THE ATACAMA LARGE MILLIMETER ARRAY CORRELATOR

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INTRODUCTION

The digital signal processing features of the correlator being constructed for the Atacama Large Millimeter Array[†] (ALMA) radio astronomy observatory are presented here.

The National Radio Astronomy Observatory (NRAO), in collaboration with other North American, European, and Japanese scientific agencies, is developing the ALMA radio astronomy array to consist of a main array of up to 64 12-meter diameter antennas and a compact array of twelve 7-meter and four 12-meter antennas. The instrument is to be used for detecting and imaging all types of astronomical sources at millimeter and submillimeter wavelengths at a 5,000 meter elevation site in the Atacama Desert of Chile.

The correlator under construction will process the outputs of the 64 antennas that are to comprise the main array of the ALMA observatory using an instantaneous bandwidth of 8 GHz in each of two polarizations per antenna. The system as originally designed, using a conventional XF architecture and working at a clock rate of 125 MHz, has recently adopted a digital hybrid design approach that will yield a 32-fold improvement in frequency resolution at the widest bandwidth.

Antenna-based electronics in the correlator include fiber optic receiver cards to recover digitized samples from the remote telescopes, digital tunable filter bank cards for bandwidth selection, bulk RAM delay lines, and signal conditioning logic to packetize the output of the high-speed digitizers (operated at 4 Gsample/s) in order to drive lower-speed correlator circuits (125 MHz) in the widest bandwidth application.

The tunable filter bank is a plug-in replacement for the single FIR filter card in the original system design. Thus, the enhanced performance provided by the filter bank is obtained with minimal cost and effort in system redesign. The tunable filter bank will be on a single 6U logic card and will provide from 1 to 32 independently programmable and tunable digital filters in binary steps. Each card processes 2 GHz bandwidth in either sense of polarization.

Baseline-based electronics can be efficiently allocated among the active filter bank outputs to provide optimum performance in spectral resolution. For continuum observing, maximum sensitivity is obtained with maximum bandwidth in the time division mode (XF correlation) by bypassing the tunable filter bank.

An application-specific integrated circuit (ASIC) has been designed for use in measuring the cross- and auto-correlation coefficients. Each correlator ASIC has 4096 lags, including 20 bits of integration and 16 bits of secondary storage for the results.

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[†] The Atacama Large Millimeter Array is an international astronomy facility. ALMA is an equal partnership between Europe and North America, in cooperation with the Republic of Chile, and is funded in North America by the U.S. National Science Foundation in cooperation with the National Research Council of Canada, and in Europe by the European Southern Observatory and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory, which is managed by Associated Universities, Inc., and on behalf of Europe by ESO.

System testing of a prototype 2-antenna correlator is currently in progress at the ALMA test facility in New Mexico. The first one-fourth of the final correlator system is under construction and testing by the NRAO at the new NRAO Technology Center in Charlottesville, Virginia.

OVERVIEW

The ALMA instrument will perform astronomical observations of the universe at radio wavelengths, covering sky frequencies between 30 and 950 GHz. The correlator is that part of the ALMA system that combines the signal from the up to 64 remote individual radio antennas and forms them into a single instrument.

The ALMA correlator measures cross-correlation coefficients of all 2016 pairings of the 64 antennas. Mathematical processing of the cross-correlation coefficients will produce EM intensity maps on the sky. The maps may be over wide bandwidths or multiple maps, each over an incremental bandwidth. Frequency resolutions from a single bandwidth, 2 GHz wide (continuum), to 8192 increments of 3.8 kHz width, spanning a 31.25 MHz band (spectral line), are supported.

The ALMA correlator evolved from an initial system design [1], [2] with a pure lag architecture incorporating simple FIR digital filter cards [3], [4] to a design implementing a digital hybrid correlator with the incorporation of 32-element digital filter bank cards. (The digital hybrid terminology reflects the history of radio astronomy correlators. Early correlators employed analog filter banks for frequency resolution, while digital correlators processed the output of a single anti-aliasing analog filter. Later, hybrid correlators used small analog filter banks with the output of each filter driving a small digital correlator. In a digital hybrid correlator, the filter bank is digital.)

