PROCEEDINGS OF SCIENCE

The Atacama Large Millimeter/submillimeter Array

A. J. Beasley[1], A. Peck
Atacama Large Millimeter Array/Joint ALMA Office
El Golf 40, Piso 18, Las Condes Santiago, Chile
tbeasley@alma.cl
apeck@alma.cl

The Atacama Large Millimeter/submillimeter Array (ALMA) is a radio telescope under construction in the Atacama Desert of northern Chile by an international partnership. ALMA is situated at 5000m elevation on the Chajnantor plateau, where excellent atmospheric transmission over the instrument wavelength range of 0.3 to 3 mm is found. ALMA will be comprised of an array of 12-m diameter antennas arranged in multiple configurations ranging in size from 150 m to ~16 km, and a closely-packed array of 7-m diameter antennas known as the Atacama Compact Array. This combination will provide sensitive interferometric and total-power astronomical information at millimetre and submillimeter wavelengths over a broad range of angular scales. High-sensitivity full-polarization spectral-line and continuum measurements between all antennas will be available from two flexible digital correlators.

Array control and support will primarily be carried out at the Operations Support Facility situated 30 km away at 3000m elevation, and ALMA Regional Centers in the US, Europe and Japan will provide the scientific portals for the use of the instrument. In this talk we will review the construction project status and early operations of ALMA.

From planets to dark energy: the modern radio universe
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1 Speaker

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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 (5000m) and dry (typically <1mm 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).

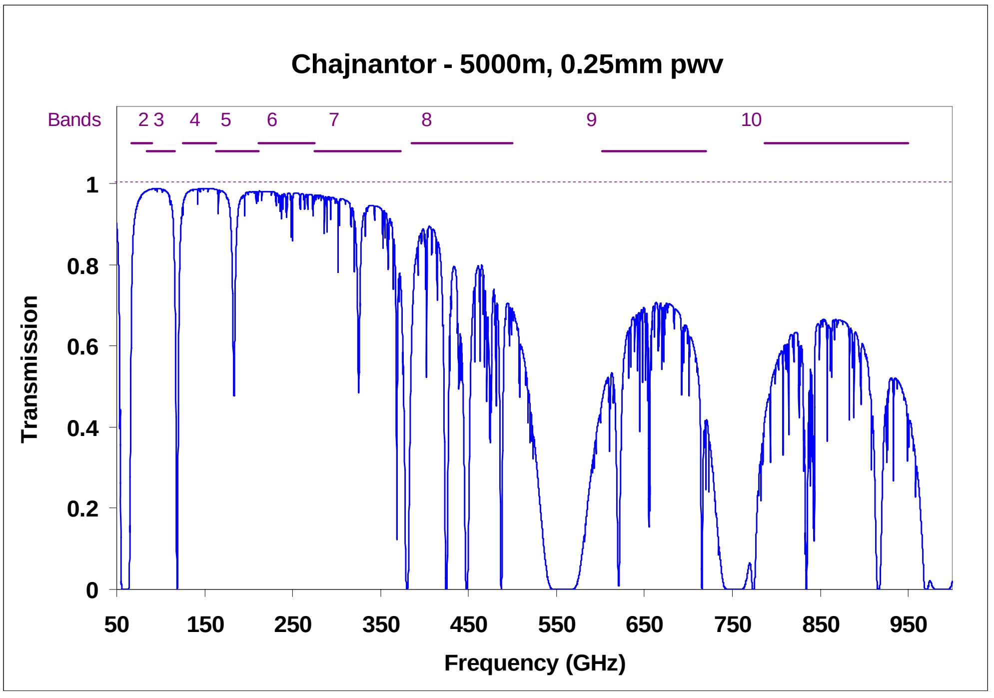

Figure 1: ALMA site millimeter/submillimeter transmission for 0.25mm of precipitable atmospheric water vapor. ALMA receiver bands are indicated in the top panel.

ALMA will provide sensitive spectra and images of atomic & molecular gas, thermal & 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 or cold molecular material.

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 of 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 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.

For more complete descriptions of ALMA science see www.alma.info.

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 ~16 km, and the ACA four 12-m and twelve 7-m antennas operating in closely-packed configurations ~50m in diameter. The distribution of antennas in the largest configuration is shown in Fig. 2.

