The Atacama Large Millimeter/submillimeter Array

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ABSTRACT

The Atacama Large Millimeter/submillimeter Array (ALMA) is an international radio telescope under construction in the Atacama Desert of northern Chile. ALMA will be situated on a high-altitude site at 5000 m elevation, allowing excellent atmospheric transmission over the instrument wavelength range of 0.3 to 10mm. ALMA will contain an array of up to sixty-four 12-m diameter high-precision antennas arranged in multiple configurations ranging in size from 150 meters up to ~15 km, and a set of four 12-m and twelve 7-m antennas operating in closely packed configurations ~50m in diameter. The instrument will provide both interferometric and total-power astronomical information on high-energy electrons, molecular gas and dust in solar system, our Galaxy, and the nearby and high-redshift universe. In this paper we outline the scientific drivers, technical challenges and construction status of ALMA.

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

1. INTRODUCTION

ALMA is the largest ground-based astronomical project yet undertaken. It is a truly international effort involving research institutes, companies and individual researchers from all around the world. The goals are ambitious: they call for large improvements in performance relative to existing telescopes to be made simultaneously in all the important parameters – angular resolution, sensitivity, frequency coverage and imaging quality – while also requiring that ALMA should be an instrument that all astronomers can use easily. The design has pushed the state of the art in many areas – precision antennas, low-noise receivers, photonic reference signal distribution and digital signal processing being some examples of interest at this conference.

The joint project grew out of what were originally independent efforts in the USA, Europe and Japan to build large aperture-synthesis arrays for millimeter-wave astronomy. Canada joined the USA to form the North American part of ALMA working with a European grouping led by ESO. Construction began in 2002 with the opening up of the site and the development of hardware and software in the partner institutes. Japan formally joined ALMA in 2004, bringing additional resources to develop the Atacama Compact Array (or ACA) and to improve the frequency coverage of the whole telescope. Taiwan joined ALMA in 2005, so the partners are now East Asia, Europe and North America, working in cooperation with the Republic of Chile. The Project has now reached an extremely exciting stage where the hardware is starting to arrive in Chile and the assembly and testing of the system is getting underway.

2. SCIENTIFIC OBJECTIVES

The original scientific inspiration for ALMA came from two related key discoveries: the realization that the early stages of star formation in our own galaxy take place deep inside clouds of dust and gas which are opaque at visible and even near-IR wavelengths, and the appreciation that the process of assembling massive galaxies, which takes place at high redshifts, is also accompanied by large amounts of extinction with the result that much of the energy released only escapes at far-IR wavelengths and is therefore received (after being red-shifted) in the sub-millimeter part of the spectrum. Both these processes are critical steps in the origin of our systems like own Galaxy and the Solar System. In order to understand the physical and chemical processes that are involved we need high quality images with high angular resolution – significantly better than 0.1 arc-seconds – and high sensitivity – ~10 micro-Jy in 1 hour at 1mm wavelength in the continuum. High spectral resolution is also required – i.e. a frequency resolution of at least 1 part in 10^6, i.e. Doppler velocities of less than 0.3 km/s – so that atomic and molecular lines can be observed to study the constituents and dynamics of the gas. In fact ALMA's frequency resolution will be at least 1 part in 10^7. A further important capability is that of measuring the polarization of the signals, since this gives information on the magnetic fields and the geometry of the objects. The goal here is to reach an accuracy in measuring Stokes's parameters of better than 0.1%.

With its ability to image dust-enshrouded objects and cold molecular material, ALMA will complement other major facilities such as the Very Large Telescope, Gemini, Subaru and the James Webb Space Telescope, and (later) the ELT's and the SKA. The resolution and sensitivity of ALMA will open up dramatic new possibilities over a great range of astronomical topics. Here are some examples of the programs that are being planned:

- Imaging the broadband emission from dust in evolving galaxies at epochs of formation as early as z = 10;
- Tracing the chemical composition of star-forming gas in galaxies throughout the history of the universe through measurements of molecular and atomic spectral lines;
- Measuring the motions of obscured galactic nuclei and quasi-stellar objects on spatial scales finer than 300 light years;
- Imaging and spectroscopy of gas-rich heavily obscured regions that are collapsing to form protostars, proto-planets and pre-planetary disks;
- Measuring the isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing ;
- Producing sub-arcsecond images of cometary nuclei, hundreds of asteroids and Centaur and Kuiper belt objects as well as images of planets and their moons;
- High time-resolution imaging of active solar regions to investigate particle acceleration on the Sun's surface.

