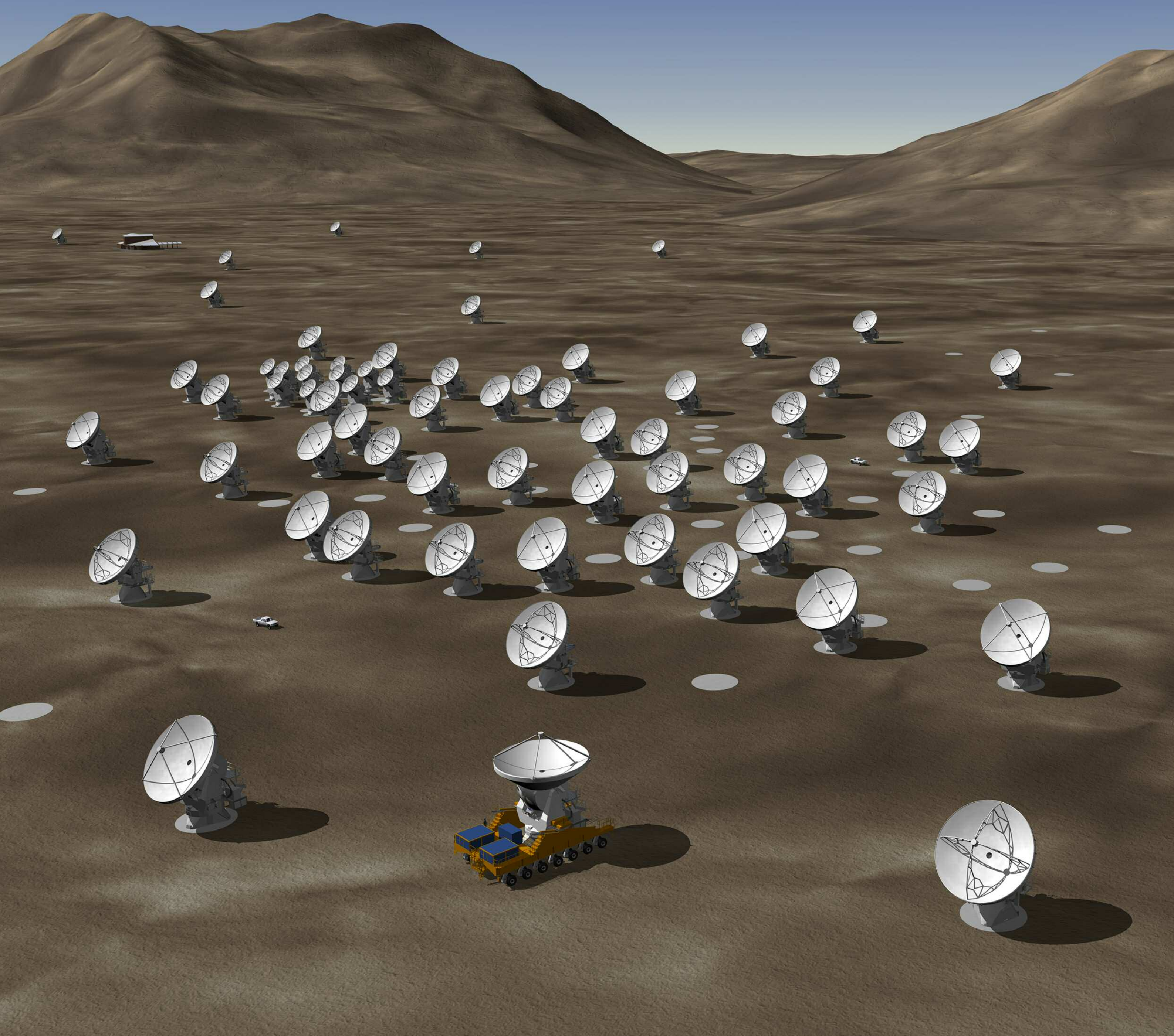
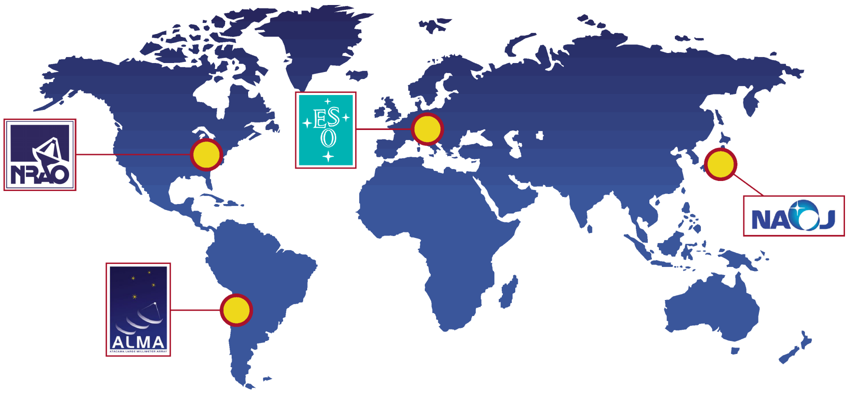
ALMA

Exploring the Universe
at Millimetre Wavelengths



The ALMA project is a partnership between Europe, Japan and North America in cooperation with the Republic of Chile. ALMA is funded in Europe by ESO, in Japan by the National Institutes of Natural Sciences in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation in cooperation with the National Research Council of Canada. ALMA construction and operations are led 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.

http://www.eso.org/projects/alma/
http://www.alma.info



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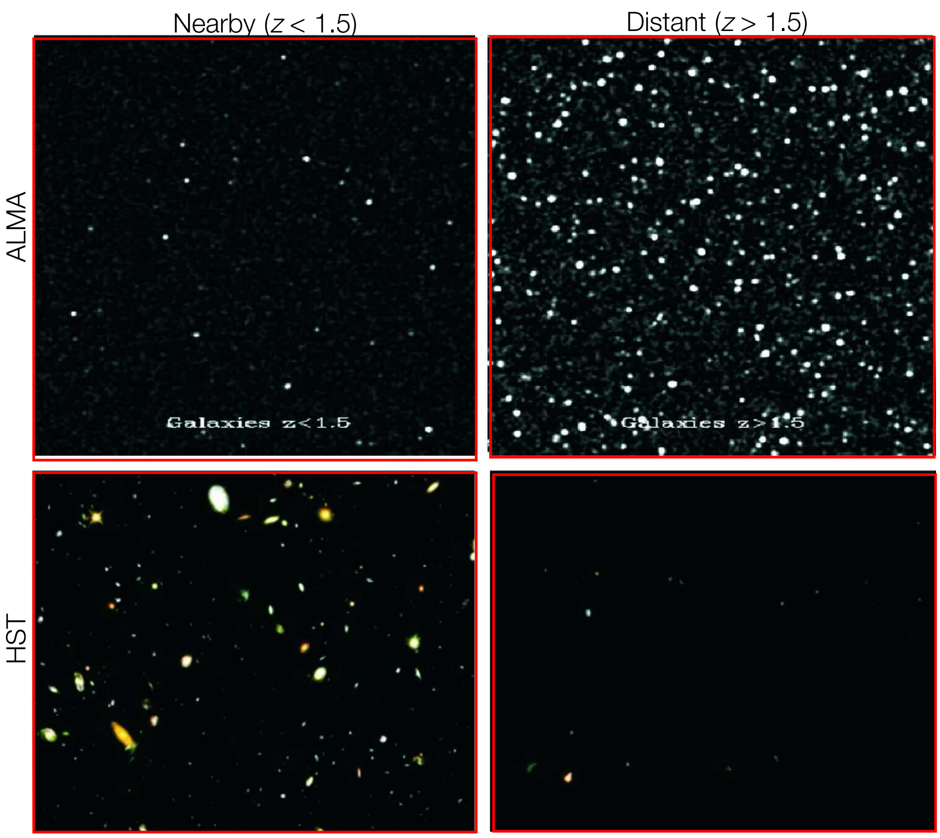
The International ALMA Project

ALMA, the Atacama Large Millimeter/submillimeter Array, will be a single research instrument composed of up to 80 high-precision antennas, located on the Chajnantor plain of the Chilean Andes in the District of San Pedro de Atacama, 5000 m above sea level. ALMA will enable transformational research into the physics of the cold Universe, regions that are optically dark but shine brightly in the millimetre portion of the electromagnetic spectrum. Providing astronomers a new window on celestial origins, ALMA will probe the first stars and galaxies, and directly image the formation of planets.

