Progress with Commissioning and Science Verification of ALMA

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Abstract

Construction and commissioning of the Atacama Large Millimeter/Submillimeter Array (ALMA) is progressing rapidly. Even with a fraction of the total number of antennas to be located at the Array Operations Site (AOS) in northern Chile in place, ALMA is the most powerful millimeter/submillimeter interferometer in the world. In this paper I report on the progress of array commissioning and science verification (CSV). I summarize the current performance of the array including noise temperatures, calibration accuracy and available observing modes. At the time of presentation of this paper, ALMA science verification observations will likely be available to the public. I will present the results and comparison data as well as update and detail the array status.

1 Introduction

When complete the Atacama Large Millimeter/Submillimeter Array (ALMA) will consist of two arrays, the baseline array and the compact array (ACA), which will be capable of operating as a single array or separately. In total, 54 12-meter and 12 7-meter antennas will occupy the Array Operations site (AOS) at an elevation of 5000 m in northern Chile. In this paper I review the status of commissioning and science verification. In section 2, I briefly review the delivered hardware and corresponding software, as well as some of the difficulties we have faced in the previous year. I discuss the current performance and status of observing modes available for use at ALMA and outline upcoming advancements in section 3. I outline how ALMA data will be compared to other facilities as part of science verification in section 4. In section 5, I summarize the current status of ALMA commissioning and science verification and provide an outlook for the near future.

2 Commissioning

At the time of submission a total of 11 distinct antennas, all of them 12-meters in diameter, have recorded observations at the AOS with this number expecting to continue to grow at a rate of about 1 antenna per month. Over the last year, the largest issues we have had to deal with regarding the antennas are jumps and large drifts in tiltmeter values, the development of both astigmatism and additional small-scale errors in the antenna surfaces, and changes in the thermal behavior of focus. We have also had problems with hexapod malfunction. Most of these problems have been fixed or have fixes ready to deploy. The cause of the astigmatism is not fully understood and contributions from the holography feeds have recently been ruled out. Various avenues are being explored including incorrect thermal and/or gravitational bias models or the incorrect application of such models to the dish surface.

Two independent correlators are located at the AOS. The baseline array correlator will eventually consistent of four quadrants, one to process each of the four basebands. Three quadrants have been delivered, but, to date, one quadrant has been configured to process all four basebands from up to 16 antennas. The second quadrant, allowing up to 32 antennas, will be integrated in the coming weeks. The ACA correlator has obtained initial fringes on the sky. Over the last year we have been presented with some problems related to the baseline correlator, most significant among these are data rate limitations. However, with the recent refactoring of the correlator software, we are now realizing near or at design limits on the performance. Additional difficulties involved frequency labeling and various delay features. Of these, the frequency labeling has been solved within the measurement accuracy of current observations and the delay features are becoming

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smaller and/or less frequent with time. The details of the implementation of the delay correction are still being corrected after the refactoring.

Each antenna at the AOS is equipped with at least four receiver bands identified as 3, 6, 7 and 9. These correspond to the traditional 3 mm, 1 mm, 850 μm and 450 μm transmission windows, respectively. An additional antenna contains bands 4 and 8 (2 mm and 650 μm), but its singularity limits testing at the AOS. Except for band 9 which is a traditional dual polarization, double sideband receiver, the systems are "two-sideband" and dual polarization. In addition to the astronomical observing receivers, each antenna front end package includes a four-channel, double sideband water vapor radiometer (WVR) used for phase correction. Each antenna is outfitted with an amplitude calibration device which has a hot load at a temperature of $\sim$350 K and an ambient load at the temperature of the cabin ($\sim$290 K). The back end systems, including the photonic LO and line length correctors, are all installed with the final production version of the LO system scheduled for delivery in March 2011. The back end provides four independently tunable basebands of 2 GHz bandwidth, subject to some first LO sideband restrictions.

Locking failures have persisted across various receiver bands on different antennas. The non-uniformity of failures across different units has made tracking a single solution difficult. A campaign is underway to systematically reassess the locking/tuning tables on the antennas to provide more robust performance. Total power oscillations were seen and attributed to the membrane, which seals the cabin from the outside, flapping in the wind. Coordinated effort by the ALMA staff has solved this problem with changes to the orientation, tilt and composition of the membrane. Periodic and regular phase fluctuations have been found within the system and addressed via interactions with the various scientists and engineers across the project. Still a major concern is the time to stabilize power after a receiver band is powered up or off. The 25 minute time period required to fully stabilize power levels represents challenges to the dynamic scheduling of observations. Another concern is the bandpass stability. While the bandpass stability has met formal specifications, it is clear that the aforementioned delay glitches and power level stabilization problems will provide challenges for the transfer of bandpass, especially if such glitches are associated with source or frequency changes.

