ALMA: Status Report on Construction and Early Results from Commissioning

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ABSTRACT

The Atacama Large Millimeter/submillimeter Array (ALMA) is an international facility at an advanced stage of construction in the Atacama region of northern Chile. ALMA will consist of two arrays of high-precision antennas: one made up of twelve 7-meter diameter antennas operating in closely-packed configurations of about 50m in diameter, and the other of up to sixty-four 12-meter antennas arranged in configurations with diameters ranging from about 150 meters to 15 km. There will be four more 12-meter antennas to provide the "zero-spacing" information, which is critical for making accurate images of extended objects. The antennas will be equipped with sensitive millimeter-wave receivers covering most of the frequency range 84 to 950 GHz. State-of-the-art microwave, digital, photonic and software systems will capture the signals, transfer them to the central building and correlate them, while maintaining accurate synchronization. ALMA will provide images of a wide range of astronomical objects with great sensitivity and very high spectral resolution. The images will have much higher "fidelity" than those from existing mm/submm telescopes. This paper gives an update on the status of construction and on progress with the testing and scientific commissioning.

Keywords: ALMA, millimeter-wave, sub-millimeter, aperture synthesis, commissioning

1. INTRODUCTION

A general description of ALMA can be found in Hills and Beasley[1]. A summary of the astronomical goals, site and technical design is given by Wootten and Thompson[2]. This paper reports on progress with the construction and the early stages of commissioning of ALMA. Five fully-equipped antennas are now in operation at the 5000m-altitude Array Operations Site (AOS) and a further four are under test at the 2900m-altitude Operations Support Facility (OSF).

Figure 1. Five ALMA antennas in operation at the Array Operations Site at 5000m altitude.

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2. CONSTRUCTION

ALMA design and development has been successfully completed and the project is well into series production of the myriad of components, subassemblies, and subsystems that make up the whole system. When manufacturing and testing of these elements is completed, they are delivered to, and formally accepted by, the Joint ALMA Observatory (JAO) in Chile. Assembly, integration and verification (AIV) of these elements into fully-equipped antennas are the next steps in the construction process. AIV began at the end of 2008. The status of these elements and of the site infrastructure is described in the following subsections.

2.1 Site Infrastructure and Configuration

Civil construction of the technical building at the Array Operations Site (AOS-TB) was completed in 2008. Outfitting and commissioning of the building is largely completed. Two quadrants of the 64-input correlator have been installed and are operational. The third quadrant is being installed and tested now. Final acceptance testing of the ACA correlator is complete. The initial version of the central local oscillator has been operational since the third quarter of 2009.

Construction of the 192 antenna foundations making up the entire array configuration is finished. Turning these foundations into operational antenna stations requires an extensive network of access roads suitable for the antenna transporters, plus power and signal connections to the central technical building. Construction of the underground power distribution and fiber optic communication networks along with installation of the precision mechanical interface to an antenna has been completed for 30 of the antenna stations located in the central region of the array.

Delays in the construction of the permanent power system (see below) have forced the power supply at the AOS to evolve from two diesel generators to a temporary multi-generator power system currently capable of supplying 2 MVA under extreme environmental conditions.

Civil construction of the technical facility at the Operations Support Facility (OSF-TF) was also completed early in 2008. However, outfitting and commissioning of that facility has turned out to be relatively costly and is still ongoing – and will be well into 2011. The problem was inadequate knowledge of the requirements for the primary initial use of the facility (AIV) when the facility was designed in 2004. This shortcoming was compounded by the descoping in 2007 that was necessary when faced with a construction cost that far exceeded the original estimates. The result is a complicated situation of occupying and using the facility in parallel with completing modifications and outfitting much of the space.

Figure 2. Left: archive system in place at the OSF. Right: antenna stations in use for AIV and initial testing, also at the OSF.

