Progress of the ALMA Project

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An overview of the current status of the ALMA project and the progress over the last two years is presented. The main focus is on the European deliverables, but the contributions of North America and Japan are also mentioned.

Science Objectives of ALMA

The Atacama Large Millimeter and Submillimeter Array (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. The three major scientific goals for ALMA can be summarised as: to detect spectral line emission from CO or C II at a redshift of $z = 3$ in less than 24 h of observation; to image gas kinematics in protostars and protoplanetary discs at a distance of 150 pc, enabling the study of the physical, chemical and magnetic field structures; to provide images with an angular resolution of 0.1″.

Developments over the last two years

The agreement to construct ALMA was signed in 2002 by the North American community, represented through the National Science Foundation (NSF), and the European community, represented through ESO. After three years of detailed design studies and prototype research, it became evident that the project could not be realised within the original timescale and within the available funds foreseen at the time of signing the agreement. The management and scientists involved in ALMA were therefore charged to develop a new configuration of the project within their foreseen budget, while still maintaining the prime scientific objectives.

During this period in-depth studies and large efforts were made to define the "rebaselined" ALMA project. A major element in cutting the cost was the reduction of the number of antennas from 64 to 50 (with an ultimate goal of 64). Fortunately, the results of testing of the prototypes for the receiver cartridge showed that several of the receivers significantly exceeded their noise temperature requirements, thus partially offsetting the loss in sensitivity through the reduced number of antennas. Independent advisory and review committees, focusing on the technical performance as well as on the cost of the project, confirmed the scientific importance of the modified ALMA project, based on the new affordable costs. By the end of 2005 the re-baselined project and the new budget were approved by the ESO Council. The North American partners received approval from their Funding Agency (NSF) by the middle of 2006.

Figure 1: The Road between Chilean Highway No. 23 and ALMA.

In parallel, Japan, through the National Astronomy Observatory of Japan (NAOJ), continued to define and formulate their participation in the ALMA project. The European and North American partners in ALMA spent a considerable amount of time with their Japanese partners in identifying the Japanese participation and reviewed various subsystems, in particular correlator, receivers and antennas. 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. NAOJ will provide four antennas of 12 metres diameter, twelve antennas of 7 metres diameter, two receiver bands for all 66 antennas of ALMA and the Atacama Compact Array (ACA) Correlator. Approval of funds required for the Japanese participation in ALMA is expected by summer 2007. With the inclusion of the Japanese partners ALMA becomes a truly global astronomy facility.

The ALMA Site

The ALMA Array Operations Site (AOS) will be located at a unique place: the Altiplano de Chajnantor, a plateau at an altitude of 5 000 metres in the Atacama Desert in Chile. This location was selected for reasons of dryness and altitude.

The ALMA Operations Support Facilities (OSF), located at an altitude of about 2 900 metres and 28 km away from the AOS will be the base camp for the everyday, routine operation of the observatory.

Constructing and operating the ALMA Observatory within the ambitious scientific goals and the unprecedented technical requirements in this environment, with its harsh living conditions, will be one of the real challenges.

Construction of the OSF and AOS sites and their access required substantial effort from the ALMA project. The OSF site, located at 2 900 metres altitude, is about 15 km away from the nearest public road, the Chilean highway No. 23 and the AOS is another 28 km away from the OSF site. A road of 43 km length was constructed to access the OSF and AOS (Figure 1), with sufficient width to regularly transport the antennas between the OSF and AOS for maintenance.

The OSF is the centre of activities of the ALMA construction project. Presently all ALMA Site contractors and their staff are accommodated at the OSF. Work is organised in 20 day working/10 day rest periods. Special camps have been erected and can now accommodate the maximum required capacity of 500 workers.

During the construction period, the OSF will become the focal point of all antenna Assembly-Integration-Verification (AIV) activities. Antenna assembly will be done at the OSF site at three separate areas, one each for the antennas provided by North America (Vertex), Japan (Melco) and Europe (AEM Consortium). AIV 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 day-to-day scientific activities. During the operations phase of the observatory it will be the workplace of the on-site astronomers and of the technical teams responsible for maintaining proper functioning of the ALMA telescope and its equipment.

ESO signed the contract for the construction of the OSF Technical Facilities in August 2006. Construction work has advanced (see Figure 2) and during this time no major problems or delays have occured. As specified in the construction schedule, foundations have been prepared and the superstructures of the buildings were completed in March 2007. Provisional Acceptance of all facilities is foreseen for the first quarter of 2008.

