High resolution sub-millimeter imaging with ALMA

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Abstract.
The Atacama Large Millimeter/Submillimeter Array (ALMA) is an international millimeter/submillimeter interferometer 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 most of the wavelength range of 0.3 to 3 mm. At the shortest planned wavelength and most extended configuration, the angular resolution of ALMA will be 5 milliarcseconds. This will give us the ability to, for example, image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars at a distance of 150 pc, or to image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as \( z = 10 \). 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.

At present, the first 7 antennas have been delivered and assembled at the Operations Support Facility (OSF) at 3000 m near San Pedro de Atacama. These antennas will be assessed by ALMA engineering and science staff and then moved to the high site for commissioning. Array commissioning will begin in 2009 with fringes and phase closure amongst at least 3 fully functioning antennas at the high site, and early science observations are expected in late 2010, with full operations in 2012.

1. Introduction
The Atacama Large Millimeter/submillimeter Array (ALMA) is an international radio telescope under construction in the Atacama Desert of northern Chile. The ALMA site is high (5000 m) and dry (typically <1 mm precipitable water vapor), leading to excellent atmospheric transmission over the instrument wavelength range of 0.3 to 3 mm (see the example in Fig. 1, produced using an atmospheric model provided by J. Pardo).

ALMA will provide sensitive spectra and images of atomic and molecular gas, thermal and non-thermal electrons and thermal dust in our Solar System, the Galaxy, nearby galaxies and the high-redshift universe. These data will provide new insights into the formation of galaxies, stars, planets and the chemical precursors necessary for life. ALMA will complement telescopes such as the Very Large Telescope, Gemini, Subaru and the James Webb Space Telescope with its ability to image dust enshrouded objects and cold molecular material.
Figure 1. ALMA site millimeter/submillimeter transmission for 0.25 mm of precipitable atmospheric water vapor. ALMA receiver bands are indicated in the top panel, with those arriving first marked in red.

Figure 2. Three antennas being transported across Chile to the Operations Support Facility (OSF).
ALMA’s flexible design will enable:

- 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 within obscured galactic nuclei and quasistellar objects on spatial scales finer than 300 light years;
- Imaging and spectroscopy of 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 resolution images of cometary nuclei, hundreds of asteroids, Centaur and Kuiper belt objects as well as images of planets and their moons;
- Observations of active solar regions to investigate particle acceleration on the Sun’s surface.

Construction began in 2002 with site development and hardware/software development in the partner institutes. Japan formally joined ALMA in 2004, bringing additional resources to develop the Atacama Compact Array (or ACA). ALMA has two key observing components – an array of up to sixty-four 12 m diameter antennas arranged in multiple configurations ranging in size from 0.15 to $\sim 16$ km; and the ACA, four 12 m and twelve 7 m antennas operating in closely-packed configurations of $\sim 50$ m in diameter.

Figure 3. A Vertex antenna at the OSF.
Both arrays are capable of providing interferometric and total-power astronomical information, and cross-correlation of the arrays, important for both scientific and array calibration reasons, is planned. High-sensitivity, dual-polarization 8 GHz-bandwidth spectral-line and continuum measurements between all antennas will be available from two flexible digital correlators. Table 1 lists the current ALMA specifications.
### Table 1. ALMA Technical Summary

**Array**
- Number of Antennas (N) up to 64 (+ 16 ACA)
- Total Collecting Area (π/4 ND²) up to 7238 m² (+ 913 m² ACA)
- Angular Resolution 0.2" λ (mm)/baseline (km)

**Array Configurations**
- Compact: Filled area diameter 150 m (+ ~50 m ACA)
- Maximum Baseline (weighted) 14.5 km
- Total Number of Antenna Stations 186 (+ 22 ACA)