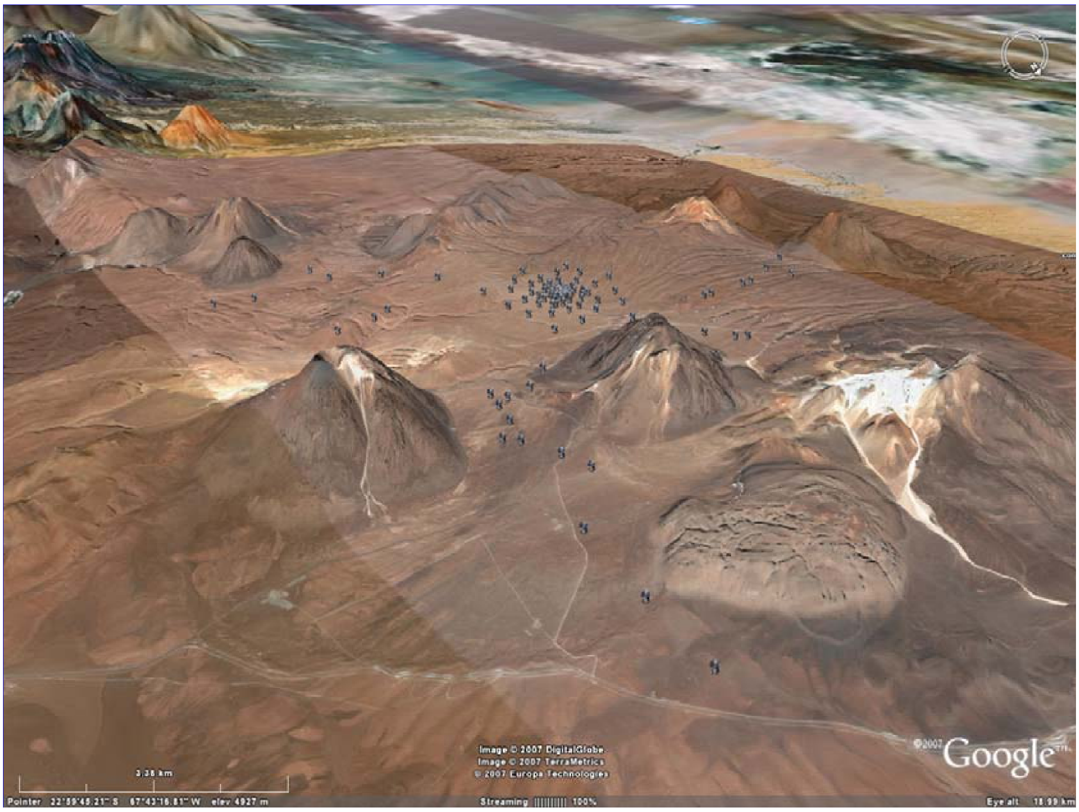

Figure 2: Google Earth Image of Chajnantor area indicating ALMA antenna locations in largest array configuration.

Both arrays are capable of providing interferometric and total-power astronomical information, and cross-correlation of the arrays (important for both scientific reasons and array calibration) 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 ($\pi/4$ ND^2)	**Up to 7238 m^2 + 913 m^2 *(ACA)***
Angular Resolution	**0.2" λ (mm)/baseline (km)**
Array Configurations	
Compact: Filled area diameter	**150 m + ~50m *(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 microns RMS**
Pointing	**0.6" RMS in 9 m/s wind**
Path Length Error	**< 15 microns during sidereal track**
Fast Switch	**1.5 degrees in 1.5 secs, 1.8 secs *(ACA)***
Total Power	**Instrumented and gain stabilized**
Transportable	**Special-purpose vehicle on rubber tires**
Front Ends	
Band 3: 84 -116 GHz	
Band 4: 125 – 163 GHz	***All receivers:***
Band 6: 211 - 275 GHz	***- Dual polarization***
Band 7: 275 - 370 GHz	***- Noise performance limited***
Band 8: 385 – 500 GHz	***- SIS***
Band 9: 602 - 720 GHz	
Band 10: 787 – 950 GHz	
Water Vapor Radiometer	**183 GHz**
Signal Transmission	
Bandwidth	**8 GHz, each polarization**
IF Transmission	**Digital (digitized at antennas)**
Local Oscillator	**Photonic**

<u>Correlator</u>	
Correlated Baselines	**2016 + 120 *(ACA)***
Bandwidth	**16 GHz per antenna**
Spectral Channels	**4096 per IF**
<u>Data Rate</u>	
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 ~0.005”. 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. Construction, maintenance and array control of the instrument are performed 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 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. An office in Santiago will house ALMA administrative and local scientific staff and support the Chilean astronomy community’s use of ALMA.

