Mem. S.A.It. Suppl. Vol. 3, 292

Memorie della
Supplementi

ALMA: the project becomes real

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Abstract. The ALMA project is now entering in the construction phase. After the signature of the bilateral agreement between NSF and ESO, which defines scopes and division of contributions, the ALMA Board is working on the management structure. Here we report about the status of the project, starting from the continuous evolution of the scientific goals and of the technologies which are at the basis of the instrumental parameters.

1. Introduction

The Atacama Large Millimeter Array (ALMA) is a revolutionary instrument in its scientific concept, in its engineering design, and in its organization as a global scientific project. ALMA will provide precise images in the millimeter/submillimeter wavelength range with extreme sensitivity and spectral capability. The science provided by ALMA spans from the detection of galaxies in formation seen as they were twelve billion years ago; it will reveal the chemical composition of stars and planets still in their formative process; and it will provide an accurate census of the size and motion of the icy fragments left over from the formation of our own solar system that are now orbiting beyond the planet Neptune. These science objectives, and many hundreds more, are made possible owing to the design concept of ALMA that combines the imaging clarity of detail provided by a 64 antenna interferometric array together with the brightness sensitivity of a single dish antenna. ALMA will be sited in the Altiplano of northern Chile at an elevation of 5000 meters (16,500 feet) above sea level. The ALMA site is the highest, permanent, astronomical observing site in the world. On this remote site superconducting receivers that are cryogenically cooled to less than 4 degrees above absolute zero will operate on each the 64 12-meter diameter ALMA antennas. The signals from these receivers will be digitized and transmitted to a central processing facility where they are combined and processed at a sustained rate greater than 10^{16} operations per second. From the technical point of view, ALMA is composed of 64 high-accuracy parabolic reflectors, superconducting electronics cryogenically cooled, and optical transmission of terabit data rates, all operating together, continuously, on a site high in the Andes mountains. Each antenna element is a 12 meters parabolic reflector with Cassegrain optics. The number and size of the anten-

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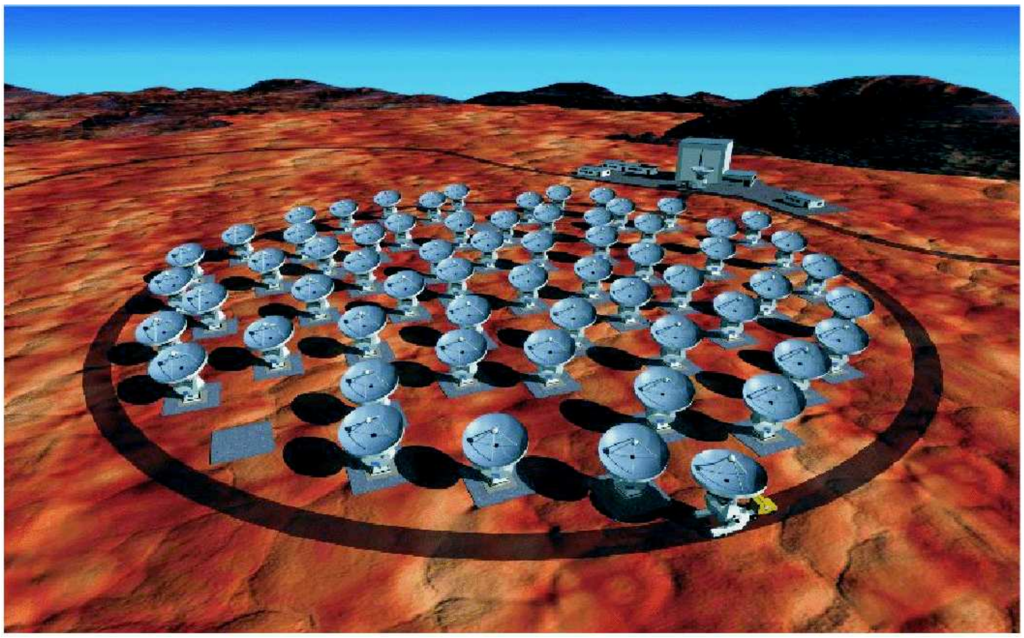

Fig. 1. Artistic view of the array

nas is determined from imaging requirements; their accuracy, stability and weight are dictated by the environmental operating condition and by the foreseen highest operational frequency of about 900 GHz. Each antenna is fully steerable; more than 85 percent of the celestial sphere is visible from the Chajnantor site. The antennas are all movable among prepared antenna foundations, or stations. Each station has a concrete foundation to support the antenna and provision for electrical power and data communications. The antennas are moved by a specially-designed antenna transporter. The ability to move the antennas, and hence to rearrange them on the ground, provides ALMA with the capability to match its angular resolution to the science requirements of its users. Antenna configurations as small as 150 meters in diameter (for the study of large or low brightness objects) and as large as 14 km in diameter (for the study of small, high brightness objects) are deliverables of the ALMA construction project.