The tunable filter bank concept was the result of a study done to investigate possible architectures for a second generation ALMA correlator [5].

The fundamental change to the original ALMA correlator system design is the replacement of the single FIR digital filter card with a tunable filter bank card [6]. The use of a 32-element filter bank instead of a single digital filter has the effect of increasing the performance of the system by factors of up to 32 in spectral resolution.

With the use of the filter bank, correlator operation can be considered to use a frequency division strategy. The digitizer wideband input (4 GHz sample rate) to the correlator is split into up to 32 subbands or subchannels 62.5 MHz wide with each subchannel being independently processed by the correlators. A single wideband time-packet or time-division mode of the original system design has been retained in the operation of the correlator to provide high time resolution where this parameter is of highest importance.

SYSTEM SPECIFICATIONS

The system specifications for the ALMA correlator can be seen in Table 1 taken from [7].

The ALMA system specification of 64 antennas with a total 16 GHz bandwidth per antenna drives the correlator input specifications. Each 16 GHz antenna input to the correlator comes in the form of 8 baseband signals of 2 GHz bandwidth each.

Signals from each 2 GHz baseband output drive into the correlator as three digital input data streams, each with an equivalent clock rate of 4 GHz reflecting the ALMA standard of the 3-bit, 4 Gsample/s digitization of the baseband analog outputs at the antennas. Signal transmission from the remote antennas to the correlator is done by the ALMA backend system over fiber optic cables [8]. Recovery of the sample streams from the optic input signal is done by Data Transmission System (DTS) receiver printed circuit cards.

PERFORMANCE

The performance of the ALMA correlator, in terms of bandwidth and frequency resolution, can be seen in the next three tables. Table 2 gives the performance of a single quadrant of the correlator in modes in which a single baseband channel of a baseband pair is processed. Table 3 gives system performance in modes in which both baseband channels of a pair are processed but no cross-correlations are performed. Table 4 gives the system performance in modes in which polarization cross-correlations are generated.

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Table 1. ALMA Correlator Specifications

Item	Specification
Number of antennas	64
Number of baseband channel inputs per antenna	8
Input sample format	3 bit, 8 level at 4 GSample/s per baseband channel
Correlation sample format	2 bit, 4 level and 4 bit, 16 level; Nyquist and twice Nyquist
Maximum baseline delay range	30 km
Hardware cross-correlators per baseline*	32,768 leads + 32,768 lags
Hardware autocorrelations per antenna*	32,768
Typical performance in digital hybrid modes	8192 spectral points provided for each pair of baseband inputs**
Product pairs possible for polarization	HH, VV, HV, VH (for orthogonal H and V)

* 62.5 MHz correlators (125 MHz clock rate), divide by 32 to get number of equivalent 2 GHz correlators.
** Resulting in 8192, 4096 or 2048 spectral points across the baseband spectrum, depending on polarization mode.

Table 2. Mode Chart With One Baseband Channel Per Quadrant Being Processed.