The selection and procurement of the permanent power system (PPS) capable of supplying ALMA with up to 7 MW of electrical power has been a long and complicated process. The elements comprising the PPS are an "island-mode" power plant located at the OSF, a 23-kV substation and power distribution network at the OSF, an underground 23-kV power transmission line between the OSF and the AOS, and a 23-kV substation and power distribution network at the AOS. The power source finally selected for the island-mode power plant will be three multifuel-turbine-powered generators. The 23-kV elements of the PPS are of conventional design with proper regard for the ALMA environment, particularly the 5000-m altitude. The 23-kV substation at the AOS includes flywheel-based energy storage equipment to cope with the surges in power demand that can occur when the antennas are executing fast motions.

The original plan for the source of energy for ALMA was to use natural gas supplied from an Argentina-to-Chile gas pipeline that transits the ALMA site. When the Argentine source quit supplying gas to the pipeline in 2007 that plan had to be abandoned. The next approach selected was to obtain electric power from the northern Chile power grid. This would require construction of a 140-km, 110-kV overhead power line from ALMA to the nearest grid substation in Calama. Although this was a formidable proposition, ALMA was able to progress very far into negotiation of a suitable contract for the construction of the power line because of synergy with the local communities of San Pedro de Atacama, which also very much wanted a connection to the grid. In the end it was not possible to bring the negotiations for supply and transmission of power to a successful conclusion and this approach was also abandoned. The final decision, made in early 2009, was to return to an island mode of power generation as described above.

The contract for construction of the 23-kV power system was awarded in November 2009 and is scheduled to be completed in February 2011. The contract for the island-mode power plant was awarded in June 2010 and should be completed in August 2011. At that time ALMA will finally have operational a reliable permanent power system. Throughout this process ALMA has considered renewable sources of energy and the ALMA PPS is designed to be supplemented with renewable energy sources when economically viable.

In summary, infrastructure is the most problematic area of ALMA construction from the perspective of those working on the project in Chile. A painful lesson learned has been that the complexity and criticality of the whole ALMA infrastructure was very much underappreciated and the importance of what might by some be regarded as uninteresting, mundane engineering was undervalued. As a result, the cost of infrastructure construction has consistently exceeded estimates by significant amounts.

2.2 Antennas

The ALMA antennas are being constructed by three separate companies. Vertex, a part of the General Dynamics Corporation of the USA, will produce 25 12-m antennas. AEM, a European consortium of Thales-Alenia Space, European Industrial Engineering and MT Mechatronics, will also produce 25 12-m antennas. MELCO, part of the Mitsubishi Electric Corporation of Japan, will produce four 12-m and twelve 7-m antennas. In each case final assembly and testing is performed at the respective supplier's erection facility at the OSF. At the time of writing 25 antennas are in various stages of assembly, integration, testing and verification at the OSF and AOS. A total of 15 Vertex antennas are on site, and six of them have been conditionally accepted by the JAO. A total of five AEM antennas are on site, and two of them are in an advanced state of assembly. Acceptance of the first AEM antenna by the JAO is expected in early 2011. Five MELCO antennas are on site – four 12-m and one 7-m. Two of the 12-m antennas have been conditionally accepted by the JAO. The 7-m antenna is in testing and acceptance by the JAO is expected in January 2011.

Figure 3. ALMA antennas (MELCO 12m & 7m – AEM 12m – Vertex 12m)

Acceptance testing of the initial Vertex and MELCO antennas was a lengthy and sometimes contentious process. The very demanding ALMA performance requirements (surface accuracy, all-sky and offset pointing, and fast switching) have been demonstrated to either be fully met, or at the least to be very close to being met. On the other hand, requirements such as reliability, maintainability, stability and performance under the extremes of the ALMA environment will take much longer to verify. After extensive acceptance testing, the JAO accepted the two antenna transporters in mid-2009. Both are now in operation routinely moving antennas over the 30-km distance (and 2100-m change in altitude) between the OSF and the AOS, as well as around the OSF and AOS.

2.3 Receivers

Receiver development of cartridges for bands 3 through 10 (85 to 950 GHz coverage) has continued at institutes in all three of the ALMA partners. Bands 3 and 6 in North America have completed development, pre-production, and are well into production with 30 and 23 cartridges, respectively, delivered. Bands 7 and 9 in Europe are similarly well into production with 28 and 30 cartridges, respectively, delivered. Bands 4 and 8 in Japan are into pre-production each with two cartridges delivered. Development of band 10 in Japan is progressing well with the first cartridge scheduled for delivery in October 2010. Finally, development of band 5 in Europe has just completed a critical design review. For all of the bands that have completed development, the critical ALMA specifications have been demonstrated to be met, with a few exceptions, but in some important cases, such as receiver noise temperatures in several bands, the performance is very substantially better than the specifications.