2. Science with ALMA

ALMA must be a general purpose telescope to study at high angular resolution millimeter wavelengths emission from all kinds of astronomical sources. ALMA will improve by an order of magnitude the present generation of millimeter-wave interferometric arrays and will allow astronomers to:

- image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z=10;
- trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies throughout the history of the universe;
- reveal the kinematics of obscured galactic nuclei and Quasi-Stellar Objects on spatial scales smaller than 300 light-years;
- assess the influence that chemical and isotopic gradients in galactic disks have on the formation of spiral structure;

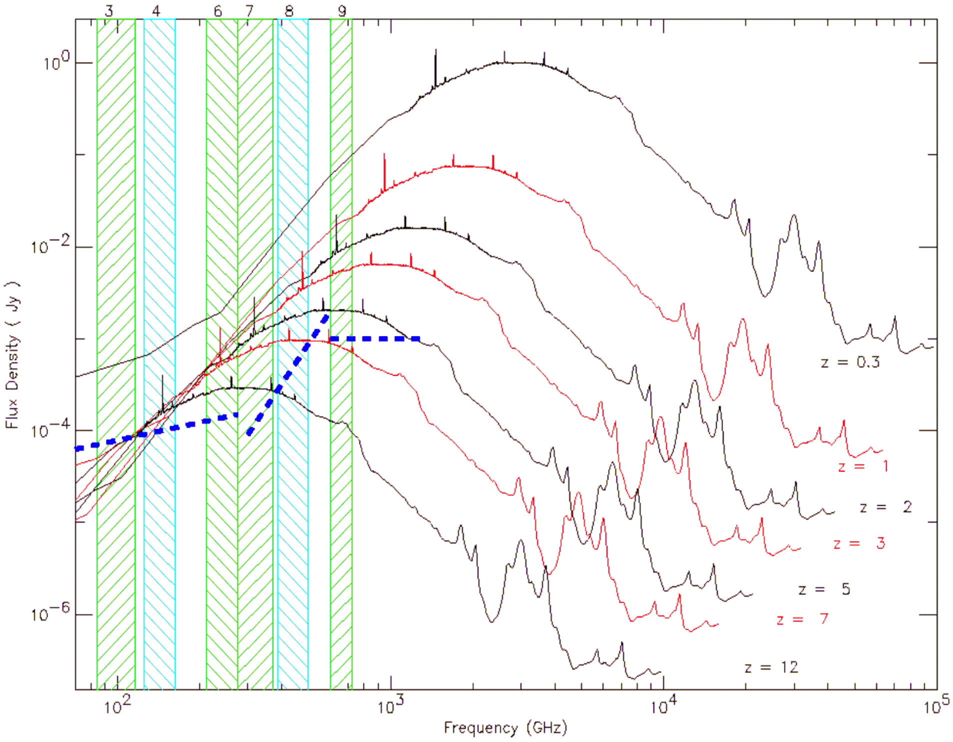

Fig. 2. The high redshift Universe and ALMA band coverage

- image gas-rich, heavily obscured regions that are spawning protostars, protoplanets and pre-planetary disks;
- reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;
- obtain unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper-belt objects in the solar system along with images of the planets and their satellites;
- image solar active regions and investigate the physics of particle acceleration on the surface of the sun.

3. Timeline, organization and budget

After a definition and feasibility Phase I which lasted until the end of 2002, the project is officially started according to the schedule of Table 1.

The complexity of the instrument is such that a budget of about 600 MEuro is planned for the basic configuration, leaving to a possible Japanese partnership the completion of receiver channels from four to nine and the construction of a smaller Compact Array. Only a complex organization could be able to manage the ALMA construction and operation. The two funding parties, represented by North America (USA and Canada) and by Europe (ESO and Spain) established a Joint Board and a Joint Project Office with the final aim of Joint ALMA Observatory. The management structure is based on the concept of Integrated Product Teams with the task of design and production responsibility of the numerous items which compose the in-

Start antenna evaluation at ALMA test facility	Q4 2002
Begin initial phase of civil works in Chile	Q4 2003
Central back-end system ready to install at array site	Q1 2005
Initial phase of civil works in Chile complete	Q2 2005
First antenna-based back-end subsystem ready for installation at OSF	Q2 2005
First production antenna available in Chile at OSF	Q4 2005
Initial front-end subsystem available at OSF	Q4 2005
Start early science operations	Q3 2007
Completion of construction project	Q4 2011
Start full science operations	Q1 2012

Table 1. Major milestones in the ALMA project

strument. It is expected that almost every task should be lead by scientific astronomy and radioastronomy institutions interacting with industries. Only antenna production will be entirely provided by the industry on the basis of call for tender following the evaluation of the two prototypes now assembled in Socorro for test of single antenna performance and for single baseline interferometer evaluation.

It is the fundamental goal to begin operating ALMA as an interferometric array for scientific research as soon as it is possible (2007):

1. in order make use of experienced scientists to uncover hardware and software problems in the course of doing their research so that such problems are readily identified and it is possible to implement design changes to solve those problems early in the construction project;
2. to refine array instruments and techniques that depend on actual array site conditions that affect science research programs;
3. to demonstrate ALMA science capabilities;
4. to gain early operating experience that can be fed back to the construction project and changes can be made to improve reliability or maintainability of the array.