ALMA will operate at wavelengths of 0.3 to 9.6 millimetres, where the Earth's atmosphere above a high, dry site is largely transparent, and will provide astronomers unprecedented sensitivity and resolution. The 12-m antennas will have reconfigurable baselines ranging from 15 m to 18 km. Resolutions as fine as 0.005" will be achieved at the highest frequencies, a factor of ten better than the Hubble Space Telescope.

ALMA will be a complete astronomical imaging and spectroscopic instrument for the millimetre/submillimetre, providing scientists with capabilities and wavelength coverage that complement those of other research facilities of its era, such as the Expanded Very Large Array (EVLA), the Extremely Large Telescopes (ELT), and the James Webb Space Telescope (JWST).



ALMA Deep Field: Most of the galaxies that will be detected in sensitive ALMA images will have large redshifts. This is illustrated in the top row that shows the number of low redshift (z<1.5) and high redshift (z>1.5) galaxies expected from a simulated deep ALMA observation. Although the high redshift galaxies are more distant, much more of the dominant emission from warm dust is redshifted into the ALMA frequency bands. The bottom row shows that with an optical image, such as the Hubble Deep Field, most of the detections are of galaxies with z<1.5. In stark contrast to the optical image, 80 percent of the ALMA detected galaxies will lie at high redshifts. Top images from Wootten & Gallimore (2000, ASP Conf. Ser. Vol. 240, pg. 54). Bottom images from K. Lanzetta, K. Moore, A. Fernandez-Soto, and A. Yahil (SUNY). © 1997 Kenneth M. Lanzetta

Science Objectives

ALMA will provide an unprecedented combination of sensitivity, angular resolution, spectral resolution, and imaging fidelity at the shortest radio wavelengths for which the Earth's atmosphere is transparent. It will provide scientists with an instrument capable of producing detailed images of the formation of galaxies, stars, planets, in both continuum and the emission lines of interstellar molecules. It will image stars and planets being formed in gas clouds near the Sun, and it will observe galaxies in their formative stages at the edge of the Universe, which we see as they were roughly ten billion years ago.

ALMA will provide a window on celestial origins that encompasses both space and time, providing astronomers with a wealth of new scientific opportunities. In particular, with ALMA astronomers will:

- 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 like the Milky Way, but at a redshift z~3 in less than 24 hours of observation;

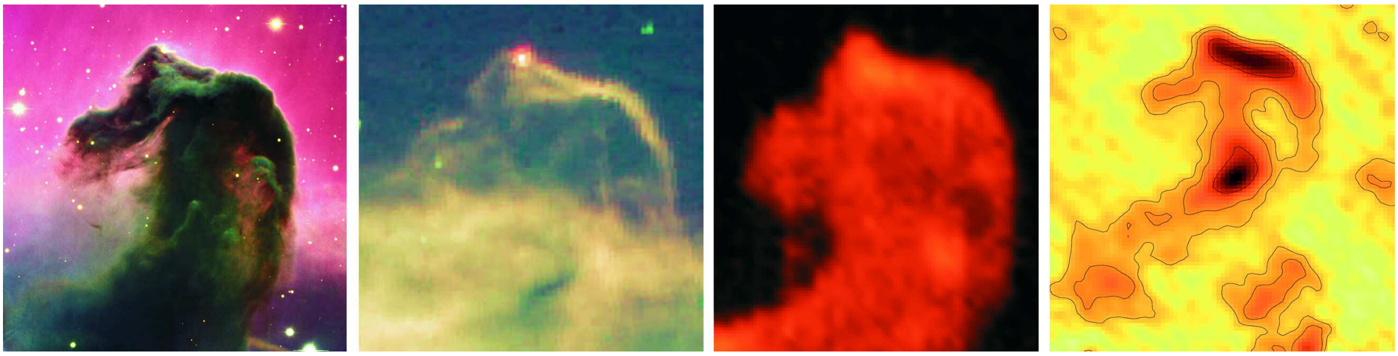
- Reveal the kinematics of obscured galactic nuclei and quasars on spatial scales smaller than 100 pc;

- Assess the influence that chemical and isotopic gradients in galactic discs have on the formation of spiral structure;

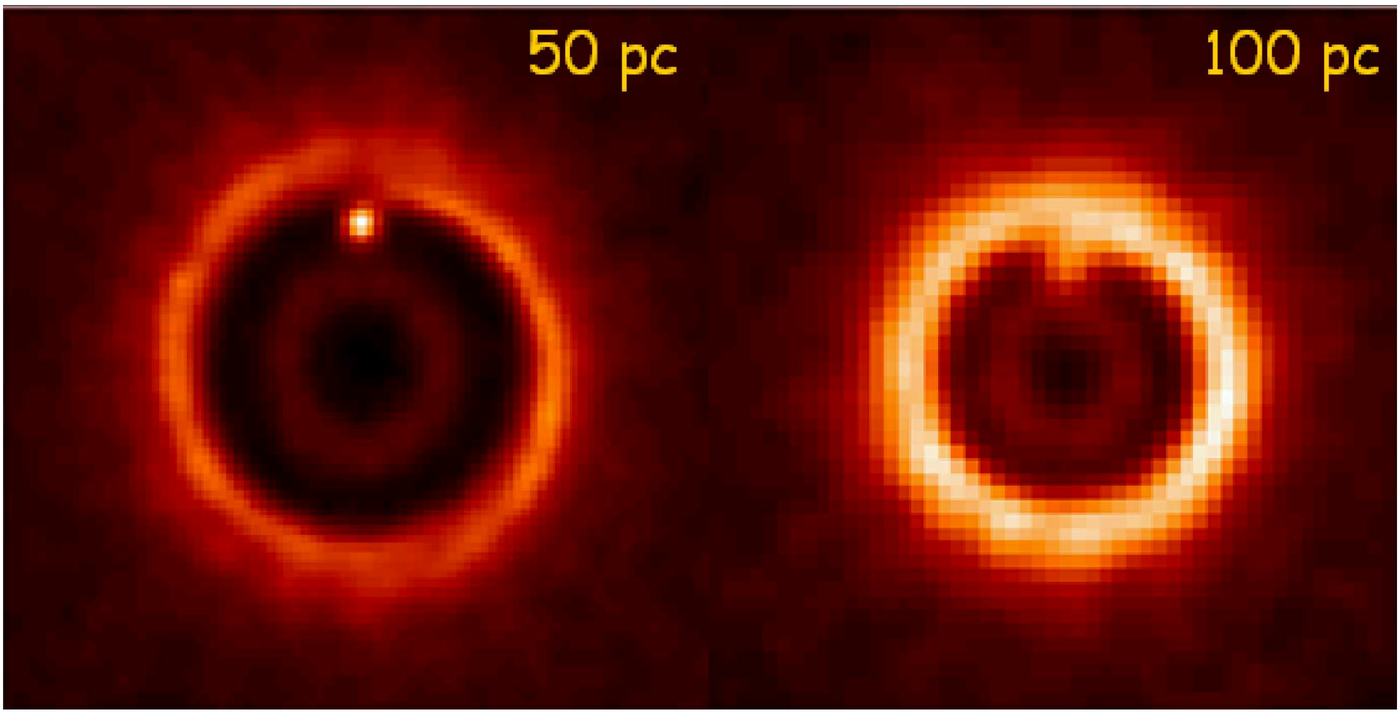
- Determine the dynamics of dust-obscured protostellar accretion discs, the rate of accretion and infall from the nascent molecular clouds, the mass distribution over the disc, and the structure of molecular outflows;