The AOS Technical Building (Figure 3) will be delivered by the North American ALMA partner. Inside the building, construction work and furnishing is expected to be completed by summer 2007. Human operations at the AOS will be limited to an absolute minimum, due to the high altitude. The AOS Technical Building will house the Back-End electronics and the Correlator. Digitised signals received from the radio telescopes will be processed here and further transmitted to the data storage facilities located at the OSF. The AOS building will become usable for installing technical equipment in June 2007.

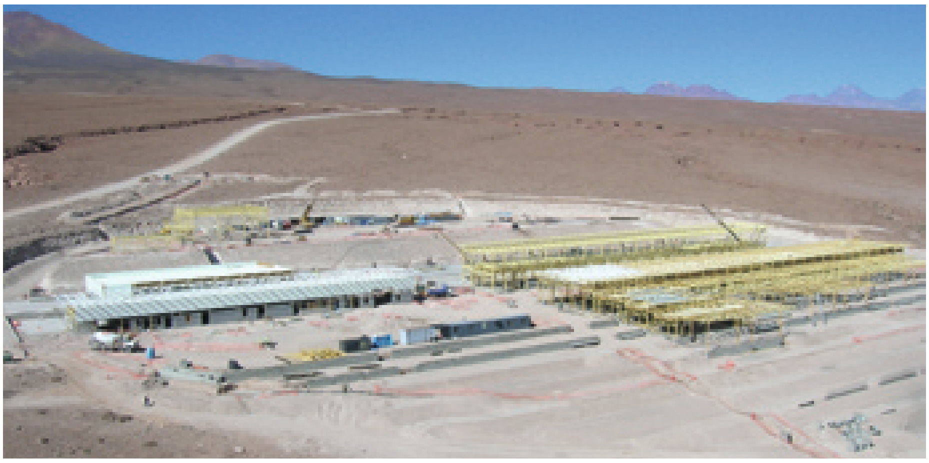


Figure 2: Construction work on the OSF Technical Buildings.

Figure 3: The AOS Technical Building.

The ALMA Antennas

Major performance requirements of each antenna are 2″ absolute pointing over the whole sky, 0.6″ offset pointing, a 25 micron rms overall surface accuracy and the ability to fast switch over a 2-degree range in less than 1.5 seconds. These requirements are at least comparable to those of existing submillimetre radio telescopes; however all of these, except the APEX antenna which is very similar to an ALMA prototype antenna, are protected from the weather by shelters.

The antennas are critical for the ALMA project and their quality and performance are a major contributor to the overall functionality of ALMA. In view of the technical criticality of the antenna specification, three prototypes were supplied by 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 (see the image on the front cover). Various groups of international experts, both internal and external to ALMA, reviewed the performance of the prototype antennas and concluded that the performance expected at the ALMA site conforms to the technical requirements for all three designs.

Following a Call for Tender for the antennas, the North American partners of the ALMA project, through Associated Universities Incorporated (AUI), signed a contract to supply up to 25 antennas, with options to increase the contract to 32 antennas, with Vertex RSI on 11 July 2005. Similarly, on 6 December 2005, the ESO Director General signed a contract (see ESO PR 31/05) with the AEM Consortium (Alcatel Alenia Space France, Alcatel Alenia Space Italy, European Industrial Engineering S.r.L., MT Aerospace) for the supply of 25 ALMA antennas (as the European share of the project), also with options to increase the number of antennas to 32. The four total power antennas of 12 m diameter, equipped with nutators, to be provided by Japan, have been ordered from Mitsubishi Electrical Company. The twelve remaining antennas of 7 m diameter will be ordered in the course of the year 2007 by NAOJ.

The first antenna to be supplied by Vertex RSI is expected to be ready for provisional acceptance in Chile in 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 delayed delivery of the AEM antennas, both suppliers are expected to deliver their 25th antenna by the end of 2011. Acceptance for the first antenna from Japan is expected to take place in December 2007.

The Preliminary Production Design Review for antennas to be produced by Vertex RSI was held in September 2006, the corresponding review for AEM antennas was held at the end of January 2007.

