The ALMA 64-antenna Correlator: Main Technical Features and Science Modes

Alain Baudry[1] ***and John Webber***[2]

[1]Université de Bordeaux 1, LAB, BP 89, 33270 Floirac (France) & European ALMA Project Office, ESO
(baudry@obs.u-bordeaux1.fr)

[2]National Radio Astronomy Observatory, Charlottesville, 22903 VA (USA) (jwebber@nrao.edu)

Abstract

We present the main features of the Atacama Large Millimeter/submm Array (ALMA) 64-antenna correlator sub-system and describe some original parts of the design. All correlator parts have been constructed, 3 quadrants are delivered to the 5000-m high site and 2 have been commissioned for ALMA Early Science. The basic observing modes are described and the huge flexibility embedded in the design is underlined.

1. Introduction

ALMA, an international partnership among Europe, North America, Japan, Taiwan and Chile, is opening a subset of its antennas for Early Science projects. The telescope should be completed in 2013 with 50 12-m antennas (main array) and 16 other antennas (ALMA Compact Array, ACA) to be deployed on the Chajnantor plateau in northern Chile at an elevation of 5000 m. Observations will be performed in the mm/submm domain up to about 1 THz. The ALMA correlator is an essential sub-system of the ALMA project where (a) the signal power received from all antennas is recovered, and (b) the amplitude and phase information contained in the fringe patterns from all independent antenna pairs of the array is used to image, after proper calibration, the observed sources. There is one correlator to process data from the main array (herein named main or 64-antenna correlator) and another one to process the ACA data. The main array correlator has been designed by a NRAO/European consortium of laboratories to process data from up to 64 antennas, the original number of antennas in the main array. With 50 antennas in the current main array, data from up to 14 additional antennas of the ACA can be processed simultaneously by the main correlator.

In this contribution, we first recall the overall architecture adopted for the ALMA 64-antenna correlator, present its main technical features and briefly mention some of the technical challenges faced by the construction teams. Then we describe the main observing modes which will be made available to the ALMA community and we outline the science potential of this large machine, especially for line spectroscopy in various astrophysical environments.

2. Main Array Correlator Specifications, Architecture and Status

Specifications of the main correlator are given in Table 1. It processes 4 Gsample/s x 3 bits x 8 = 96 Gbit/s from each antenna and up to 64 x 63/2 = 2016 independent antenna pairs in the ALMA array. The adopted correlator architecture is presented below and some technical details on individual parts are discussed in the following Section.

Table 1. Top level specifications of the ALMA main array correlator .

Item	Specification
Antennas	≤64
Baseband inputs per antenna	8 x 2 GHz
Input sample format	3-bit, 8-level at 4 Gsample/s
Output correlation sample format	2-bit, 4-level or 4-bit, 16-level
Processing rate	125 MHz
Baseline delay range	30 km
Spectral points per baseband *(Frequency Division Mode)*	≤8192 per correlator quadrant
Spectral points per baseband *(Time Division Mode)*	64, 128 or 256
Polarization products	1, 2 or 4

The ALMA 64-antenna correlator is a large digital hybrid machine which first divides the 2 GHz input baseband into several sub-bands and allows placing sub-bands within that 2 GHz. This is accomplished in the Tunable Filter Bank (TFB) sub-system (Sect. 2.1) before the cross-correlation coefficients (X-part of the system) are derived for

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

all same sub-bands and all independent antenna pairs in the correlator chips and cards (see Sect. 2.1). Fourier transform of the correlation functions provides a measure of the spectral content of the input signal. The digital hybrid XF design is thus neither a pure FX nor a pure XF architecture. However, when the TFB is bypassed the correlator behaves as a conventional XF system. In the hybrid mode, the frequency agile sub-bands add much flexibility to the entire system ; this is illustrated in the discussion on observing modes (Sect. 3). To understand the basic operation of the digital hybrid architecture suppose that we have 2L lags available in the correlator cards from which we get L complex spectral outputs after Fourier transform. With the TFB active and for N sub-bands the required processing power for each sub-band goes down to 2L/N lags but now at a clock rate of 4 GHz/N for the ALMA 2 GHz baseband. The number of sub-bands is optimized when the 2 GHz bandwidth matches the correlator chips clock frequency. In that case no time multiplexing is required which means for the adopted ALMA correlator processing rate N = 32 sub-bands. Hence, 32 more spectral channels are available in comparison with the pure XF scheme.