**Antennas**
- Diameter (D) 12 m (+ 12 & 7 m ACA)
- Surface Accuracy 25 μm RMS
- Pointing 0.6" RMS in 9 m/s wind
- Path Length Error <15 μm during sidereal track
- Fast Switch 1.5° in 1.5 secs, (1.8 secs ACA)
- Total Power Instrumented and gain stabilized
- Transportable Special-purpose vehicle on rubber tires

**Front Ends**
- 84 -116 GHz
- 125 - 163 GHz
- 211 - 275 GHz
- 275 - 370 GHz
- 385 - 500 GHz
- 602 - 720 GHz
- 787 - 950 GHz

**Water Vapor Radiometer** 183 GHz

**Signal Transmission**
- Bandwidth 8 GHz, each polarization
- IF Transmission Digital (digitized at antennas)
- Local Oscillator Photonic

**Correlator**
- Correlated Baselines 2016 (+ 120 ACA)
- Bandwidth 16 GHz per antenna
- Spectral Channels 4096 per IF

**Data Rate**
- Data Transmission from Antennas 120 Gb/s per antenna, continuous
- Signal Processing at the Correlator 1.6 x 10^16 multiply/add per second
At the shortest planned wavelength and largest configuration, the angular resolution of ALMA will be $\sim 0.005^\circ$. Each antenna will be equipped initially with a receiving system (Front End) capable of detecting astronomical signals in seven wavelength bands. 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 (see top panel in Fig. 1). ALMA uses 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 which would otherwise limit the performance of the array over long baselines and/or shorter wavelengths. Amplitude calibration of ALMA will use a multiple-temperature load system and standard astronomical flux-density benchmarks.

A complex optical fiber network will transmit the digitized astronomical signals from the antennas to the two correlators in the Array Operations Site Technical Building, and post-correlation, to the lower-altitude Operations Support Facility (OSF) data archive, situated approximately 30 km away. Initial construction and maintenance of the instrument, as well as array control, are done at the OSF. ALMA Regional Centers (ARCs) in the US, Europe and Japan will provide the scientific portals for the use of ALMA; the astronomical community will interface with ALMA using tools and assistance provided by the ARCs, allowing further calibration, image processing and analysis of the astronomical data. A primary goal of ALMA development is to produce an easy-to-use system for both novices and experts, allowing the involvement of a diverse research community.

The ALMA computing system has the task of scheduling observations on the array, controlling
Figure 7. Left: Two quadrants of the 64-input correlator under test in Charlottesville. Right: The installation of the ACA correlator at the OSF.

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 are produced. Finally, the science data and all associated calibration data, monitor data, and derived data products are archived and made available for network transfer. An office in Santiago will house ALMA administrative and local scientific staff for ALMA.

Current status:

• Site: AOS Technical Building and OSF facilities completed in early 2008. Construction of the AOS antenna stations begin in early 2008.
• Antennas: seven antennas are undergoing assembly at the OSF (April 2008); the final deliveries are scheduled for late 2011. The ALMA transporter has been formally accepted and is undergoing further testing with a dummy antenna load at the OSF. One move of an antenna using the transporter has been successfully completed.
• Receivers & electronics: first Front End has been shipped to Chile for testing and use in antenna integration. Digital transmission systems and local oscillator systems have been tested at the ALMA Test Facility in New Mexico.
• Correlators: The Japanese correlator has been installed at the high site; the bilateral correlator first quadrant is complete and awaiting shipping. Interferometry is now possible using the 2-antenna correlator at the ALMA Test Facility and is expected at the OSF by the end of 2008.
• Computing: the distributed computing team is producing software for all aspects of array testing, commissioning, operations and offline data reduction.
• Call for Early Science proposals from the community is expected in 2010.
• Start of full operations (66 antennas) is expected in late 2012.
Figure 8. Three Vertex antennas assembled in the Site Erection Facility.

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Figure 9. One of the ALMA antennas being moved on the transporter.

Figure 10. A partial spectrum of Orion taken with non-production receivers at the ALMA Test Facility. These observations were made as a demonstration of the end-to-end software capabilities.