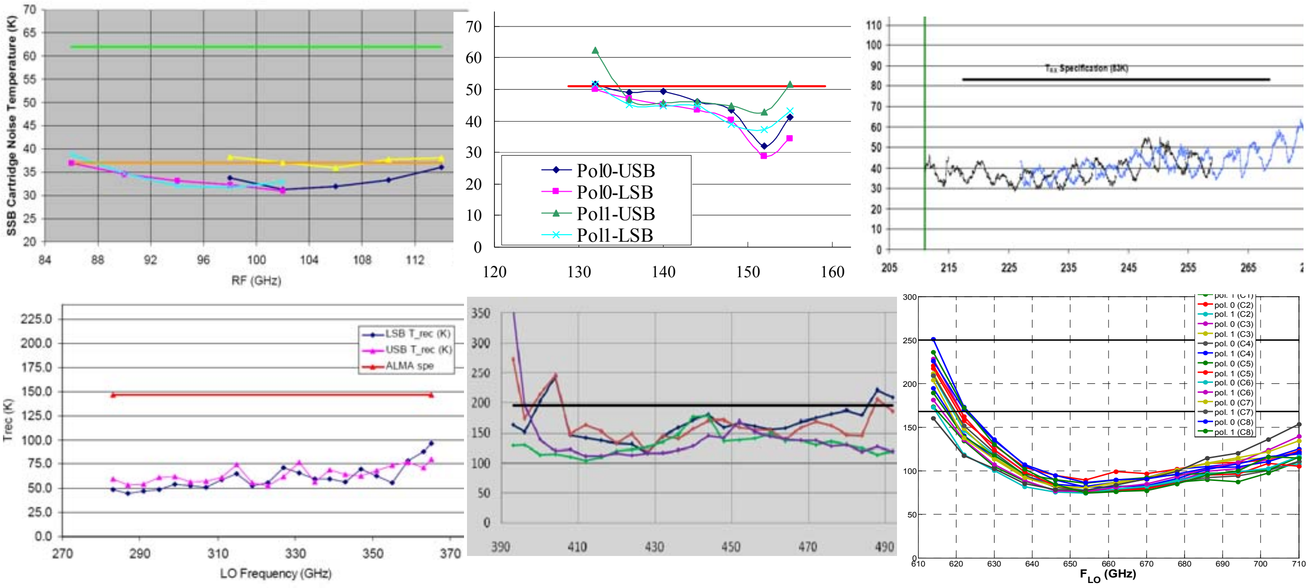

Figure 4. Examples of receiver performance vs. specification

The production lines for other front end components are well established with some significant exceptions. These exceptions tend to be relatively low-tech items, again indicating a lack of appreciation of the importance of more mundane production engineering. In all cases we expect production units to start being delivered by August 2010 at latest. All of these front end components are delivered, for integration into a FE assembly, to one of three Front-End Integration Centers (one FEIC in each of the ALMA partners – this in itself is a challenging supply chain management problem). All three FEICs are in operation, but with less than the full test capability, which should however be available in the near future.

Following successful testing at a FEIC, the FE assemblies are delivered to the JAO in Chile to enter into AIV. Up until this time FE assemblies have been the pacing item (i.e., on the critical path) for AIV. Consequently, ALMA decided that the delivery of the first ten FE assemblies to the JAO would be with less than complete FEIC testing. The risk of a serious problem showing up at the JAO was deemed to be low enough to warrant proceeding into AIV. Thus far this strategy has worked. As of the end of June 2010, ten FE assemblies have been delivered to the JAO and eight have been successfully integrated into antennas.