Number of Active Filters	Total Bandwidth	Number of Spectral Points	Spectral Resolution	Velocity Resolution at 230 GHz	Correlation*
32	2 GHz	8192/4096/2048	244/488/976 kHz	0.32/0.64/1.28 km/s	2B-N/2B-2N/4B-N
16	1 GHz	8192/4096/2048/1024	122/244/488/976 kHz	0.16/0.32/0.64/1.28 km/s	2B-N/2B-2N/4B-N/4B-2N
8	500 MHz	8192/4096/2048/1024	61/122/244/488 kHz	0.08/0.16/0.32/0.64 km/s	2B-N/2B-2N/4B-N/4B-2N
4	250 MHz	8192/4096/2048/1024	30/61/122/244 kHz	0.04/0.08/0.16/0.32 km/s	2B-N/2B-2N/4B-N/4B-2N
2	125 MHz	8192/4096/2048/1024	15/30/61/122 kHz	0.02/0.04/0.08/0.16 km/s	2B-N/2B-2N/4B-N/4B-2N
1	62.5 MHz	8192/4096/2048/1024	7.6/15/30/61 kHz	0.01/0.02/0.04/0.08 km/s	2B-N/2B-2N/4B-N/4B-2N
1	31.25 MHz	8192/2048	3.8/7.6 kHz	0.005/0.01 km/s	2B-2N/4B-2N
Time Division Mode	2 GHz	64	31.25 MHz	40.8 km/s	Full 3-bit x 3-bit, Nyquist sampling

Table 3. Mode Chart With Two Baseband Channels Per Quadrant Processed With No Polarization Cross Products.

Number of Active Filters	Total Bandwidth	Number of Spectral Points	Spectral Resolution	Velocity Resolution at 230 GHz	Correlation*
32	2 GHz	4096	488 kHz	0.64 km/s	2B-N
16	1 GHz	4096/2048/1024	244/488/976 kHz	0.32/0.64/1.28 km/s	2B-N/2B-2N/4B-N
8	500 MHz	4096/2048/1024/512	122/244/488/976 kHz	0.16/0.32/0.64/1.28 km/s	2B-N/2B-2N/4B-N/4B-2N
4	250 MHz	4096/2048/1024/512	61/122/244/488 kHz	0.04/0.08/0.16/0.32 km/s	2B-N/2B-2N/4B-N/4B-2N
2	125 MHz	4096/2048/1024/512	30/61/122244/ kHz	0.04/0.08/0.16/0.32 km/s	2B-N/2B-2N/4B-N/4B-2N
1	62.5 MHz	4096/2048/1024/512	15/30/61/122 kHz	0.02/0.04/0.08/0.16 km/s	2B-N/2B-2N/4B-N/4B-2N
1	31.25 MHz	4096/1024	7.6/30 kHz	0.01/0.04 km/s	2B-2N/4B-2N
Time Division Mode	2 GHz	128	15.6 MHz	20.4 km/s	2B-N

Table 4. Mode Chart With Two Baseband Channels Per Quadrant Processed With Polarization Cross Products.

Number of Active Filters	Total Bandwidth	Number of Spectral Points	Spectral Resolution	Velocity Resolution at 230 GHz	Correlation*
32	2 GHz	2048	976 kHz	1.28 km/s	2B-N
16	1 GHz	2048/1024	488/976 kHz	0.64/1.28 km/s	2B-N/2B-2N
8	500 MHz	2048/1024/512	244/488/976 kHz	0.32/0.64/1.28 km/s	2B-N/2B-2N/4B-N
4	250 MHz	2048/1024/512/256	122/244/488/976 kHz	0.16/0.32/0.64/1.28 km/s	2B-N/2B-2N/4B-N/4B-2N
2	125 MHz	2048/1024/512/256	61/122/244/488 kHz	0.08/0.16/0.32/0.64 km/s	2B-N/2B-2N/4B-N/4B-2N
1	62.5 MHz	2048/1024/512/256	30/61/122/244/ kHz	0.04/0.08/0.16/0.32 km/s	2B-N/2B-2N/4B-N/4B-2N
1	31.25 MHz	2048/512	15/61 kHz	0.02/0.08 km/s	2B-2N/4B-2N
Time Division Mode	2 GHz	64	31.25 MHz	40.8 km/s	2B-N

* 2B-N, 2-bit by 2-bit correlation, Nyquist sampled

* 4B-N, 4-bit by 4-bit correlation, Nyquist sampled

* 2B-2N, 2-bit by 2-bit correlation, twice Nyquist sampled

* 4B-2N, 4-bit by 4-bit correlation, twice Nyquist sampled