The block diagram of the 64-antenna correlator includes (Fig. 1) : (a) antenna-based electronics (TFB cards, fine and bulk delay lines, signal conditioning to ‘packetize’ signal samples); (b) baseline-based electronics (correlation cards, long-term accumulation, interface to real time computer performing fast Fourier transform to the spectral domain). Selected details on the TFB and Correlator cards are given in the next Section.

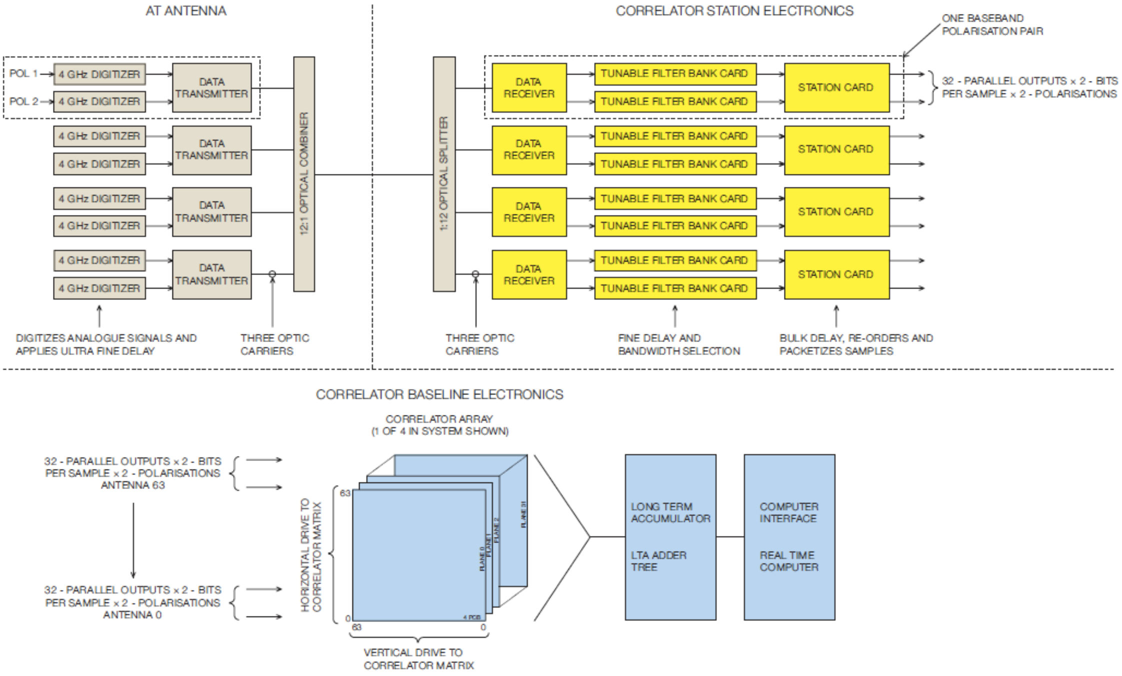

Fig. 1. ALMA 64-antenna correlator block diagram (adapted from Escoffier R., Webber J. and Baudry A. in ALMA-60.00.00.00-001-C-SPE document).

The correlator is organized by quadrants each processing 2 polarizations for one 2 GHz band. The antenna and baseline electronics are distributed in 32 racks to which we add power supply racks, the post-correlation data processors and control computer racks. Dissipated total power remains below 130 kW. Communication between antenna- and baseline-based electronics racks requires 16384 cables carrying data at 250 Mb/s.