Figure 5. Front End assembly in integration at the East Asian FEIC and delivered to the OSF

2.4 Photonic Systems

Development of the very challenging and critical photonic system, which distributes a precise reference signal to each antenna to keep the local oscillators synchronized, has been successfully completed. Sufficient components of the system have been produced, integrated and tested to deliver the initial version of the Central Local-Oscillator Article (CLOA1), which can provide reference signals for 16 antennas. This CLOA1 was installed at the AOS-TB and successfully tested in October 2009. Another critical component of this system is the buried fiber optic network that connects each antenna (via an antenna station) to the CLOA. Thus far commissioning activities at the AOS have demonstrated the successful performance of the entire system over distances up to about 600 m under severe environmental conditions. The local oscillator photonic receivers integrated into the FE assembly of each antenna are also in production with 23 units delivered to the FEICs so far.

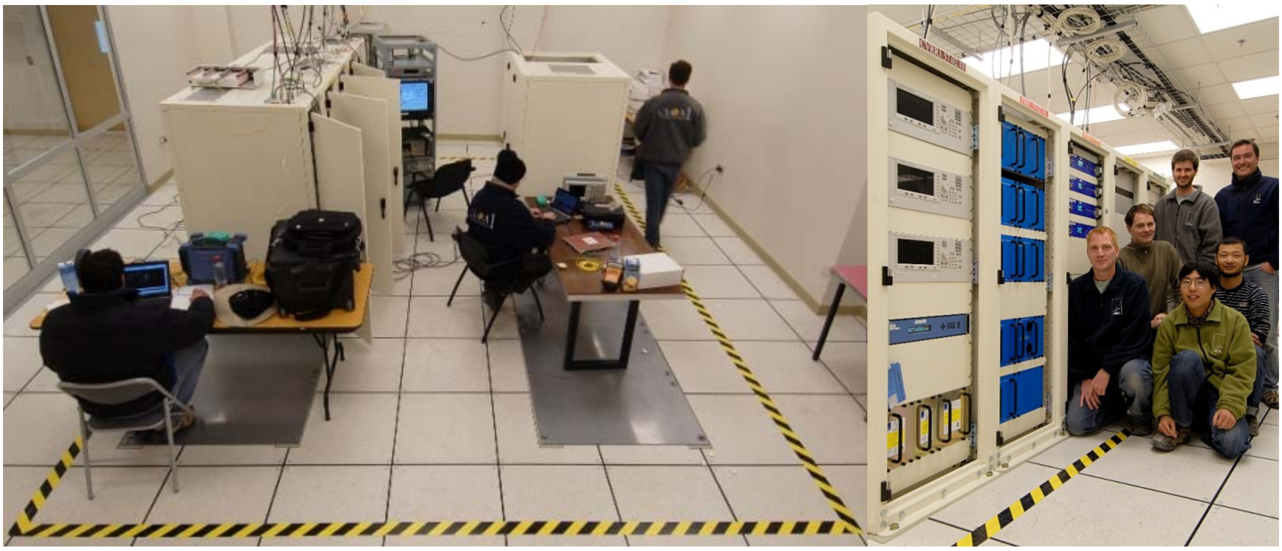

Figure 6. Installation and testing of the central local oscillator system at the AOS Technical Building

2.5 Digital Systems

The ALMA digital signal processing components are integrated into a so-called back-end antenna article. This assembly physically consists of two racks of equipment that are integrated into antenna receiver cabins during AIV. Production of all back end components is well established and 20 antenna articles have been integrated, tested and accepted by the JAO to date. These units have been delivered well in advance of the AIV need dates.

The digital correlators, both the 64-input XF correlator and the ACA FX correlator, are another ALMA success story. The first quadrant of the 64-input correlator has completed installation and testing at the AOS-TB and was accepted by the JAO in September 2008. The same milestone was passed for the second quadrant in January 2010. The third quadrant is currently under test at the AOS-TB and scheduled to be accepted by the JAO in November 2010. The fourth quadrant is scheduled to be accepted in February 2011. Installation and testing of the ACA correlator at the AOS-TB has been completed and acceptance is expected in July 2010.