- Image the gas kinematics in protoplanetary discs around young sun-like stars

Optical (ESO) Infrared (ESA/ISO/ISOCAM) Radio CO 3-2 Line (CSO) Submm (APEX)



In the optical, dust obscures star-forming activity in the Horsehead Nebula. In the infrared, the hot, thin layer of dust around the cloud glows. At radio wavelengths, both dust and molecules glow, providing a wealth of information on the internal structure, density and kinematics of optically invisible regions. ALMA will map the glowing emission (the two rightmost panels) at the resolution of the optical image (leftmost panel).



A simulation (Wolf & D'Angelo 2005) of ALMA observations at 950 GHz of a disc shows an embedded protoplanet of 1 Jupiter Mass around a 0.5 Solar Mass star (orbital radius: 5AU). The assumed distance is 50 pc or 100 pc as labeled. The disc mass is set to that of the Butterfly Star (IRAS 04302+2247) in Taurus. Note the reproduced shape of the spiral wave near the planet and the slightly shadowed region behind the planet in the left image. Image courtesy S. Wolf.

with a resolution of a few astronomical units out to a distance of 150 pc (roughly the distance to the star forming clouds in Ophiuchus or Corona Australis), enabling the study of their physical, chemical and magnetic field structures and detection of the tidal gaps created by planets undergoing formation in the discs;

* Detect the photospheres of stars in every part of the Hertzsprung-Russell diagram and resolve the photospheres and chromospheres of giant and supergiant stars within a few hundred parsecs;

* 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.

Developments during the Last Years

During the last years the ALMA organisation, management and construction has been established and substantial progress has been made. The birth of ALMA dates back to the end of the last century. Large millimetre/submillimetre array radio telescopes were studied by astronomers in Europe, North America and Japan and different possible observatories had been discussed. After thorough investigations, it became obvious that the ambitious projects of all of these studies could hardly be realised by a single community. Consequently, a first Memorandum was signed in 1999 by the North American community, represented through the NSF, and the European community, represented through ESO, followed in 2002 by an agreement to construct ALMA.

By the end of 2005 the baseline project and the budget were approved by the ESO Council. The North American partners received approval from their Funding Agency (NSF) by the middle of 2006. By the end of 2006, the budget to start contrcution of the first phase of ALMA (50 antennas, four frequency bands) was secured at ESO and NSF.

In parallel, Japanese scientists, through the NAOJ, have continued to work out details to define and formulate their participation in the ALMA project. Details on the partnerships were defined and an official, trilateral agreement between ESO, the NSF, and the National Institute for Natural Sciences (NINS, Japan) was signed in summer 2006. In addition to the equipment which NAOJ will provide for the bi-lateral ALMA configuration (50 antennas), NAOJ will provide four antennas of 12 metres diameter, twelve antennas of 7 metres diameter, as well as two receiver bands for all 66 antennas of ALMA. With the inclusion of the Japanese partners ALMA becomes a truly global astronomy facility, involving scientists from four different continents. Then “the sun never sets on ALMA”.

In parallel to the ongoing construction, an ALMA Operations Plan has been worked out. The plan foresees the start of operations in the year 2006, followed by a ramp up phase, including Early Science starting in the year 2010. The Joint ALMA Observatory shall reach full operation by 2012.

Recent Progress in Building ALMA

- The antennas have been purchased, with both North America and Europe each placing contracts for at least 25, and Japan having contracted for their first three. These antennas are the highest precision radio telescopes ever built. The first antenna arrived at the ALMA OSF on April 27, 2007. Three more are expected before the end of the year.

- Construction of the building on the 5000 m elevation Array Operations Site will be completed soon, and construction continues at the mid-level Operations Support Facility.

- Prototype receivers all meet specifications: near quantum-limit noise, unprecedented bandwidth, and no mechanical tuning. The ALMA receiver system will be the largest assembly of superconducting electronics in the world.

- The first quadrant of the ALMA correlator is complete and being tested. Blazingly fast in its single-minded functionality, the complete correlator will achieve greater than 10^{16} floating point operations per second.

- ALMA Regional Science Centers in North America and Europe are being planned and organised, with a third centre expected for the East Asian partners (Japan and Taiwan).

The ALMA Management

The ALMA Board has the overall responsibility for the ALMA Observatory. Upon decision of the ALMA Board, the Joint ALMA Office (JAO) was created during the year 2004. Prime objective of the JAO is to provide an overall management structure for ALMA, to lead the ALMA project, and coordinate ALMA construction activities in four different continents.

The JAO is located in Santiago (Chile) and synchronizes activities of the Executives in Europe, North America and Japan, as well as on the ALMA site near San Pedro de Atacama. One of the most important responsibilities of the JAO is the management and organisation of the Assembly, Integration, Verification and Commissioning (AIVC) of the telescopes in Chile.

The European ALMA activities are managed by the European ALMA Project Office, located at ESO in Garching. The Project Office is led by the European ALMA Project Manager, who is also the Head of the ALMA Division at ESO. He is supported by the European ALMA Project Scientist, the ALMA Regional Center (ARC) Manager, a Management Team, and several Integrated Product Team (IPT) Leaders. The IPT Leaders direct their team of engineers and scientists for the various subsystems of the ALMA Project.

Similar Project Offices have been organised at NRAO in Charlottesville (USA) for North America, and NAOJ in Mitaka (Japan) for corresponding construction activities for ALMA. These three Project Offices collaborate closely with each other, not only at the level of the Executive's Project Managers, but also the Management Teams and IPT Leaders. In addition, the ALMA Project Manager and his team at the JAO coordinate overall aspects of the project. Besides the management, described above, which deals with all operational aspects of the construction on a day to day timescale, there are several external (independent) advisory bodies, dealing, for example, with scientific, technical, personnel, financial, management, and organisational issues.

The various ALMA boards and committees deal in some cases with overall aspects of ALMA, in other cases also with regional aspects related to the specific circumstances of the respective Executives.

At present there are
- the ALMA Management Advisory Committee (AMAC),
- the ALMA Scientific Advisory Committee (ASAC),
- the ALMA North American Scientific Advisory Committee (ANASAC),
- the ALMA European Scientific Advisory Committee (ESAC), and
- the ALMA Japanese Scientific Advisory Committee (JSAC).

The ALMA Site

A World Class Observatory in the Desert

The ALMA Array Operations Site (AOS) will be located at a truly unique and unusual place: the Altiplano de Chajnantor, a plateau at an altitude of 5000 metres in the Atacama Desert in Chile. Of course, this location was selected because of many well justified scientific reasons, particularly dryness and altitude. Considering these aspects, the ALMA Observatory will not only be unique because of its ambitious scientific goals, and the unprecedented technical requirements, it will also be unique because of the very specific, harsh environment and living conditions in which the most challenging radio telescope array will operate with high efficiency and accuracy.