The ALMA Antenna Transporters

The antenna array at an altitude of 5 000 m can be reconfigured by relocating antennas on the stations located on the Chajnantor plateau. The configurations can be changed from a compact one, in which all antennas operate within an area of 160 m × 250 m, to an extended confi-guration for which the maximum separation between antennas reaches about 15 km. In order to move antennas, each with a mass of around 100 tons, the ALMA project has designed a special transport vehicle (Wilson 2006). Two vehicles will be needed to cover the operational relocation requirements. These transporters will move antennas between the assembly and maintenance area at the OSF and the AOS and at the AOS between different antenna stations for reconfiguration of the array. By means of the transporter (Figure 4) the antennas can be positioned to an accuracy of a few millimetres on the high-precision station interface.

The mass of the antennas, their high-precision and the hostile, high altitude environment impose severe requirements on these vehicles. Each transporter will have a mass of about 150 tons, and dimensions of about 10 × 15 × 6 m (width × length × height). The contract for the production of these truly unique tranporters was signed by ESO with Scheuerle Fahrzeugfabrik GmbH (Germany) on 22 December 2005. The first of the transporters will roll out of the hangar and will be tested in summer 2007 (see Figure 4) to be transported and 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.

Figure 4: ALMA Antenna Transporter.

Photo: Scheuerle Fahrzeugfabrik GmbH

The ALMA Front-End

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

The ALMA Front-Ends are superior to almost all existing systems. Indeed, development work for the ALMA prototypes has also led to improved receivers for existing millimetre and sub-millimetre observatories.

They are comprised of numerous elements (Figure 5), produced at different locations in Europe, North America and Japan. In the initial phase of construction ALMA decided, after the prototyping and developing stage, to build a set of eight preproduction units before moving to full production. This initial phase started in the years 2004 and 2005. Some components were successfully and completely preproduced by the end of 2006 and the rest are expected to be completed in the course of 2007.

The largest single element of the Front-End system is the cryostat, a 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. Six cryostats (Figure 6) have been fully assembled. The remaining two units are in manufacture and the Cryostats production contract was signed in April 2007.

A development and pre-production phase was also launched for the six dif-

Table 1: The ten frequency bands of ALMA.

ALMA Band	Frequency Range (GHz)	Receiver Noise Temperature (K) over 80 % of the RF Band	at any RF Frequency	To be produced by[1]	Mixing scheme
1	31.3–45.0	17	26	to be decided	Single Side Band
2	67–90	30	47	to be decided	Single Side Band
3	84–116	37	60	HIA	Dual Side Bands
4	125–163	51	82	NAOJ	Dual Side Bands
5	163–211	65	105	OSO (6 only)	Dual Side Bands
6	211–275	83	136	NRAO	Dual Side Bands
7	275–373	147	219	IRAM	Dual Side Bands
8	385–500	196	292	NAOJ	Dual Side Bands
9	602–720	175	261	NOVA	Double Side Band
10	787–950	230	344	NAOJ (to be confirmed)	Double Side Band

[1] 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)

ferent receiver cartridges (Table 1). The technical specification of the various receiver cartridges are demanding, set at the state of the art or even beyond at the time of definition. The development programmes were successful, meeting essentially all of the requirements – and sometimes substantially exceeding them – specifically for the receiver noise temperatures. This is a very important achievement as to some extent the better noise performance and higher sensitivity partially compensate the loss in collecting area.

In the frame of the European FP6 programme, ESO is leading a group of European institutes to develop and build six Band 5 receiver cartridges and to develop associated software. This project was approved by the European Community at the end of 2005. In parallel, NAOJ is leading activities related to the development of Band 10 receivers. The Band 9 cartridge was built by NOVA in the Netherlands and is shown in Figure 7. The receivers for Band 10 are still in an R&D phase; it is expected that in 2008 a final decision will be made on implementing this ALMA band with the highest frequency.

Pre-production of the cryogenic low-noise amplifiers for Band 7, 4–8 GHz, and for Band 9, 4–12 GHz, receivers has been successfully completed by Centro Astronómico de Yebes (CAY, Spain). Amplifier series production for Band 7 commenced in February 2007 by Spanish industry.