3. SITE AND CONFIGURATION

ALMA's specified wavelength range is from 10 mm and 0.3 mm, corresponding to frequencies of about 30 to 950 GHz. Because these wavelengths are strongly absorbed by clouds and water vapour in the atmosphere, the instrument is located in the very dry Atacama region of northern Chile. At 230 GHz the zenith optical depth, measured over the period 1995 to 2000, had a median value of 0.061 and the 25% and 75% points in the distribution were 0.036 and 0.115.

The center of the array is on the Chajnantor plateau which is at an altitude of 5000 meters but is remarkably flat. For the longest baselines the antennas have to be fitted around protruding volcanic cones as shown in figure 1.

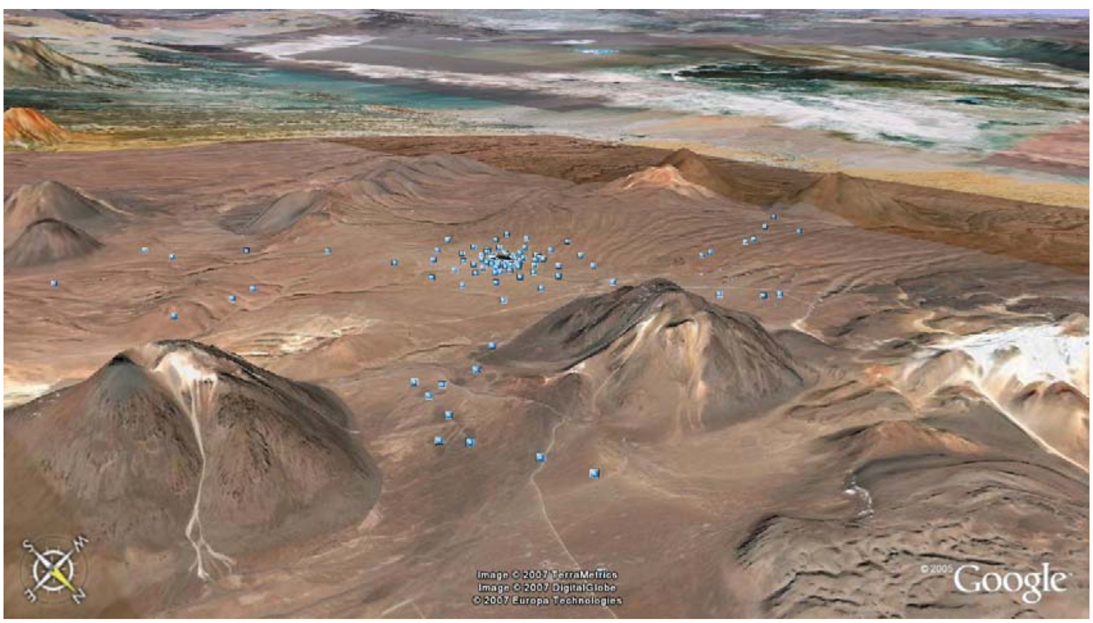

Fig. 1. Google Earth Image of the Chajnantor area indicating the antenna locations in the largest array configuration.

ALMA has two key observing components – an array of up to sixty-four 12-m diameter antennas arranged in multiple configurations ranging in size from 0.15 to ~16 km, and the ACA four 12-m and twelve 7-m antennas operating in closely-packed configurations ~50m in diameter. There are in total nearly 200 "pads" – foundations equipped with power and communications. Their positions are shown in figure 2.