The ALMA Observatory will be operated at two distinct sites, far away from comfortable living conditions of modern civilization. The ALMA Operations Support Facilities (OSF) will be the base camp for the every-day, routine operation of the observatory. It is located at an altitude of about 2900 metres, quite high compared to standard living conditions, but still quite acceptable for scientific projects in astronomy of similar scope. However, the OSF will not only serve as the location for operating the Joint ALMA Observatory, it is also the Assembly, Integration, Verification, and Commissioning (AIVC) station for all the high technology equipment before being moved to the Array Operations Site (AOS), located at 5000 metres altitude.

A High Altitude Road with Super-Highway Dimensions

The construction of the OSF and AOS sites and their access required substantial efforts of the ALMA project. Obviously, there was no access to these two remote locations (see Figure 3). The OSF site, located at 2900 metres altitude, is about 15 kilometers away from the closest public road, the Chilean highway No. 23. The AOS is another 28 kilometers away from the OSF site. Thus, one of the first projects to be accomplished by ALMA was to construct an access road not only to the OSF but also to the AOS – a road, 43 km in length (Figure 3), not only at high altitudes, but also with sufficient width to regularly transport a large number of large radio telescopes with a diameter of 12 metres.

Figure 3: The Road between Chilean Highway No. 23 and ALMA

Figure 4: Contractor's Camp at the OSF

The Operations Site Facilities (OSF)

The OSF is and will continue to be, in many aspects, the centre of activities of the ALMA project. Focus of the activities will change as ALMA achieves several and quite different objectives of the entire project.

Presently it is the area where all ALMA Site contractors and their staff are accommodated. Special camps have been erected and by now can accommodate the maximum required capacity of 500 workers (see Figure 4).

The OSF, of course, does not only serve as the base camp for contractors. It will become the focal point of all antenna assembly and AIVC activities. AIVC activities will be carried out at the OSF, after preliminary acceptance of the antennas, and prior to moving them to the AOS.

Ultimately, the OSF and its Technical Facilities will become the centre of all scientific activities related to the daily operation of the Joint ALMA Observatory. The OSF will be the central location for running the observatory and taking care of all maintenance and operations aspects. During the operations phase of the observatory it will be the workplace of the astronomers and of the teams responsible for maintaining proper functioning of all the telescopes. The quality of all ALMA data will be assessed at the OSF.

ESO signed a very important contract for the construction of the OSF Technical Facilities in August 2006. Construction work has started (see Figure 6). Provisional Acceptance of all facilities is foreseen for the first quarter of 2008.

A Challenging Problem: 8 MWatt Power Demand in the Desert at 2900 and 5000 metres Altitude

Supplying energy for an observatory at altitudes of 2900 metres and 5000 metres in the Chilean desert of Atacama is not at all trivial. Initially it was planned to generate power for the OSF and AOS by using dual fuel (natural gas and diesel) energy generators, installed on the OSF premises. This scheme was expected to be the most cost efficient and reliable for the required power demand of about 8 MWatt.

During the last few years energy supply and prices have rapidly and drastically changed. By the beginning of the year 2006 it became obvious that no gas provider in Northern Chile was ready to supply ALMA with the required quantity. In view of these developments on the

Figure 5: The AOS Technical Building

Figure 6: The Museum along the Access Road between the OSF and AOS

energy market, ALMA decided to change the baseline configuration for the power supply of the observatory and to move toward using electricity provided by Northern Chilean electricity suppliers. This scheme requires the erection and operation of an overhead power line from the best suited electricity generator to the OSF and AOS. Technical and commercial details are being worked out and it is planned to start construction of an overhead line in the second half of 2007. Depending on the power generation station chosen for the supply, the construction of the overhead line is expected to be completed within 18 to 24 months.

An Observatory Located at an Altitude Higher than Europe's Highest Summit

The construction of the AOS Technical Building, a project to be delivered by the North American partner in ALMA, started in October 2005 and the outer shell was completed by mid 2006 (Figure 5). Inside construction work and furnishing is expected to be completed by summer 2007. Operations at the AOS will, because of the harsh environment, be limited to an absolute minimum. The AOS Technical Building will house the receiving end of the Back End and the Correlator. Digitized signals received from the radio telescopes are processed here and further transmitted to the data storage facilities located at the OSF.

Respecting Culture and Nature

Although it is one of the most ambitious high-technology scientific projects, activities on the ALMA site not only focus on building the world's most advanced and challenging astronomical ground-based observatory. Historical and environmental aspects in this unique region are of concern. The remains of a small local settlement located along the access road at km 21 have been rebuilt taking into account the advice of the last owner and after consulting an archaeologist from San Pedro. The place serves now as a museum and an interpretive centre for local cultures and history (Figure 6).

Wildlife in these altitudes is protected. Colonies of Vizcachas, a local species of rodents (Figure 8), were identified along the ALMA-AOS access road at km 30. Local Chilean Authorities are carefully monitoring the movements of these colonies. The goal is that ALMA Site construction will not disturb wildlife.

Figure 7: Vizcachas Live in Colonies near the AOS

The ALMA Antennas

Mobile High Precision Instruments

Figure 8:The pedestal of the first ALMA Antenna arrives at the OSF

The antennas are central to the ALMA project. Their quality and performance define the overall functionality of ALMA.

The specifications of each antenna are 2” absolute pointing over the whole sky, 0.6” tracking, and a 25 micrometre RMS surface accuracy. These are very tight specifications for radiotelescopes fully exposed to the harsh weather environment at 5000m altitude.

In view of the difficulties in fullfilling these requirements, prototype antennas were supplied by three companies: the AEC Consortium (procured by ESO), Vertex RSI (procured by NRAO for North America) and Mitsubishi Electrical Company (procured by NAOJ, Japan). All three prototypes were extensively tested at the ALMA Test Facility in Socorro, New Mexico (Figure 9). Several groups of international experts, both internal and external to ALMA, reviewed the performance of the prototype antennas and concluded that on the basis of the tested functioning their expected performance at the ALMA site conform to the technical requirements.

The North American partners of the ALMA project, through AUI, signed a contract to supply up to 25 antennas, with options to increase to 32 antennas,

Figure 9: The Three Prototype Antennas at the ALMA Test Facility in Socorro

Figure 10: The ALMA antenna transporter

with Vertex RSI on July 11, 2005. On December 6, 2005, the ESO Director General signed a contract with the AEM (Alcatel Alenia Space France, Alcatel Alenia Space Italy, European Industrial Engineering S.r.L., MT Aerospace) Consortium for the supply of 25 ALMA antennas, with options to increase the number of antennas to 32. The four antennas of 12 metres diameter, to be provided by Japan, have been ordered from Mitsubishi Electrical Company. The twelve remaining antennas of 7 metres diameter will be ordered during the year 2007 by NAOJ.

The first antenna to be supplied by Vertex RSI is expected to be ready for provisional acceptance in Chile during the second half of 2007. The first antenna to be supplied by the AEM Consortium is expected by the third quarter of 2008. Despite the later delivery of the first AEM antenna, both suppliers are expected to deliver their 25th antenna by the end of 2011. This is due to a higher delivery frequency of AEM antennas.

The ALMA Antenna Transporters

The ALMA antennas will be operating at an altitude of 5000 metres. The antenna array can be reconfigured in order to achieve the imaging requirements by relocating antennas on the stations at the AOS. There is a compact configuration in which all antennas operate within an area of 160 x 250 metres, and there is an expanded configuration for which the maximum separation between antennas reaches about 15 km. In order to move antennas, each weighing more than 100 tons, the ALMA project has designed a special, dedicated transport vehicle. Two units will be manufactured. These transporters are truly unique. They will first move antennas from their assembly area, the OSF (2900 metres) to dedicated positions at the AOS (5000 metres).