Water Vapour Radiometers (WVRs) are needed to provide a correction of the phase fluctuations due to atmospheric water vapour fluctuations. The development of two prototype WVRs, at Cam-

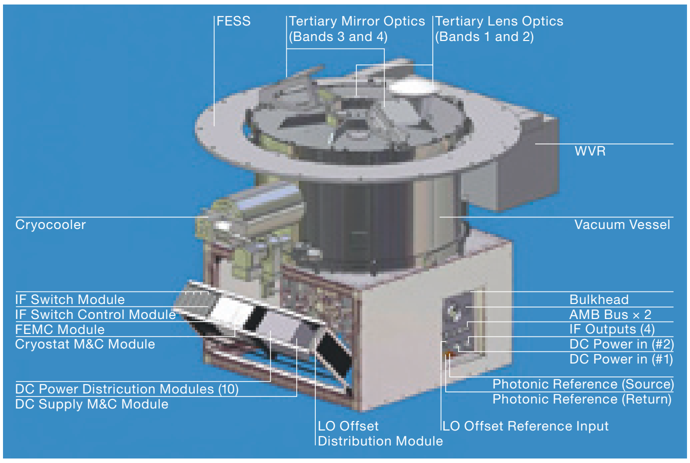


Figure 5: Schematic of the ALMA Front-End System.

Figure 6: ALMA Cryostat pre-production at RAL/UK.

Figure 7: ALMA Band 9 Cartridges ready for delivery, at NOVA in the Netherlands.

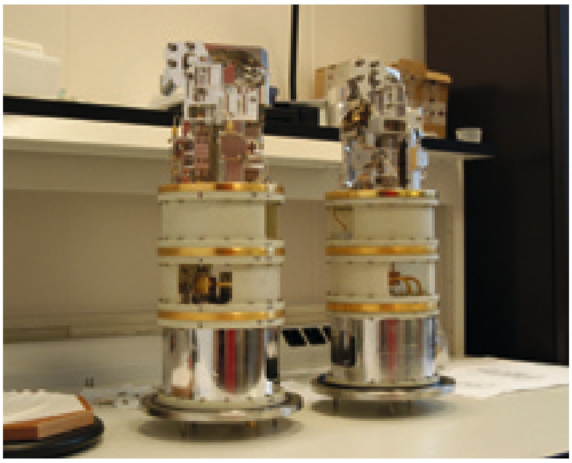
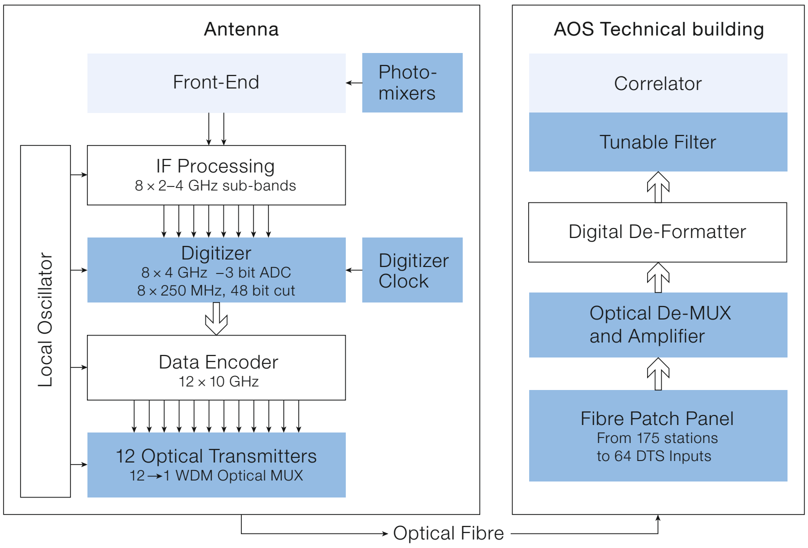


Figure 8: Schematic of ALMA Signal Processing and data transfer from the Front-End to the Correlator. Parts to be provided by ESO are shaded in dark blue.



bridge University (UK) and Onsala Space Observatory (Sweden), was completed and both underwent intensive testing at the Sub-Millimeter Array (SMA) on Mauna Kea (Hawaii). The performance of both prototypes meets the requirements and demonstrated the atmospheric correction method. The Call for Tender for the final detailed design and full WVR production was issued in February 2007 to industry in ESO member states and production should commence in mid-2007.

The ALMA Back-End

The ALMA Back-End systems deliver signals generated by Front-End units installed in each antenna to the Correlator installed in the AOS Technical Building. Signal processing and data transfer is schematically shown in Figure 8. In each of two orthogonal linear polarisations an intermediate frequency (IF) of 8 GHz bandwidth can be processed and recorded at any time. Analogue data, produced by the Front-End electronics, are processed and digitised before being formatted for the transmission through the optical transmitter units and multiplexers. All these elements are installed in the receiver cabins of each antenna. Optical signals are then sent through optical fibres to the AOS Technical Building. The total distance in the most extended antenna configuration is about 15 km. At the AOS Technical Building the incoming optical signals are de-multiplexed and deformatted before entering the Correlator.