Current status:

- Site: completion of AOS Technical Building and OSF facilities scheduled for late 2007. Construction of the AOS antenna stations will begin in early 2008.
- Antennas: five antennas are undergoing assembly at the OSF (Dec. 2007); the final deliveries are scheduled for late 2011. The ALMA transporter has been formally accepted and is expected at the OSF in March 2008.
- Receivers & electronics: testing of first production receiver in underway, with shipping to Chile expected early 2008. Digital transmission systems and local oscillator systems have been tested at the ALMA Test Facility in New Mexico.
- Correlators: The Japanese correlator will be installed at the high site late 2007; the bilateral correlator first quadrant is complete and awaiting shipping. Interferometry is now possible using the 2-antenna correlator at the ALMA Test Facility.
- 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 3: The Array Operations Site Technical Building, housing the two correlator and central local oscillator equipment.

Figure 4: A Vertex antenna situated at the OSF undergoing assembly.

Figure 5: The ACA Fujitsu correlator undergoing testing in Japan.

Figure 6: Front-end cryostats in development at Rutherford Appleton Laboratories.

Figure 7: The Operations Support Facility, located ~30km from the Array Operations Site.

Figure 8: Construction at the OSF - antenna assembly area

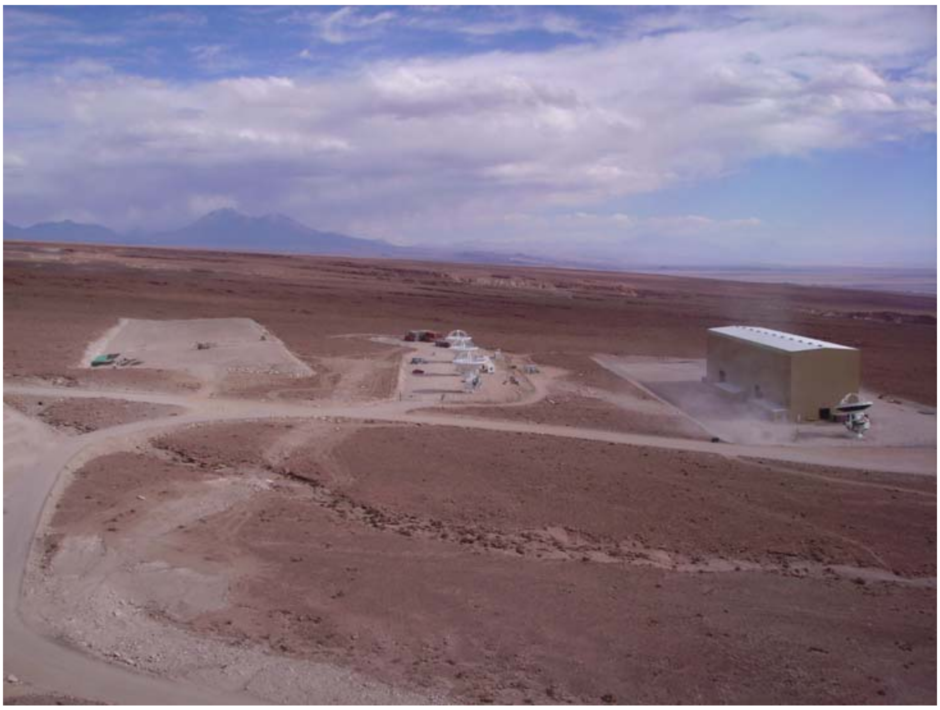

Figure 9: The OSF antenna contractor areas (left Alcatel, middle Mitsubishi, right Vertex).

Figure 10: The ALMA antenna transporter (photo courtesy ESO).

Figure 11: A Mitsubishi antenna undergoing holographic surface measurement.

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); this paper is presented by the JAO on behalf of the scientists, engineers, technical and administrative staff of ALMA.