After the initial move from the OSF they will move antennas around on the AOS – to compact or expanded configurations – and position the antennas to an accuracy of a few millimetres. In addition, these transporters shall also move antennas for extended maintenance and repair from the AOS to the OSF.

The weight of the antennas, their high precision and the hostile, high altitude environment impose severe boundary conditions on the transport vehicles. They will have a weight of about 150 tons, and their dimensions are about 10 m x 15 m x 6 m (width x length x height). The first of the transporters will be delivered to the OSF in the fourth quarter of 2007. The second vehicle is expected to be delivered about six months after the first one.

The ALMA Front End

High Sensitivity Receivers at Low Temperatures

The ALMA Front End system is the first element in a complex chain of signal receiving, conversion, processing and recording. The Front End is designed to receive signals of ten different frequency bands (Table 1). In the initial phase of operations the antennas will be equipped with six bands. These are Band 3, Band 4, Band 6, Band 7, Band 8 and Band 9. It is planned to equip the antennas with the missing bands at a later stage of ALMA operations.

The ALMA Front End is far superior to any existing systems. Indeed, spin offs of the ALMA prototypes are leading to improved sensitivities in existing millimetre and submillimetre observatories around the world. The Front End units are comprised of numerous elements (see Figure 12 on next page), produced at different locations in Europe, North America and East Asia. In the initial phase of construction, ALMA has decided, after the prototyping and development stage, to build a set of eight pre-production units before moving to series production. This initial phase started in 2003. Some components have been successfully developed and completely pre-produced by the end of 2006. Others are expected to be complete during 2007.

The ALMA Cryostats

The largest single element of the Front End system is the cryostat (vacuum vessel) with the cryo-cooler attached. The cryostats will house the receivers, which are assembled in cartridges and can relatively easily be installed or replaced. The corresponding warm optics, windows and IR filters were delivered by the *Institut de Radio Astronomie Millimétrique* (IRAM, France).The operating temperature of the cryostats will be as low as 4 K.
ESO and the Rutherford Appleton Laboratory (RAL, UK) launched a development and pre-production programme for the manufacture of eight completely operational cryostats.

Figure 11: Work at the Rutherford Appleton Laboratory

ALMA Band	Frequency Range (GHz)	Receiver Noise over 80% of the RF Band	Temperature (K) at any RF Frequency	To be produced by[1]	Receiver Technology
1	31-45	17	26	tbd	HEMT
2	67-90	30	47	tbd	HEMT
3	84-116	37	60	HIA	SIS
4	125-163	51	82	NAOJ	SIS
5*	163-211	65	105	OSO	SIS
6	211-275	83	136	NRAO	SIS
7	275-373	147	219	IRAM	SIS
8	385-500	196	292	NAOJ	SIS
9	602-720	175	261	NOVA	SIS
10	787-950	230	344	NAOJ (tbc)	SIS

Table 1: The Ten Frequency Bands of the ALMA Radio Telescopes

[1] tbd: to be decided
tbc: to be confirmed
IRAM: Institut de Radio Astronomie Millimétrique (Grenoble, France)
HIA: Herzberg Institute of Astrophysics (Victoria, Canada)
NAOJ: National Astronomical Observatory of Japan (Mitaka, Japan)
NOVA: Nederlandse Onderzoekschool voor Astronomie (Groningen, the Netherlands)
NRAO: National Radio Astronomy Observatory (Charlottesville, USA)
OSO: Onsala Space Observatory/Chalmers Univeristy (Onsala, Sweden)
*EU FP6 receivers from Onsala.

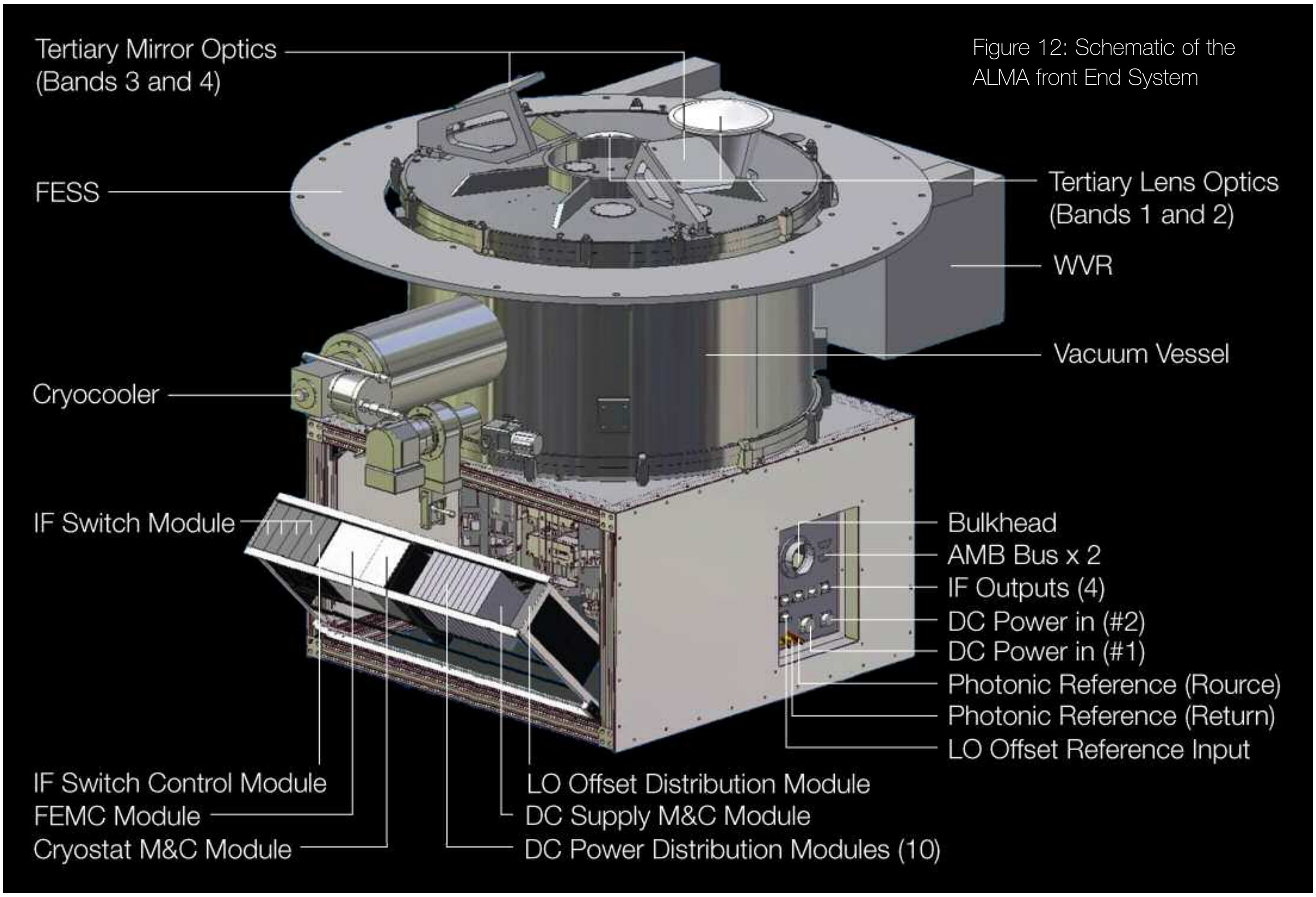


Figure 12: Schematic of the ALMA front End System

The ALMA Receiver Bands

In the initial phase of operations the radio telescopes of the ALMA Observatory will be equipped with six receiver bands (see also Table 1). Also for the receiver bands a development and pre-production phase was launched. The Technical Specifications of the various receivers is quite demanding, and, at the time of definition, at the state of the art level or in some cases even beyond. The development programmes were successful, as the requirements could be met – and sometimes the performance is even better than defined in the specifications. With respect to the reduction of the number of antennas from initially 64 to 50 (initial baseline, without Japanese participation), the positive result of the development programme is an extremely important achievement. To some extend the performance and higher sensitivity of the receivers partially compensates the loss in collecting surface.