The European deliverables in the ALMA Back-End project are a number of components, which are produced by several European institutes, working closely with ESO, and NRAO. These deliverables are: digitizer chips and digitizer assembly; digitizer clock assembly; optical data transmission system; fibre patch panel; optical multiplexers (MUX) and de-multiplexers (De-MUX); Erbium-Doped Fibre Amplifiers (EDFA), and photonic local oscillator photomixers.

Development and pre-production of these components has been successfully completed; the components will be integrated at NRAO in Socorro and installed in the European and North American prototype antennas for tests at the ALMA Test Facility ATF.

An example of one of the various Back-End components produced in Europe is the 4 GHz digitizer in its final layout (see Baudry et al. 2006, Figure 3). The clock rate is 4 GHz, allowing an input bandwidth of 2 GHz. The digitization uses three levels to preserve the signal-to-noise ratio. During the prototype and development phase, the initial layout was optimised 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 units have been shipped to Socorro for final acceptance and integration with 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 takes as input the digitized signals from the individual antennas and outputs amplitude and phase on all of the interferometer baselines in each of a large number of spectral channels. 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 joints. The first quadrant was completed at NRAO 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, which allow a major increase in the flexibility by subdividing the frequency range into 32 independently configurable sub-channels. Four TFB cards are needed for the data coming from a single antenna. The TFB cards have been developed and optimised by the University of Bordeaux over the last few years. Prototypes and preproduction units were extensively tested and their performance was critically reviewed in the first half of 2006. In the meantime, series production is progressing and the first batch of 108 out of 560 TFB cards has been produced.

System Engineering and Integration

An important ALMA-wide activity is the System Engineering and Integration (SE&I) task, which covers coordination of activities across the project. One of the prime objectives of SE&I is to ensure that modules and equipment produced for an ALMA subsystem, often in different locations of the world, fit physically and functionally together. SE&I is also responsible for the ALMA system design, technical budgets and for ensuring the system integrity, and hence has to ascertain that all interfaces between the various subsystems are completely understood, well defined, rigorously reviewed and properly documented.

In order to achieve the tasks mentioned above, the SE&I team takes a central role in the preparation and management of project performance and engineering requirements and Interface Control Documents ICD. SE&I is also very active in organising, holding and chairing technical reviews of the project, which could be internal to ALMA or external, reviewing the status and progress of the design and manufacturing of ALMA components by industry or scientific institutes. Product and Quality Assurance is another task and will receive a high visibility specifically during the manufacturing phase.

The SE&I group is also leading the activities related to Prototype System Integration and the testing at the ALMA Test Facility (ATF) in Socorro (see front cover). During the years 2007 and 2008 the ATF will serve as a facility where ALMA hardware and software will be integrated into an operational system using the two prototype antennas from Europe and North America. In a joint effort with the ALMA Science team, first fringes were recorded in March 2007 (see ESO PR 10/07). The ATF is also used for training integration and operations personnel for Chile and for qualifying equipment needed for acceptance tasks in Chile, such as the Optical Pointing Telescope and the Holography System.

Another major activity for the coming years is the Assembly, Integration and Verification (AIV) at the OSF. Equipment acceptance has already started and AIV at the OSF will begin with the antenna delivery in the middle of 2007 for which preparations are currently ongoing.

Computing

The development of a unified software system for the ALMA Observatory is another important activity which requires intensive interactions with all of the ALMA engineering project teams. The nature of software development calls for a common approach and policy from the very beginning – not only with respect to the engineering teams, but also between the European and North American partners. In contrast to some cases of hardware oriented activities, where specialised instruments are provided, this project requires entire software packages to be developed under a single management and organisation.

ALMA Software Development is managed as a truly integrated, trilateral organisation. The European, North American and Japanese Executives have identified individual work packages under a common leadership.

Work in Europe is organised through ESO. 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 developing and testing the required software. Table 2 gives an overview of software projects carried out by various European institutes in association with ESO.

Table 2: 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
ALMA Common Software	OAT

[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)
OAT Osservatorio Astronomico di Trieste

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

Figure 9 shows as an example the Operator Master Console. This is part of the Executive subsystem, for which ESO is responsible.