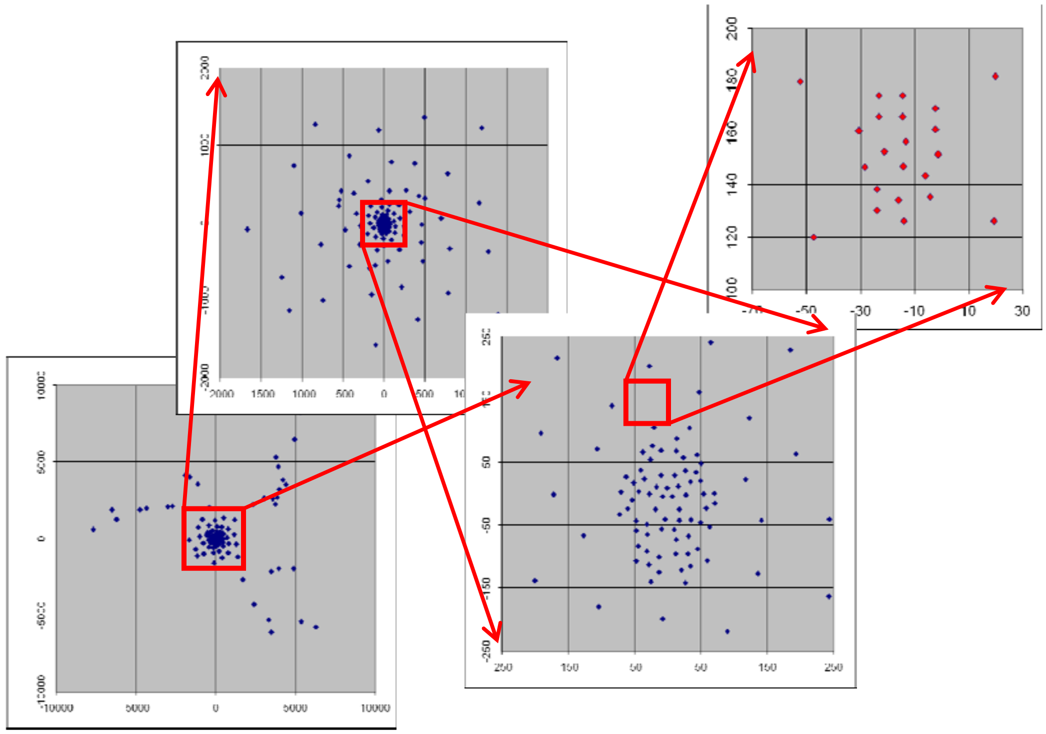

Fig. 2. Plots showing the layout of the foundations on a range of scales. Units on the axes are meters. ACA is at top right.

The 12-m antennas will be moved a few at a time, so that the array gradually expands and contracts over a period of months, according to the needs of the observing program, but always maintaining a configuration that will give good imaging performance. The ACA will provide accurate measurements of the lower spatial frequency components which cannot be observed by the 12-m antennas: the 7-m antennas provide the short interferometric spacings and the four total power antennas, which will be equipped with special subreflectors which can move rapidly to allow sky subtraction, provide the “zero-spacing” components. Because it will obtain such a complete coverage of the UV plane, ALMA will be able to make much more accurate images of extended objects than existing millimeter-wave telescopes.

The correlators and other central facilities, such as the local oscillator system, will be housed in a building near the ACA.

Fig. 3. Technical Building at the Array Operations Site (AOS – at an altitude of 5000m.

It will be possible to add oxygen to the rooms in this building when people are present but whenever possible operations will be conducted from the Operations Support Facility (OSF) which is at a lower altitude. The assembly of equipment, including the antennas, will be carried out at the OSF, along with as much as possible of the maintenance. The buildings at these two locations are complete and are in the process of being commissioned (see figures 3 and 4).

Fig. 4. Buildings at the Operations Support Facility (altitude 3000m).

4. ANTENNAS

The antennas are required to maintain a surface accuracy of better than 25 microns rms over the full range of observing conditions. These include ambient temperatures from −20°C to +20°C, full sunlight (including pointing at the Sun) and winds of up to 6 m/s (9m/s at night). They are also required to point to an accuracy of 2 arcseconds rms over the whole sky and to perform "offset pointing", i.e. using a nearby source as a reference, to 0.6 arcseconds rms. Rapid movements are needed so that fast-switching observations (using a reference source to calibrate the phase) can be made: the specification is to move the beam 1.5 degrees on the sky and settle to within 3 arcseconds all in 1.5 seconds of time.

At the time of writing a total of nine antennas are at the OSF in various stages of assembly and testing (see figure 5).

Fig. 5. Antennas at the OSF. Left, the four 12-m antennas from MELCO, and right, three of the five Vertex antennas on site at the time of writing.