The plan for an early operation is based on the delivery of an adequate number of antennas, probably seven, and of at least two receiver channels.

4. The instrument

The development of the ALMA project follows the lines of the technical summary reported in Table 2.

Beside the their enhanced electromagnetic performances, another important antenna requirement is its capability of fast switch between two adjacent positions. At high frequencies the interferometer will be limited by the atmosphere. The use of reference calibrators will represent the best solution to overcome this problem. Each antenna will be equipped with a receiving system, or front-end, capable of detecting astronomical signals in four frequency bands. These are coherent detectors, meaning that they employ a common local oscillator signal to convert the received signal frequency to a much lower intermediate frequency that is subsequently transmitted to the central electronics building where it is combined with the signals from all other antennas. The local oscillator is a deliverable of the front-end electronics task, but the intermediate frequency transmission and processing is a task of the back-end subsystem. Further, each of the four frequency band cartridges includes two receivers operating in orthogonal senses of linear polarization so that the full polarization state of the received radiation may be measured. The receivers are based on superconducting mixers that operate at temperatures below 4 °K. All of the cartridges are included in a single cryogenic dewar located at the Cassegrain focus. Also at the Cassegrain

Array

Number of antennas	64
Total Collecting Area	7238 m^2
Total Collecting Length	768 m
Angular Resolution	0.2"

Array Configurations

Compact Filled	150 m
Continuous Zoom	200-5000 m
Highest Resolution	14 km
Total Antenna Stations	250

Antennas[1]

Diameter	12 m
Surface Accuracy	20 μm RMS
Pointing	0.6" RMS, 9 m/s wind
Path Length Error	$< 15\ \mu$ in sidereal track
Fast Switch	1.5° in 1.5 sec
Transportable	By vehicle with tires

Front-Ends[2]

84 - 119 GHz SIS	All frequency bands:
211 - 275 GHz SIS	• Dual polarization;
275 - 370 GHz SIS	• Noise performance
602 - 720 GHz SIS	limited by atmosphere;
WV Radiometer	183 GHz

Intermediate Frequency (IF)

Bandwidth	8GHz per polarization
IF Transmission	Digital

Correlator

Correlated baselines	2016 (= 64 × 63/2)
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	1.6×10^{16} multiply/add per second

[1] The antenna specifications are detailed in Request for Proposals for a Prototype Antenna for the Millimeter Array/Large Southern Array, dated March 30, 1999.

[2] These four frequency bands are those required on the first-light ALMA as specified by the ALMA Science Advisory Committee at committee meeting of March 11, 2000. Receivers in six additional atmospheric windows are deferred to future development.

Table 2. ALMA Technical Summary

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. This instrument is used to compensate, for each antenna, the effects of atmospheric propagation. The output from the front-end is amplified and digitized at the antenna by the back-end electronics. In order to process the 8 GHz bandwidth of the intermediate frequency signal, the back-end electronics subdivides that signal into four 2 GHz sub-bands for transmission to the correlator, which combines the digitized intermediate frequency signals from all the antennas pair wise; there are 2016 pairs of antennas in ALMA. Images of the astronomical source are created by Fourier inversion of these complex (phase and amplitude) data. The 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 back-end electronics and presentation of these data to the correlator. The output of the correlator is again responsibility of the computing task where it is processed through an image pipeline, calibration is applied, 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. The first generation correlator has been built by NRAO and it is expected to provide most of the data analysis for the initial activity.

5. ALMA operations and logistics

The major objective for ALMA science operations is to make the millimeter and submillimeter Universe accessible to a wide range of astronomers, particularly those who are not specialists in this area. Therefore users need to find a complete organization from the level of the proposal preparation to the final data analysis. Associated with this constrain, ALMA will be organized, even logistically, in different structures. In Chile, the ALMA Observatory will manage the Array Operation Site (AOS), where the array will be operated remotely from the Operation Support Facility (OSF), located near San Pedro de Atacama. A Central office in Santiago will manage the standard pipeline data reduction and data quality assessment. All astronomical and monitor data and pipeline-produced images, once checked, are transmitted to the joint ALMA archive, with copies sent to the Regional Support Centers (RSC), to be distributed to the users. The Santiago facility will contain offices for the staff astronomers to pursue their personal research as well. The Santiago office is also the natural location for all those business and administrative functions. In Europe and North America several RSC are planned for the direct interaction with users and developments in the observational procedures and processing.

6. Conclusions

The agreement between NSF and ESO, which defines for ALMA scopes and activities, has been signed on 25 February 2003. The ALMA project is now proceeding toward the construction phase with a large effort of coordination between numerous institutions and groups of experts in widely different areas.

Acknowledgements. I thank Pietro Bolli for the helpful suggestions. A large amount of information about the ALMA project can be found in the web sites: http://www.alma.nrao.edu/ and http://http.hq.eso.org/projects/alma/.
An italian site is also available: http://www.arcetri.astro.it/science/ALMA/