Figure 7. The ACA correlator and the 64-input correlator (two quadrants visible) installed at the AOS Technical Building

2.6 Software

ALMA software has been systematically developed by an integrated team distributed in institutions located throughout the ALMA partnership. The process uses annual incremental critical design reviews and version releases to introduce increased functionality progressively. Testing of the software at the ALMA Test Facility in New Mexico was found to be essential to successful development and was extended for as long as possible. In order to maintain the ability to test software releases off-line before acceptance as the current operational software, a two-antenna interferometer was set up at the OSF-TF. Late in the AIV process at the OSF, fully-equipped antennas are cycled through this test facility before being transported to the AOS to complete AIV and join the commissioning array. Release 7.1 is the current operational ALMA software version, and Release 7.1.1 is currently under test at the two-antenna interferometer. These releases have a high degree of functionality that supports the commissioning of the complete end-to-end ALMA system. Full functionality should be achieved with Release 9.0 late in 2011.

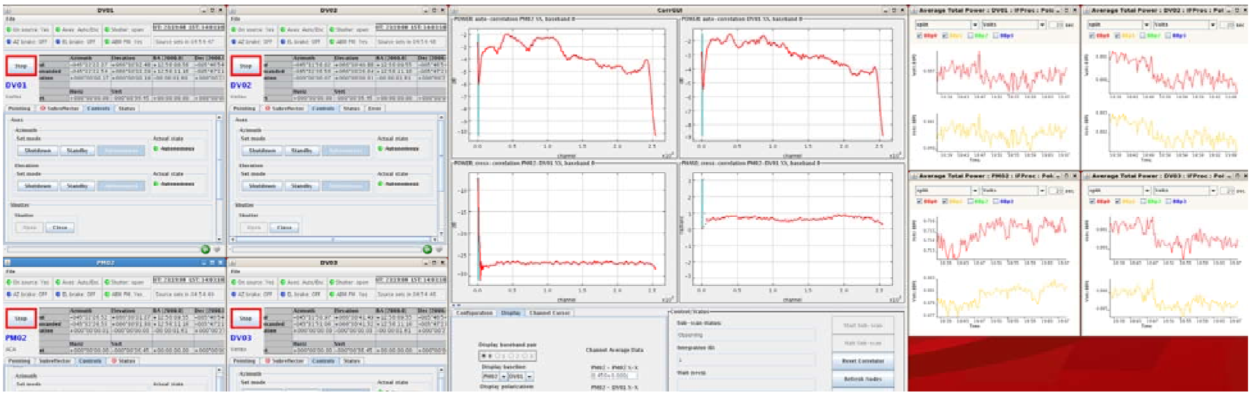

Figure 8. A small part of the display on the operator's console (in the OSF control room) running the systems at the AOS

2.7 Assembly, Integration and Verification (AIV)

As part of the ALMA construction phase the AIV team receives antennas and instrumentation from the partners, verifies that the elements perform as expected, performs the assembly and integration of the scientific instrumentation, and verifies that functional and performance requirements are met through a four-station AIV process. A detailed description of the AIV process and its development is given by Lopez, McMullin, Whyborn and Duvall[3].

With the first antennas entering acceptance testing on site the team started to gather experience with AIV Station 1 beacon holography measurements for the assessment of the overall antenna surface quality and optical pointing to confirm the antenna pointing and tracking capabilities. With the arrival of the first receiver AIV Station 2 was developed which focuses on the installation of electrical and cryogenic systems and incrementally establishes the full connectivity of the antenna as an observing platform. Stations 3 and 4 involve the verification of the antenna with integrated instrumentation by the AIV science team.

The ALMA top-level milestone that was a key objective of AIV is the start of commissioning and science verification (CSV), for which the main requirement is three antennas operating as an interferometer at the AOS. In November 2008 this milestone was forecast to have slipped from November 2009 to February 2010. A subproject, led by the AIV manager, was set up within the overall construction project with the specific objective of pulling the date for the start of CSV back into 2009. Through an intense, focused effort and many workarounds this subproject achieved the milestone on 22 January 2010. At the time of writing a total of five antennas have completed the AIV process and have been handed over to the commissioning team.