By mid-2007, the pre-production for the various receivers was almost completed. Figure 14 shows a completely assembled Band 9 receiver cartridge.

In the frame of the European FP6 programme, ESO is leading a group of European institutes to develop and build six single polarisation Band 5 receiver cartridges. This project was approved by the European Commission at the end of 2005. In parallel, NAOJ is leading activities related to the development of Band 10 receivers.

Pre-production of the cryogenic low noise amplifiers for Band 7 and for Band 9 receivers has been successfully completed by Centro Astronómico de Yebes (CAY, Spain).

A review of the ALMA amplitude calibration device was held in August 2005 at IRAM in Grenoble (France). Various concepts and their expected performance (multi load, dual load and semi-transparent vane) were presented and compared with each other to find the most suitable solution for ALMA. The review panel recommended continuing with the detailed development of the relatively simple two load calibration device. It is planned to install two prototype devices on the antennas at the ALMA Test Facility and the first ALMA antenna at the OSF.

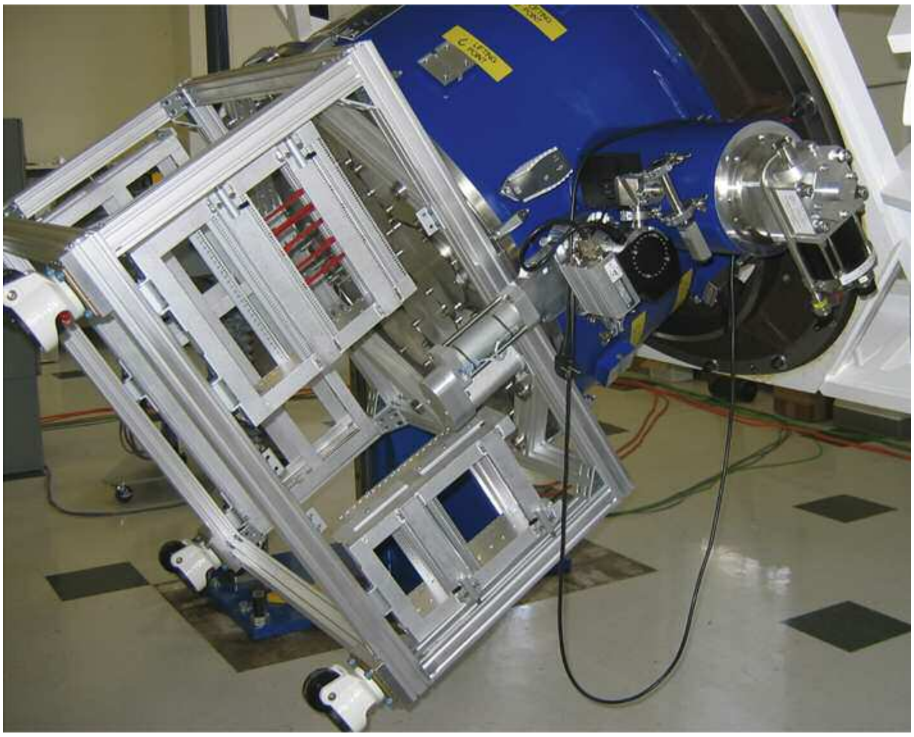


Figure 13: One of the First Cryostats assembled at RAL

Figure 14: Band 9 Receiver Cartridge assembled by NOVA

The ALMA Front End Integration Centres

A construction project like ALMA, involving several partners in four different continents, requires consensus on several organisational and managerial decisions concerning the actual execution of certain construction activities. These decisions are dominantly driven by technical and financial considerations. One of these decisions, in fact a major one, was taken during 2005 for the organisation of the Front End Integration Centers (FEIC) for the equipment to be provided by Europe and North America.

Several different scenarios for assembling and integrating the Front End components were extensively studied. This study revealed that the best solution was a "parallel approach", installing half of the Front End in Europe and the other half in North America with identical and parallel procedures. This scenario was preferred in view of logistics, organisation and programme risks. Mainly based on considerations of risk mitigation the parallel FEIC was selected. At present it is planned that the European FEIC will be located at RAL; the North American FEIC will be installed at NRAO. During 2006 it was decided that a third FEIC be installed in Taiwan to carry out the integration of Front End assemblies required for the antennas to be supplied by NAOJ.

The Water Vapor Radiometers

Water Vapor Radiometers (WVRs) are needed to provide a correction of the atmospheric water vapor fluctuations. The development of two different prototype WVRs at Cambridge University and Onsala Space Observatory (OSO, Sweden) has been completed and both prototypes have undergone intensive tests at the Sub-Millimeter Array (SMA) on Mauna Kea (Hawaii). Key performance of both prototypes is well in agreement with the requirements. The WVRs will be manufactured by qualified industry and ESO has contracted in 2007 for the production of 53 units.

The ALMA Back End and Correlator

Modern Communication Technology

The ALMA Back End system link signals generated by Front End units installed in each antenna with the central Correlator installed in the AOS Technical Building. Signal processing and data transfer is schematically shown in Figure 15. Analog data, produced by the Front End electronics, is processed and digitized before entering into the data encoder, followed by the optical transmitter units and multiplexers. All these elements are installed in the receiver cabins of each antenna. Optical signals are then transmitted by fibres to the AOS Technical Building. The total distance is, in one antenna configuration, about 15 kilometers. At the Technical Building the incoming optical signals are de-multiplexed and de-formatted before entering the Correlator.

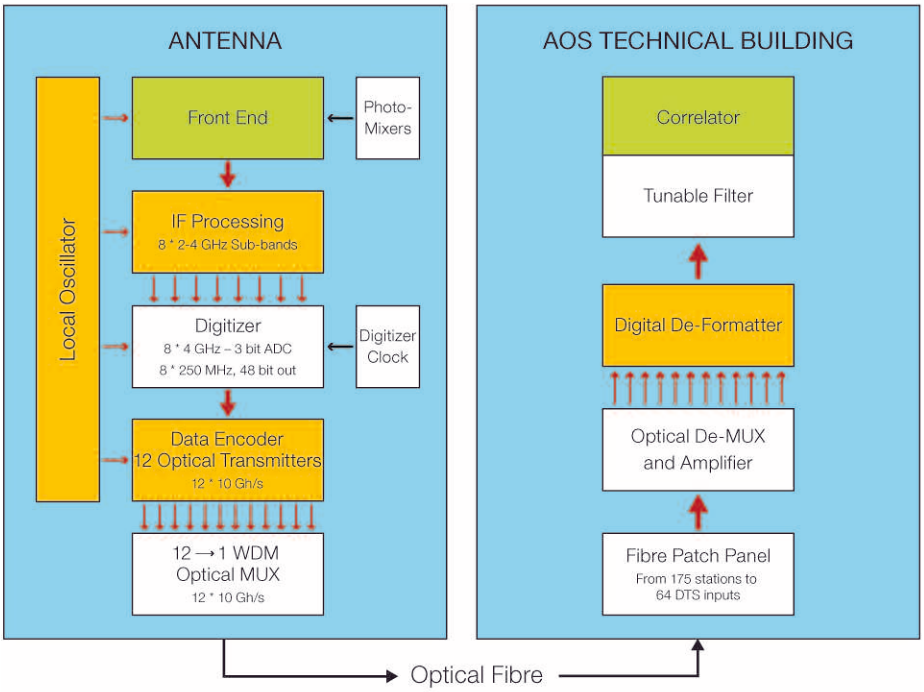


Figure 15: Schematic of ALMA Signal Processing and Data Transfer from the Front End to the Correlator. Parts to be provided by ESO are shaded in yellow.