Phase correction via the WVR is within defined specifications although correction in extreme weather conditions and on long (1 km) baselines remains to be tested. Basic phase transfer between sources at the same frequency seems to be limited by baseline errors and those baseline errors seem to be somewhat variable. However, until recently, total observing length was restricted and this may have resulted in poor antenna position measurements given the sparse sky coverage.

Receiver temperature measurements suggest that the bulk of the receivers, with the possible exception of band 3, exceed the performance specifications. Band 3 performance typically mets the performance requirements. These limits are 37 K, 83 K, 147 K and 175 K, for bands 3, 6, 7 and 9, respectively, with lower limits required at the lower edges of the band. Initial tests of flux recovery suggest our repeatability over ranges of elevation is a few percent. However, our flux estimates appear to be systematically lower than other observatories, suggesting our applied system temperatures are too low or we are losing gain in some other respect.

3 Performance & Capabilities

Observing capabilities are rapidly expanding. Currently single pointing interferometry and single dish, on-the-fly raster maps have been made. Pointed mosaicking observations are currently being tested and we expect to being science verification on this observing mode soon. Initial tests of on-the-fly interferometry have been made but the mode is far from being fully verified. Fringes at all four bands have been demonstrated. Interferometric pointing and focus have been well established. Pointing and focus differences between bands have been measured and transfer of results occurs automatically within the system. Such capabilities makes testing the validity of phase transfer between frequencies rather straight-forward. Initial tests look promising on this needed mode, but further testing is required.

Various calibration modes are being tested. System temperatures have been calculated using the classic chopper wheel approach as well as using the WVR measurements and the hot and ambient load. Currently we are exploring and comparing the "alpha" method, which uses a linear combination of a hot and ambient load, and the WVR method. In the near term it appears that the alpha method is better but with further development of the algorithm, the WVR method may prove superior.

Correlator configurations are somewhat limited when compared to final capability. Currently one spectral window is allowed per baseband, limiting the number of spectral windows to four. The spectral resolution of the windows is fixed across the various basebands. Due to this restriction, we have begun testing the ability to transfer gains between correlator modes. Initial results suggest this type of transfer does not require frequent calibration (<0.25 hour^{-1}). Modes can be selected with 1, 2 and 4 linear polarization products. Observations are routine in a variety of bandwidths. Short integration times (<100 ms) are available with (256/N) channels over 2 GHz of bandwidth, where N is the number of polarization products. Slower data rates are required to utilize the higher resolution modes, which have bandwidths of 2^{1-n} GHz where n ranges from 0 to 5 with nearly 8000 channels to be divided among the polarization products. Likely by the time this paper is presented, the restriction of uniform bandwidth among spectral windows will be relaxed. Eventually, multiple spectral windows per baseband will be allowed providing the opportunity, for example, to have a 1 GHz bandwidth chunk with two narrow band spectral windows at higher spectral resolution.

Polarization studies have only just begun at ALMA with a dedicated campaign concluding at the time of submission of this paper. Initial results suggest significant but stable structure in the instrumental polarization as a function of frequency. These spectral features appear stable over the period of at least days with suggestions of stability ranging back to earlier datasets taken months before. Measurements of the off-axis polarization have begun as well but a more dedicated set of observations is required to make definitive conclusions. It is clear, however, that the on-axis polarization is calibratable to $\sim$1-2%, perhaps better.

4 Verification

Calls for suggestions of targets for science verification went out to the astronomical community in January 2011. At this time, nearly 100 targets have been suggested by parties spanning the globe. Initially two sources, TW Hydrae and NGC 3256, were selected. These sources have some structural complexity but avoid being too complicated for still limited uv-coverage. These two sources have been extensively observed with the current generation of submillimeter interferometers, making them ideal candidates for initial science observations. Both sources will test continuum and spectral line imaging capabilities and both have been observed at spatial resolutions comparable to that available at this time with ALMA.

In the near future, additional sources will be selected to test specific aspects of the ALMA system, e.g., frequency scale, spectral dynamic range, and amplitude calibration. Preference will be given to sources that demonstrate several capabilities over the full range of ALMA bands. Existence of comparison data is clearly a requirement, preferably from interferometers at the same frequency. By the time this paper is presented, observations of these first two sources will almost certainly be public. I will provide a detailed comparison of those data with existing data. Additional datasets will be reviewed.

5 Conclusions & Summary

ALMA is already the most powerful submillimeter interferometer and its capabilities will only improve in the coming years as the push to 66 antennas is made. Calibration techniques will continue to be refined offering the astronomical community the capability to obtain deeper and more accurate images than possible at other facilities. This year, early science observations will begin. More flexible correlator modes will be available as well. Sideband separation with 90-degree Walsh switching will enable larger bandwidth

measurements at band 9. On-the-fly mosaicking observations will be commissioned with hopes of offering such a new and dynamic mode for proposal cycles in the near future. With ALMA, truly transformational science is in sight.

6 Acknowledgments

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