The antennas are being designed and constructed by three separate companies. AEM is a European consortium including Thales-Alenia Space, European Industrial Engineering and MT Mechatronics, MELCO is part of the Mitsubishi Electric Corporation of Japan, and Vertex is part of the General Dynamics Corporation of the USA. The designs make use of advanced techniques to achieve ALMA's demanding requirements. There is extensive use of CFRP to provide very stiff and thermally stable structures and various combinations of metrology sensors are employed in order to obtain the necessary pointing accuracy.

Two special-purpose transporters have been designed and built by Scheuerle Fahrzeugfabrik GMBH in Germany to move the antennas between foundations, when the array is being reconfigured, and to carry them between the OSF and the AOS. These impressive machines are also at the site undergoing tests (see figure 6).

Fig. 6. Antenna transporters at a passing place on the road between the OSF and the AOS. The one on the right is carrying a dummy load which simulates the mass and physical interface of an antenna.

5. RECEIVERS

The full frequency range of ALMA is divided into 10 bands, each having a fractional bandwidth of about 25%. The key concept of the receivers is that a complete dual-polarization receiver covering each band is built in the form of a "cartridge" and up to 10 cartridges can be housed in a common cryostat.

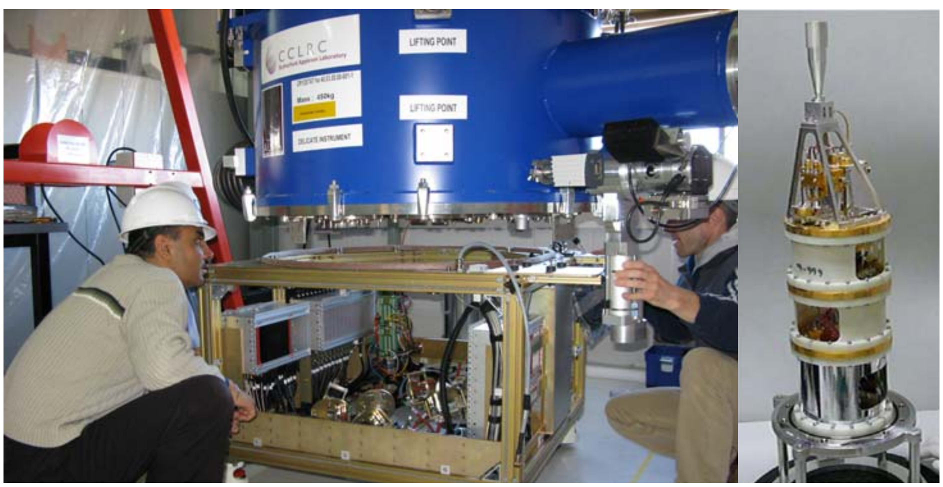

Fig. 7. Left: Re-assembly of the first Front-End after delivery at the OSF. Right: a Band 4 cartridge.

At present cartridges for bands 3 to 10 are being developed, which means that all the transparent atmospheric windows between 85 and 950 GHz are covered. All these use SIS mixers and provide either sideband-separation or double-sideband operation, with an instantaneous bandwidth of 8 GHz per polarization. The receiver development is being performed by teams based in institutes in all three of the ALMA partners. Remarkable advances have been made in the course of this work. The noise temperatures are of order 0.2 to 0.3 K multiplied by the observing frequency in GHz, which is getting close to the quantum limit for coherent receivers. The receivers are also very stable, which is important for calibration and total power measurements.

6. PHOTONIC SYSTEMS

One of the major challenges for ALMA is distributing a reference signal to the antennas, which may be as much as 16km apart, with sufficient precision to keep the local oscillators synchronized to an accuracy of much better than a radian of phase, even at the highest observing frequencies. In fact the limit on noise in the timing is 38 femto-seconds (fsec) on short time scales with drifts of only 13 fsec allowed on times of 20 to 300 seconds. An advanced photonic system has been developed to achieve this. The reference signal, typically at a frequency of about 100 GHz, is distributed on optical fibers as the beat between two tunable lasers – a "slave" laser locked to an ultra-stable "master". This beat is detected by a photo-mixer at each receiver cartridge and used to lock the local oscillator. A small sample of the laser light is taken off at the receiver, shifted in frequency by 50 MHz and returned to the central laboratory. The optical path in each fiber is then monitored and changes due to thermal expansion or mechanical movements can be compensated by means of a "line-stretcher" in which a coil of fiber is stretched under control of a servo loop. This scheme has been extensively tested and production of the various parts of the system is now underway (see figure 8).