The European deliverables in the ALMA Back End project are various components, which are produced by several European institutes, closely working with ESO, and NRAO. These deliverables are:

- the digitizer chips production and assembly,
- the digitizer clock and assembly,
- the optical data transmission system design,
- the fiber patch-panel,
- the optical multiplexers (MUX) and de-multiplexers (De-MUX), and
- the photonic local oscillator photomixers

Development and pre-production of these components has been successfully completed. The components will be integrated at the Back End Integration Center at Socorro and installed in the European and North American prototype

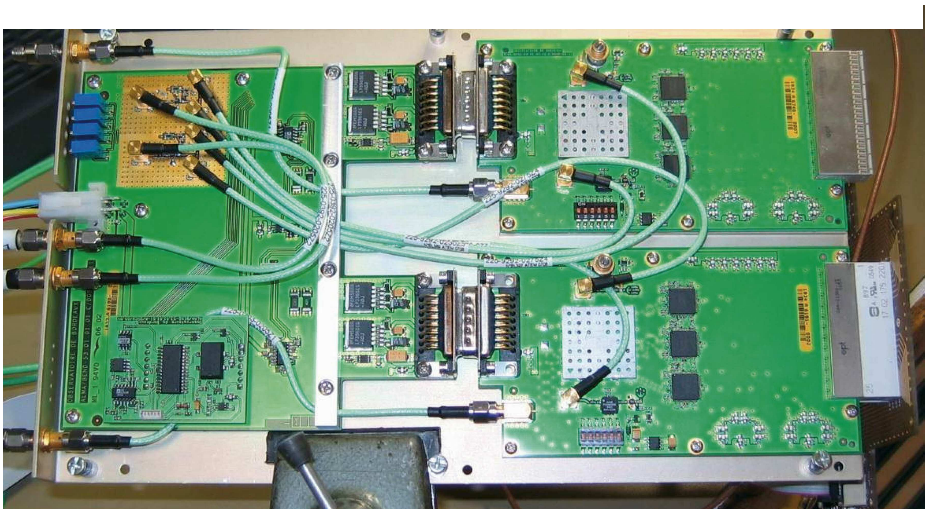


Figure 16: The ALMA 4 GHz Digitizer

Figure 17: The First of Four Quadrants of the ALMA Correlator

antennas for tests to be made at the ALMA Test Facility.

As one example of the various Back End components produced in Europe, Figure 16 shows the 4 GHz digitizer in its final layout. The clock rate is 4 GHz, allowing an input bandwidth of 2 GHz. The digitization is 3 levels to preserve the signal to noise ratio. Comparable digitizer chips have been announced, but are not yet commercially available. During the prototype and development phase the initial layout was optimized in order to reduce the number of parts and the assembly costs. The final digitizers show an improved performance and a higher reliability. This work was carried out in close collaboration between ESO and the University of Bordeaux. The first four units have been shipped to Socorro for final acceptance and integration for the tests at the ATF.

The ALMA Correlator

The ALMA Correlator, to be installed in the AOS Technical Building, is the last component in the receiving end of the data transmission. It is a very large data processing system, composed of four quadrants, each of which can process data coming from up to 16 different antennas. The complete correlator will have 2912 printed circuit boards, 5200 interface cables, and more than 20 million solder points. The first quadrant was completed at NRAO (Figure 17) in the third quarter of 2006. Work on the second quadrant is progressing on schedule.

Integral parts of the Correlator are Tunable Filter Bank (TFB) cards. The layout is such that four TFB cards are needed for the data coming from a single antenna. The TFB cards have been developed and optimized by the University of Bordeaux (Figure 18) over the last few years. Prototypes and preproduction units have been extensively tested and their performance was critically reviewed in the first half of 2006.

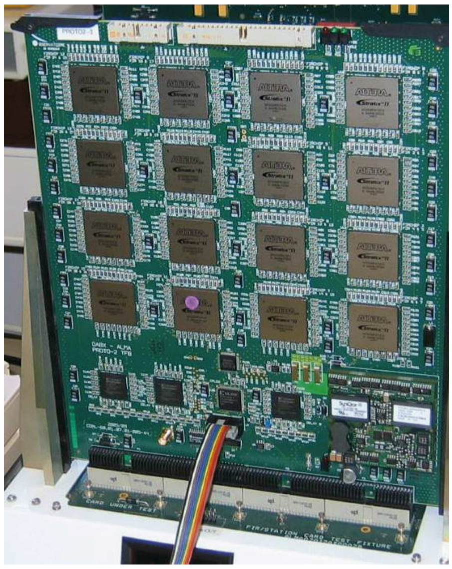


Figure 18: Tunable Filter Board Card Developed by the University of Bordeaux

Project Wide Activities at ESO

System Engineering and Integration

An important ALMA wide activity is the System Engineering and Integration (SE&I) task. This IPT has quite a variety of tasks and responsibilities, coordinating activities across other IPTs. Obviously, one of the prime objectives of SE&I is to ensure that modules and equipment designed and produced for an ALMA subsystem, often in different locations of the world, fit together and meet the system requirements. SE&I is also responsible for ensuring system integrity and hence has to ascertain that all interfaces between the various IPTs are completely understood, well defined, severely reviewed and properly documented.

In order to achieve the tasks mentioned above, the SE&I team takes a central role in organising, holding and chairing technical reviews of the project. The reviews are either ALMA internal, in order to define specifications and/or requirements of various instruments, or they are external, reviewing the status and progress of the manufacturing of ALMA components by industry or scientific institutes.

The SE&I group is also very deeply involved in all activities related to Prototype System Integration and the testing at the ATF in Socorro. The ATF was the site where tests of the antenna prototypes took place before production contracts were placed. During the years 2007/8 the ATF will serve as a facility where ALMA components will be integrated into an operational system.

Table 3: Software Development in European Institutes

Software Activity	Institute[2]
Science Software Requirements	IRAM
Pipelining	UKATC, MPIfR
Archiving	Man.Un./JBO
Observing Preparation	UKATC
Offline Data Processing	MPIfR, CNRS
Telescope Calibration	IRAM, IEM-CSIC

[2] IRAM: Institut de Radio Astronomie Millimétrique (Grenoble, France)
UKATC: United Kingdom Astronomy Technology Centre (Edinburgh, United Kingdom)
MPIfR: Max-Planck-Institut für Radioastronomie (Bonn, Germany)
Man. Un.: University of Manchester (Manchester, United Kingdom)
JBO: Jodrell Bank Observatory (Macclesfield, United Kingdom)
CNRS: Observatoire de Paris & Centre National de la Recherche Scientifique (Paris, France)
IEM-CSIC: Instituto de Estructura de la Materia (Madrid, Spain)

During this phase of the construction the Assembly, Integration and Verification team (which later will be responsible for these activities at the OSF) will have an ideal opportunity to learn how to carry out their duties for the entire ALMA.