3. COMMISSIONING

The formal start of Commissioning was marked by the hand-over of an interferometer system consisting of three antennas each equipped with four receiver bands covering the most critical parts of the frequency range 80 to 700 GHz, together with back-end electronics, a photonic LO system, the first quadrant of the correlator and sufficient software to perform initial operation and data analysis. Basic single-dish and interferometric operation had been verified at that point including a demonstration that the phases in three-element operation "close" – i.e. that on a point source, the ordered sum of the phases on the three baselines was close to zero, as it should be.

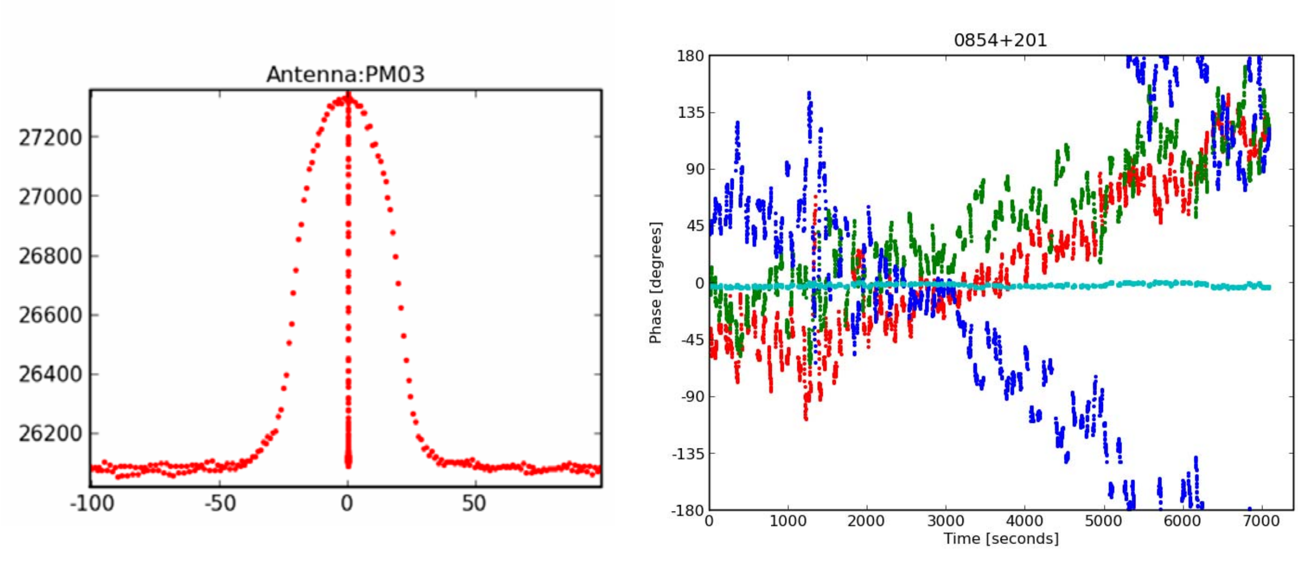

Figure 9. Two examples of early test results. Left – total-power scans of the planet Jupiter at 660GHz. Right – interferometric phase measured on a quasar: red, green and blue points are the phase for the three baselines, showing variations due mainly to fluctuations in the water vapour, and the light blue points show the closure phase.

In practice the work towards commissioning had started at least a year earlier with the processes of planning, developing and trying out test procedures and helping to solve the many problems that came up during the AIV phase.

The work has continued on two main fronts: 1) investigating in depth the performance of individual parts of the system, such as the antennas, the LO system and the correlator, and 2) gradually building up the capability to perform complete observations of the type that ALMA is expected to carry out when it is operational.

An important example of the former is making measurements to see whether the antennas have the required high surface accuracy over the full range of operational conditions – temperatures from -20 to +20ºC, in sunlight and in shade, elevation angles from 0 to 90 degrees, winds up to 10m/s, etc. Our best tool for measuring the surface shape is "holography" using astronomical sources. The term "holography" here means determining the complex far-field beam pattern of the antenna and then taking the Fourier Transform to obtain the amplitude and phase in the aperture plane. The phase gives a measure of the surface errors. The beam pattern is obtained by keeping one or more antennas pointing at a bright source and performing a rectangular scanning pattern around the source with the antenna(s) under test while recording the correlated signals. The following figure shows the impressively high resolution we have achieved with this technique.