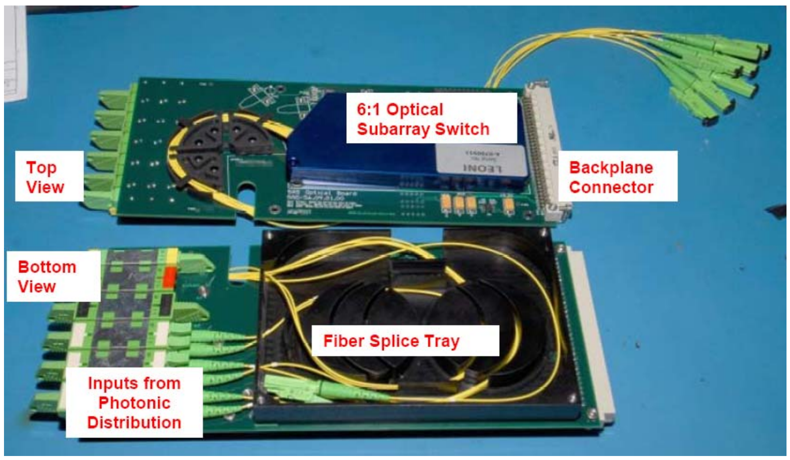

Fig. 8. An example of the photonic components used in the distribution of the Local Oscillator signal

7. DIGITAL SYSTEMS

The IF signals are amplified, down-converted and then separated into a set of 8 sub-bands each covering 2 to 4 GHz. These are digitized, formatted and sent back to the central building on optical fiber. Special-purpose A-to-D converters were developed for this and these are now in production (see figure 9). The data rate from each antenna is 120 Gb/s.

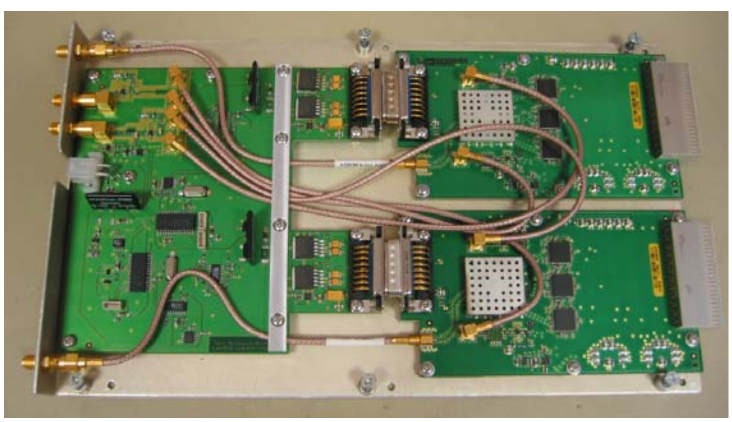

Fig. 9. The dual Analogue to Digital Converter which digitizes two IF sub-bands at 4 Gsamples/s with three bits per sample.

For the 64-element array, a large correlator based on the XF principle (correlation before Fourier) has been built which is capable of handling the full data rate and producing complex spectra (including the 4 Stokes's parameters) with 2048 resolution elements per spectrum for each of up to 2016 baselines. The performance of the basic correlator has been enhanced – especially the ability to divide up the band into subsections which can then be studied at high resolution – by applying digital filtering to the signals before the correlator. The cards for these filters are shown in figure 10.

Fig. 10. Digital Filters used to provide flexible selection of spectral windows. Left: prototype Board. Right: Production.

A separate correlator using the FX principle has been developed to handle the signals from the ACA. For some observations it will also be possible to correlate signals from the ACA antennas with those in the rest of the array.