Acknowledgements

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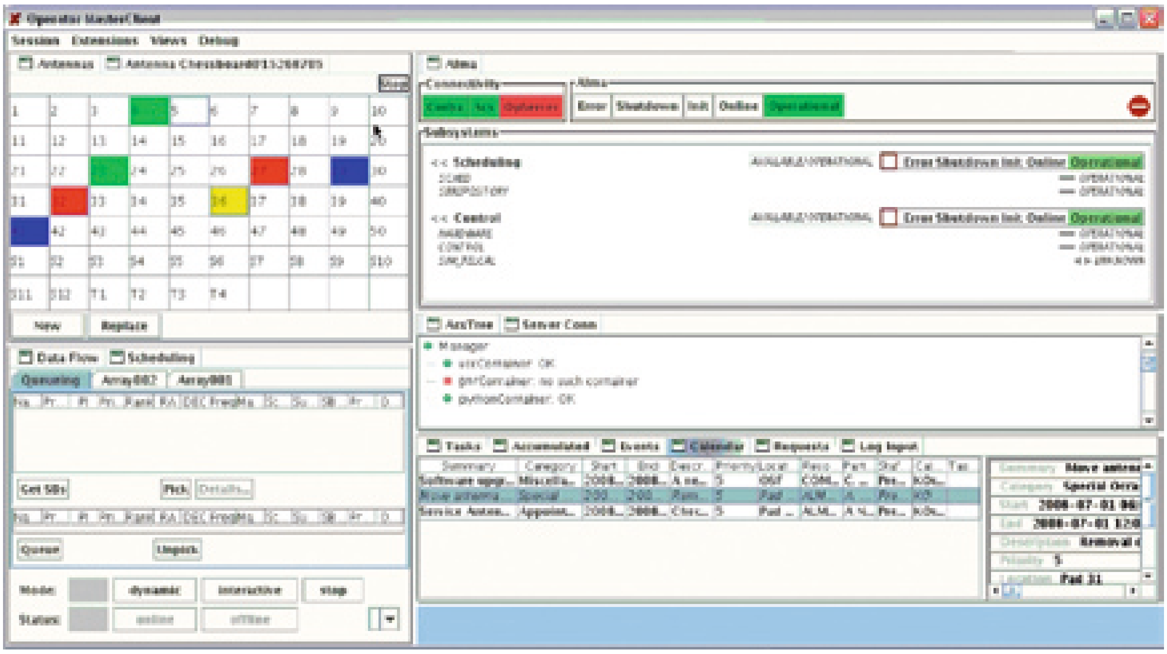

Figure 9: The ALMA Operator Master Console.

ALMA European Project Scientist Appointed

Tom Wilson (ESO)

The new ALMA European Project Scientist is Dr. Leonardo Testi. He took up the appointment in May 2007. Leonardo Testi received his Ph.D. from the University of Florence in 1997. Subsequently he was a postdoctoral fellow at the Owens Valley Radio Observatory of Caltech. In 1998 he joined staff of the Arcetri Astrophysical Observatory, and later on of INAF, for which he also served on the Science Council. Leonardo has been chair of the European ALMA Science Advisory committee and a member of the ALMA Science Advisory committee, so he well knows the details of the project as well as the science that can be carried out with ALMA.

Leonardo's main scientific interest is the study of circumstellar discs around newly formed stars. It is believed that many of these discs of dust and gas will develop into planetary systems, so such studies are complementary to the optical searches for extrasolar planets being carried out, for example, with HARPS and the ESO 3.6-m telescope. The major drawbacks to present-day studies of circumstellar discs are sensitivity and angular resolution. With ALMA, the sensitivity will be more than 40 times better, and the angular resolution more than 5 times better, than current instruments. Thus ALMA will allow breakthroughs in this area, as well as for studies of star formation, galaxy evolution and dynamics, Solar System science and cosmology.

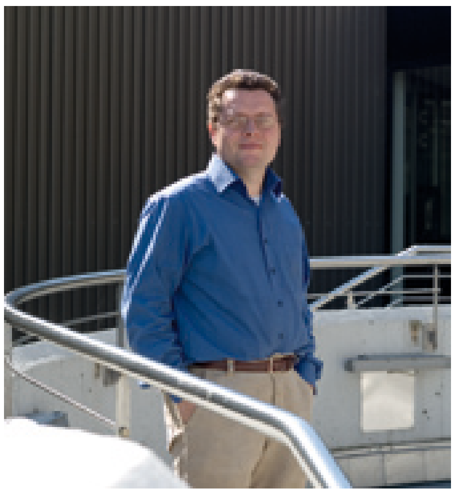

Photo: H. H. Heyer, ESO

Dr. Leonardo Testi