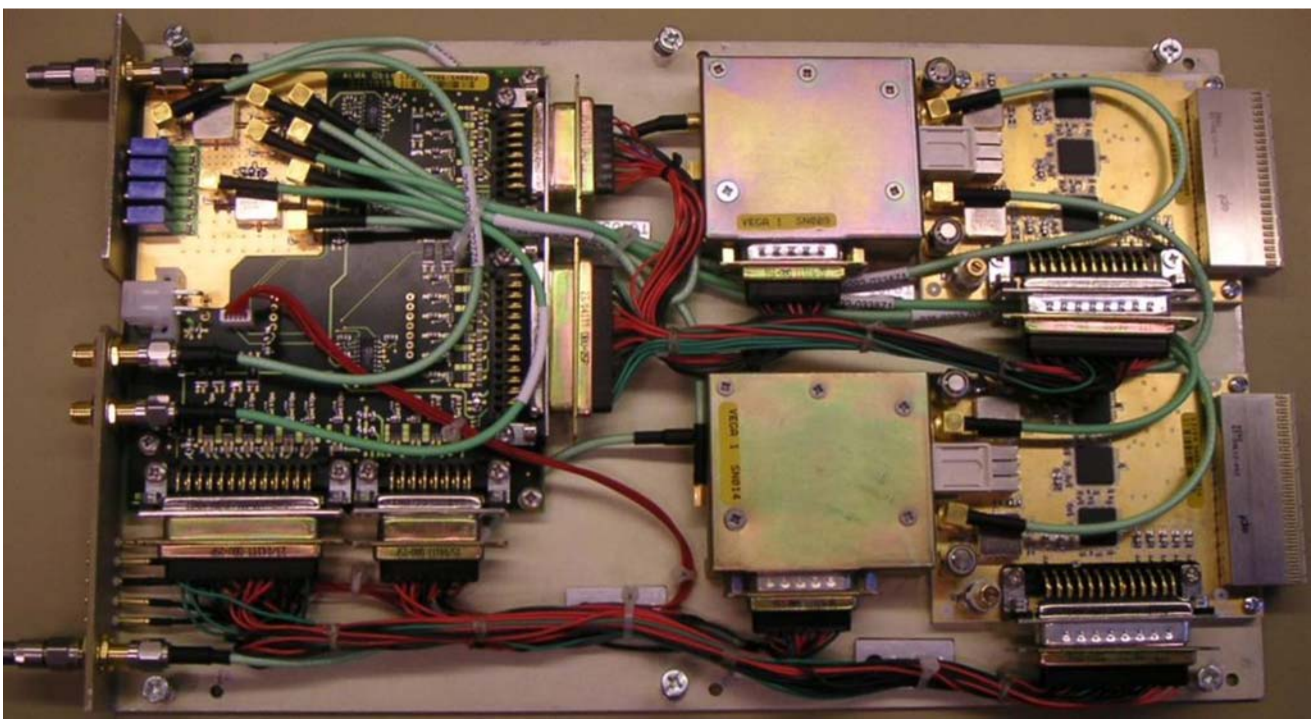

**Fig. 8** University of Bordeaux high-speed digitizer developed for ALMA

a pipeline. The user will receive these images, together with the correlated data (*uv*-data files), calibration files, and monitor information files. The average data rate is expected to be 6 MB/s, with a peak projected rate an order of magnitude higher. These results will also be stored in a data archive and delivered to the astronomers in a timely manner.

An office in Santiago will house ALMA administrative and local scientific staff. Additional support facilities in North America and Europe (the ALMA Regional Centers, or ARCs) will provide interfaces and user support between the instrument and the regional astronomical communities. Further image processing of the astronomical data will be carried out at the ARCs. A diverse community will use and benefit from ALMA's powerful scientific capabilities, and producing an easy-to-use system for both novices and experts is a system design goal.

Major upcoming milestones for the project include:

First production antenna accepted for start of assembly, integration & verification tasks: 2007
Completion of the AOS-TB and OSF buildings: 2007
Two-antenna interferometry at the OSF: 2008; three-antenna interferometry at the AOS: 2009
Call for Early Science proposals from the community: 2009
Start of full operations: Q3 2012.