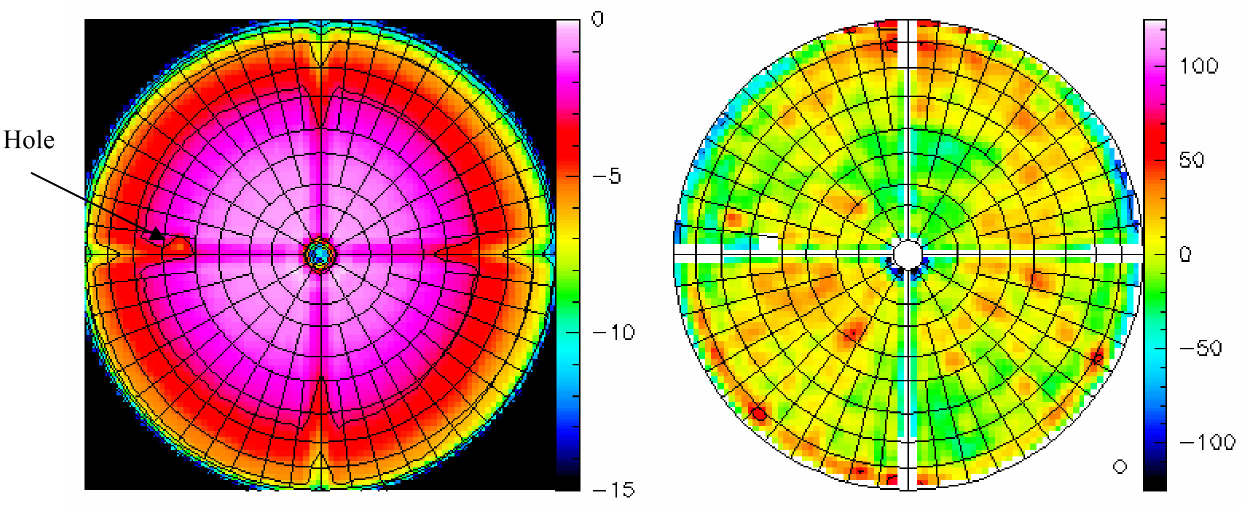

Figure 10. "Holographic" antenna measurement performed using Saturn as a source. Left – amplitude showing shadowing due to the subreflector support legs and (arrowed) the hole for the optical pointing telescope. Right – phase giving the surface errors. The weighted rms surface error is about 18 microns. The pattern of reflector panels is superimposed.

Other important antenna tests include the pointing accuracy, which can be established by making interferometric observations of objects all over the sky, tracking errors – seen from the signal fluctuations when following an object with an offset of half a beam-width – and path-length errors due to e.g. the wind causing the dish to deflect. The latter are difficult to measure: correlating the interferometric phase changes with variations in wind speed is the most direct method available and we plan to do this.

We are also working on tests of many other aspects of the system, including phase and amplitude stability, noise performance and tuning range. In all these cases the initial results are generally very promising – it is clear that the basic designs are sound and that the system is behaving in the intended manner. In almost every case, however, we are finding subtle effects or occasional "glitches" which will need to be sorted out before we can consider the job to be done. In addition there remain some important topics, such as the polarization performance, where we have barely started detailed testing.

Another important area that has shown promising initial results is the system for correcting the phase errors that are caused by fluctuations in the amount of water vapour in the atmosphere. We have two tools for doing this. 1) We switch between the object of interest and a compact source (a phase calibrator) at a nearby position in the sky. This takes out the slowly varying part of the atmospheric phase, as well as instrumental phase variations. 2) We use radiometers on each antenna to make measurements of the water vapour content along each line of site of though the atmosphere. These radiometers operate at 183GHz where there is a sufficiently strong emission line of water to give an accurate reading even on short timescales (less than a second) so that the fast fluctuations can be removed.

So far the tests have concentrated on the second of these, since the software for very rapid switching to a calibration source is not yet in place. We find that, so long as there are no clouds, a large fraction of the effect of the water can be removed. We expect that this can be improved significantly with more sophisticated treatment of the data, although it is clear that doing this in the presence of clouds containing liquid water will be difficult.