Software Development

The development of a unified software system for the ALMA Observatory is another important project which requires intensive interactions with the other ALMA IPTs. The nature of software development calls for a common approach and policy from the very beginning – not only with respect to the IPTs, but also between the European and North American partners. In contrast to some cases of hardware oriented activities, where specialized instruments are provided, in software entire packages need to be developed under a single management and organisation. This requires that all parties involved are fully integrated.

The ALMA Software Development IPT is managed as a truly integrated, tri-lateral program. The European, Japanese and North American Executives have identified individual work packages, to be delivered by one or the other partner, under a common leadership.

Work in Europe is organised through ESO and the centre of European software development and management is at ESO's headquarters in Garching. Many software packages are developed by ESO in collaboration with European institutes who have experienced and qualified staff to develop and test the required software. Table 3 gives an overview of software development projects carried out by various European institutes in association with ESO.

Major Computing subsystems for which ESO has direct responsibility include:
- the ALMA Common Software (ACS), the infrastructure used by all other software;

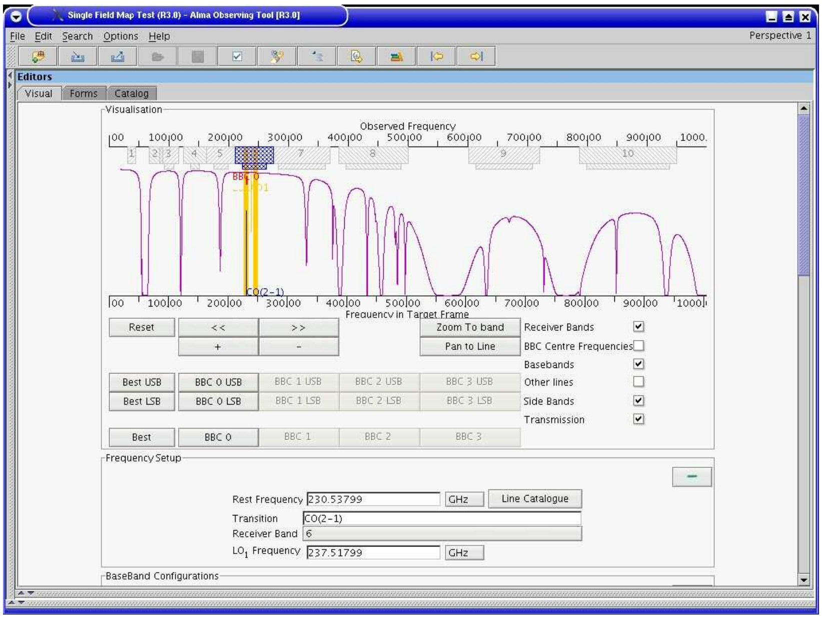


Figure 19: ALMA Visual Spectral Editor

- the Archive, both Front End and Science archive, collecting not only science data, but also any other information used by the ALMA observatory software;
- the integration and test activity, to get a coherent and tested software system out of the many subsystems;
- the High Level Architecture activity, responsible for the design of the ALMA software and consistency of its interfaces;
- the Executive subsystem, which provides the operator user interfaces;
- the Observatory Support Software, which provides the support tools needed by time allocation teams and the support for data packages;
- the software engineering activity, which maintains the standards to be used in hardware and software.

As an example of the software development, Figure 19 shows an input screen produced by the ALMA Visual Spectral Editor, which allows selecting the frequency bands to be observed. This is part of the Observation Preparation Computing subsystem, for which the UK ATC has responsibility.

Science

The Science IPT is another project which has ALMA-wide tasks and responsibilities. It has to ensure integrity and balance of all instrumentation to be used in ALMA, thus that the overall scientific requirements can be met in the most reliable and efficient way. The Science IPT had major obligations during the re-baselining phase of ALMA. It was charged to study the impacts of reducing the number of antennas without jeopardizing the major scientific goals of the project.

The Science IPTs of Europe, North America and Japan interact very closely with each other on a regular basis. In addition, members of the three Science IPTs directly collaborate with the various Scientific Advisory Committees in ALMA (ASAC, ESAC, ANASAC and JSAC) to respond to specific charges defined by the ALMA Board.

As a specific example of the work of the Science IPT, it is noted here that it had to redefine the antenna locations for the various 50 antenna array configurations. The Science IPT has also given important and valued advice to the Antenna IPT with respect to optimizing the design and increasing sensitivity of the antennas.

At the initial stage of the project, the manufacture of ALMA instrumentation, the reasonability of the Science IPT also implies that the team members are strongly involved in all important aspects related to the definition of technical specifications and assist in various technical reviews of ALMA equipment. Assembly, Integration, Verification and Commissioning (AIVC) is the next important activity in which Science plays an important role. The definition of procedures and protocols is part of the charge. The Science IPT will be centrally involved in all AIVC activities.

ALMA Timeline

1995 →	NRAO/ESO/NAOJ joint site testing with Chile
May 1998 →	Start of Phase I (Design & Development)
June 1999 →	U.S. / European Memorandum of Understanding for Design & Development
February 2003 →	Final North American / European ALMA Agreement
April 2003 →	Testing of first prototype antenna begins at the ATF site in New Mexico
October 2004 →	Opening of Joint ALMA Office, Santiago, Chile
July 2005 →	North American contract for up to 32 ALMA production antennas
October 2005 →	Groundbreaking at 5000m altitude ALMA Array Operations Site
December 2005 →	European contract for up to 32 ALMA production antennas
July 2006 →	Agreement signed by North America, Europe, and Japan
March 2007 →	"First Fringes" dectect by two linked antennas at the ATF
April 2007 →	Delivery of first ALMA production antenna to Chile
2010 →	Call for shared-risk Early Science proposals; Early Science
2012 →	ALMA Construction complete

Specifications

		12 m Array	Atacama Compact Array (ACA)
Array	Number of Antennas	up to 64	12 (7 m) + 4 (12 m)
	Total Collecting Area	up to 7240 m^2	460 + 450 m^2
	Angular Resolution	0.02" (λ /1 mm)(10 km/baseline)	5.7" (λ/1 mm)
	Baseline Lengths	15 - 18 500 m	
Antennas	Diameter	12 m	7 m, 12 m
	Surface Precision	<25 μm	<20 μm, <25 μm
	Offset Pointing	<0.6"	<0.6"
Correlator	Baselines	up to 2016	120
	Bandwidth	16 GHz per baseline	16 GHz per baseline
	Spectral Channels	4096	4096

ALMA Sensitivity Goals for the 12 m Array

For an integration time of 60 seconds, a spectral resolution of 1 km/s, the RMS flux density, ΔS, and brightness temperature sensitivity, ΔT, with a 64 antenna array and maximum baseline, B_{max}, will be:

Frequency (GHz)	Continuum ΔS (mJy)	Spectral Line ΔS (mJy)	B_{max} = 0.2 km: Beam (arcsec)	B_{max} = 0.2 km: ΔT_{cont} (K)	B_{max} = 0.2 km: ΔT_{line} (K)	B_{max} = 14.7 km: Beam (arcsec)	B_{max} = 14.7 km: ΔT_{cont} (K)	B_{max} = 14.7 km: ΔT_{line} (K)
110	0.047	7.0	3.18	0.0005	0.070	0.038	3.3	482
140	0.055	7.1	2.50	0.0005	0.071	0.030	3.8	495
230	0.100	10.2	1.52	0.0010	0.104	0.018	6.9	709
345	0.195	16.3	1.01	0.0020	0.167	0.012	13.5	1128
409	0.296	22.6	0.86	0.0031	0.234	0.010	20.5	1569
675	1.042	62.1	0.52	0.0108	0.641	0.006	72.2	4305

ALMA