2.1 The Tunable Filter Bank (TFB) and Correlator Matrix Sub-systems

Signal digitization (4 Gsample/s) and demultiplexing allow transmitting a low frequency parallel bit-stream from each antenna to the correlator room through optical fibers. The digitized samples are then recovered in fiber optic receiver cards and sent to the correlator TFB sub-system for frequency division prior to signal correlation. 32 sub-bands, each 62.5 MHz wide, are extracted from the 2 GHz baseband in a 3-stage digital filter design implemented in a programmable logic device (FPGA). To provide 32 sub-bands and optimize the available logic resources without too much power dissipation we have selected a commercial large FPGA using 90 nanometer technology (just available at the time of the design). We have implemented 32 sub-bands in 16 Altera StratixII FPGA’s assembled on a single card.

The first stage filter, a Comb-type decimating filter, is crucial in the TFB card power budget. It is followed by a 16-tap quarter band low pass filter and a 64-tap half-band filter which determines the passband ripple, stop-band rejection and final bandwidth (depending on the actual taps selected by the users). Each card dissipates less than 60 W when all 32 digital filters are active. Much versatility is embedded in the TFB because all sub-bands are mobile across 2 GHz; the input signal is processed in a digital complex mixer to translate each sub-band frequency center to zero frequency. (It is interesting to note that phase corrections can be added in the TFB digital LO to phase up the array in view of VLBI observing or to compensate 1st LO offsets introduced for front-end sideband separation or DC offsets removal.) There is one TFB card per antenna and baseband; hence, 8 x 64 = 512 TFB cards are required to process data from 64 antennas.

Following digital filtering and delay tracking, the signal is passed to the correlator antenna baseline electronics. The basic element in the correlator architecture is the 'correlator plane' which processes one 2 GHz baseband in two polarizations and places the 64x64 antenna matrix in 4 correlator cards to derive all 2016 cross-correlation and all 64 auto-correlation products. The essential building block in the correlator card is the application specific integrated circuit (ASIC) designed in CMOS 0.25-micron technology to maximize the number of lags in a single chip without too high dissipation. 4096 lags are implemented in a single chip. Each lag performs a 2-bit by 2-bit multiplication and provides 20-bit integration and secondary storage for correlation coefficients readout. The ASIC is housed in a standard multi-pin package allowing easy chip soldering or removal from printed circuit boards. The basic element in a correlator chip is a 256-lag block which can be programmed to support single or double polarization observations or full polarization (providing all 4 cross-products each with 64 lags). A total of 64 correlator chips are assembled on a single card. The full correlator 'array' consists of 32 correlator planes as required for frequency division or time division modes (see Sect. 3). A total of 512 cards (for all 4 baseband pairs) and 32768 correlator chips are needed when the full system is at work.

2.2 Status and Reliability

All individual cards have been fabricated with high quality industrial production and control rules and, for the most complex TFB and Correlator cards, special test fixtures and control firmware were developed to check functionality. The 4 quadrants of the ALMA correlator have been constructed; 3 have been delivered to the 5000-m high site and the 4th one is kept at the integration center in Charlottesville for further software and firmware development or verification. Two quadrants were commissioned to support up to 32 antennas and to process the 8 ALMA basebands in two polarizations. Many different observing modes have been validated and a subset of these modes is available for ALMA Early Science (Table 2). Two scaled-down models of the production main correlator have also been produced and one is used at the intermediate site (3000-m) in 2-antenna interferometry mode for assembly, integration and verification tasks before newly outfitted antennas are moved to the high site.

We have now significant experience on the reliability of critical components used in the main correlator. Very few correlator ASICs failed and it was demonstrated that after an initial period of about 40 days showing a higher failure rate there seems to be no further failures. However, several thousands of spare chips are available and would be rather easily replaced if needed (the ASIC's are QFP packaged and there are no BGA's). The FPGA's assembled on the TFB cards show high reliability and none has been replaced so far after a long 'burn-in' period and a few years operational use at the high site. However, several spare TFB cards have been fabricated and two different techniques have been validated to replace the BGA's. One key issue in the correlator reliability is power dissipation because the air density at the ALMA site is nearly half that at sea level (and also because supplying power at 5000-m is expensive). The junction temperature of each FPGA in the TFB card is kept below 60 K (thanks to an optimal digital filter design and optimal air circulation). Dissipation per correlator ASIC is also kept low by design (around 1.6 W). Nevertheless, the power dissipated by all 4 quadrants may reach 130 kW and an efficient air circulation system and management is thus in place in the correlator room to improve the components lifetime.