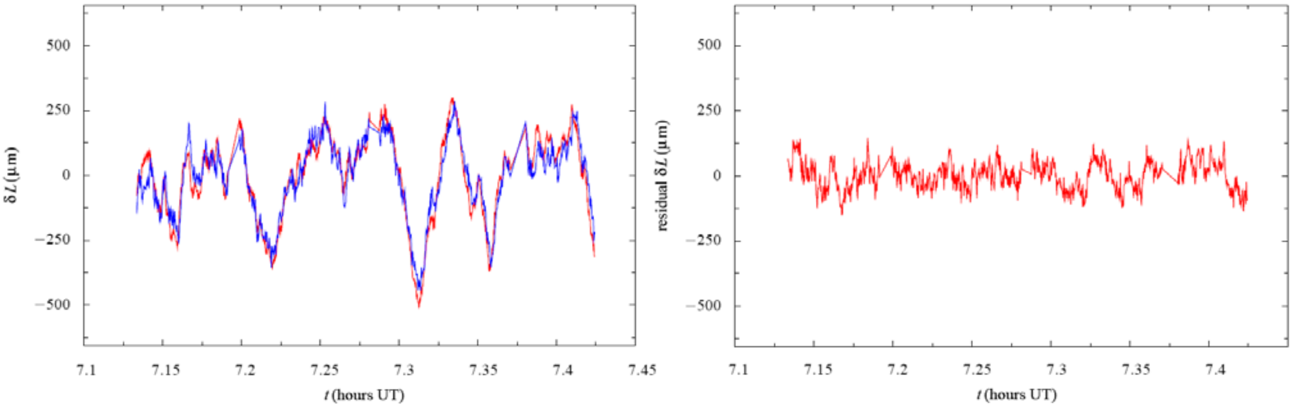

Figure 11. Correction for atmospheric phase variations. Left – measured phase (red) and phase predicted from the measurements of the water vapour. Right – residual after applying the correction.

In addition to testing particular items of the hardware we are of course working hard to check out the large and extremely complex set of software that has been created to run ALMA. Work on software in fact takes up by the far the largest part of the time of the commissioning team, since all access to the hardware and to the data goes through the software.

Figure 12. The scene in the control room at the OSF, from where operations at both the OSF and the high site are conducted.

The complete software cycle for performing an observation makes use first of the Observing Tool which the astronomers use to describe the measurements that they want to make. This produces one or more Scheduling Blocks containing detailed instructions. These are stored in the Archive and then executed by the Control System resulting in data sets, which are again stored in the Archive. The data is then extracted and processed to produce images and spectra using the CASA data reduction system. We are already able to perform complete end-to-end tests of this system for several different types of astronomical projects, although with only a small number of antennas and limited calibration capabilities the images produced are not yet of a quality to publish. As we complete the detailed technical tests in the coming months, the emphasis will shift to this area of demonstrating that ALMA is capable of producing high quality astronomical data – the Science Verification phase.

4. SCHEDULE

The top-level milestones for the Project are as follows:

- Start of CSV (three antennas at the AOS operating as an interferometer with phase closure) – 16 November 2009;
- First call for early science proposals (operational readiness demonstrated with at least eight antennas operating at the AOS) – 22 November 2010;
- Start of early science (operational 16-antenna array with a subset of observational modes available) – 22 July 2011;
- ALMA inauguration (fully operational 50-antenna array) – 01 September 2012, and;
- 66 antennas in service (completion of the 66-antenna array) – 01 April 2013.

The Start of CSV milestone was reached on 22 January 2010. The current forecast for the first call for early science proposals is 02 December 2010. Start of early science is forecast to be 30 July 2011, ALMA inauguration to be 08 January 2013, and 66 antennas in service to be 13 July 2013. A major challenge for the construction project is to improve schedule performance and achieve these top-level milestones by the reference dates.

5. ACKNOWLEDGEMENTS

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None of the progress described in this paper would have been possible without the sustained and dedicated efforts of the large number of very talented people and institutes who make up the ALMA partnership and we gratefully acknowledge all of these.

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