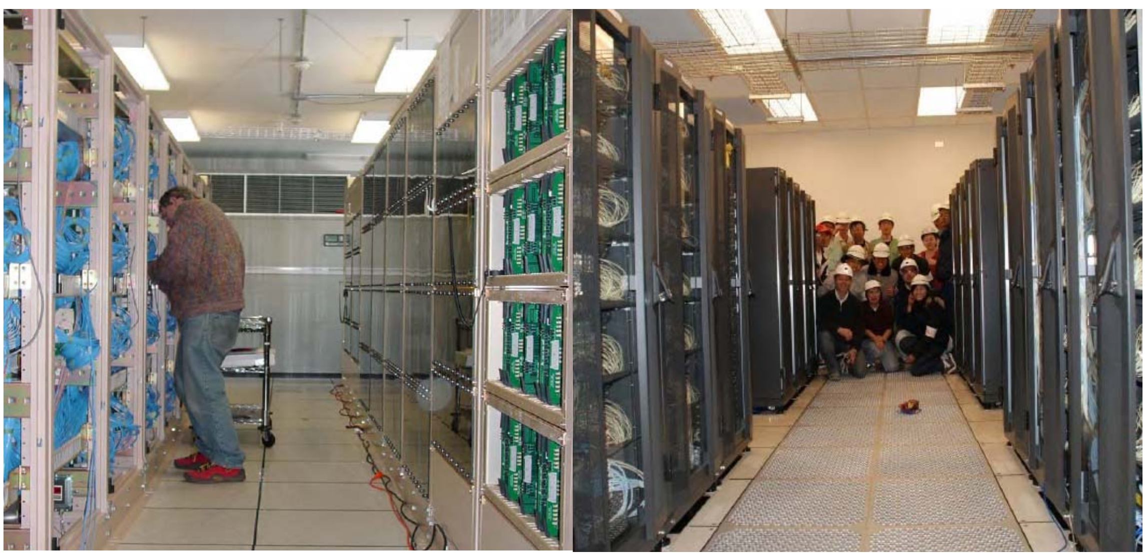

Fig. 11. Left: Two quadrants of the 64-input correlator under test in Charlottesville. Right: the ACA correlator after installation at the AOS.

The ACA correlator has been installed at the AOS and checked out. The first quadrant of the 64-input correlator has been completed and will be shipped to Chile soon. The second quadrant is nearing completion. See figure 11.

8. SOFTWARE

A very large amount of effort has been put into the development of a comprehensive set of software for ALMA, covering everything from the preparation of observing procedures, the monitoring and control of the hardware to the calibration and presentation of the data. Much of this is presently being tested on the two prototype antennas currently at the ALMA Test Facility, which is at the VLA site in New Mexico. It is already possible to prepare a simple observing sequence, known as a “scheduling block”, and have it control the system to take the data, observe calibrators, etc. The data can then be read into the recently-released data-reduction package, which is called CASA, for processing and plotting. Figure 12 shows a recent example. There is, of course, a lot more to be done before the software will be able to run the full ALMA system in all its possible operational modes.

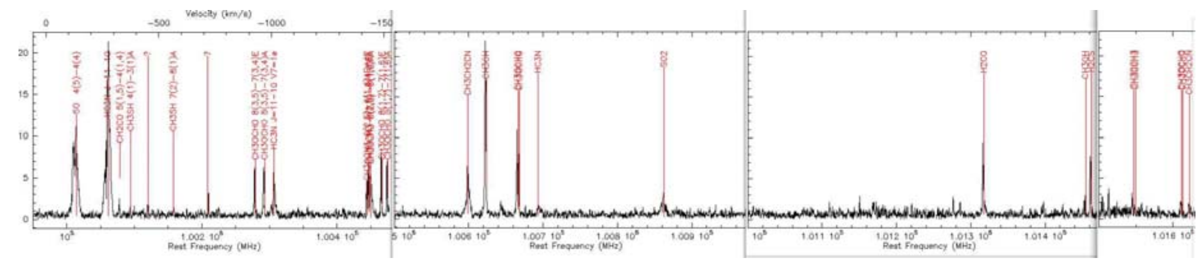

Fig. 12. Interferometric spectrum of molecular emission from Orion obtained at the ALMA Test Facility.

9. SCHEDULE

We are presently testing the first production antennas at the OSF. This includes using auxiliary optical telescopes to check the pointing accuracy and derive a pointing model and making measurements and adjustments of the antenna surface by radio holography. The latter involves mapping the amplitude and phase of the response pattern of the antenna to a source on a located on a tower at a distance of about 300 meters.

The first front-end is also being tested at the OSF, together with its associated electronics and a small section of the correlator. The next big step will be to install the front-end in an antenna and start radiometric tests.

We expect to begin two-element interferometry at the OSF at around the end of 2008. The scientific commissioning will start when we have three antennas operating interferometrically at the AOS in 2009. We hope to begin “Early Science” with at least 16 antennas by late in 2010. The goal for reaching full scientific operations remains the end of 2012.

10. ACKNOWLEDGEMENT

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