3. Observing Modes

The observing modes offered to the astronomers reflect the digital hybrid architecture adopted for the 64-antenna correlator. When the correlator is used as a pure XF system each 1 millisec packet of 4 Gsample/s data taken from the digitizers is split into 32 'time bins' sent in parallel from the station electronics cards to 32 correlator planes each processing 1/32th of the digitizer samples. Then, all 32 lower speed time bins must be summed to recover the initial data rate and the true cross-correlation coefficients. In the XF case the observing modes are called Time Division Modes (TDM) for which the correlator lag resources are massively used to process the individual time bins. In Frequency Division Mode (FDM) each TFB card provides 32 sub-bands (each 62.5 MHz) and up to 32 sub-bands can be processed in 32 correlator planes. The cross-correlation coefficients measured for each sub-band are independent and no summation is required. However, after Fourier transform the individual sub-band spectra must be stitched together to recover the original 2 GHz baseband spectrum. In the end we obtain a 32-fold improvement in spectral resolution compared to the TDM mode. Even higher spectral resolution is obtained by processing fewer than 32 filter outputs (corresponding to less input bandwidth) with all available correlator resources; this is easily programmed by proper addressing of the microcontroller driving the TFB card outputs. Double Nyquist sampling and 4-bit correlation are available to provide higher sensitivity at the expense of lower frequency resolution. In addition, with special taps loaded in the last stage of the TFB card a 31.25 MHz sub-band can be achieved; it provides a maximum resolution of 3.8 kHz with 8192 channels in 31.25 MHz. Accounting for all polarization modes (1, 2 or 4 polarization cross-products), there are 63 different FDM spectral modes which have all been validated by the correlator team. These modes are best suited to high resolution spectral observations while the TDM modes offer a coarser spectral resolution and are best suited to continuum observations and fast readout rates. In Table 2 we give a subset of all modes which will be supported for Early Science projects (no double Nyquist or 4-bit correlation will be supported). The effective bandwidth is limited by the anti-aliasing 2 GHz analog bandpass filter and for smaller bandwidths by the sub-band channel overlap required to optimize full spectrum reconstruction.

Modes in Table 2 allow addressing a broad range of astrophysical cases. For instance, resolutions around 10 to 100 kHz are required to investigate molecular line emission in protostellar discs, interstellar clouds or Galactic masers and 500 kHz to 1 MHz are well adapted to the widespread CO lines observed in Galactic outflows. FDM modes are most appropriate for all of these cases. On the other hand, TDM modes and maximum instantaneous bandwidth are desirable to improve the sensitivity in broad band continuum sources or to study distant galaxies with smooth, broad spectral line profiles. In distant extragalactic line sources exhibiting large velocity spreads (e.g. 2000 km/s or more), and for high frequency receiver bands, analysis of the full line profiles may require to concatenate 2 or more basebands.

Table 2. Frequency and Time Division Modes (FDM and TDM) supported for ALMA Early Science. This is a subset of 21 modes among 67 modes 'cabled' in the correlator. For a given effective bandwidth, spectral resolution depends on the number of polarization cross-products (1, 2 or 4 products are selectable).

Effective Bandwidth (MHz)	**Channel Separation (kHz) FDM**								**Channel Separation (MHz) TDM**		
	7.6	**15.3**	**30.5**	**61**	**122**	**244**	**488**	**977**	**7.8**	**15.6**	**31.3**
1800						1	2	4	1	2	4
938					1	2	4				
469				1	2	4					
234			1	2	4						
117		1	2	4							
62.5	1	2	4								

The various modes presented here apply to a single spectral band (from 2 GHz to 62.5 MHz) but the digital hybrid architecture allows us to use the TFB card and correlator plane resources in an even more flexible manner. For instance, as TFB sub-bands are frequency agile, it is possible to 'break' the bandwidth associated with a selected mode into several disjoint spectral 'windows' so that various spectral lines spread across the input bandwidth can be analyzed simultaneously. Multi-spectral resolution is another possibility allowing to zoom on a complex spectral profile by splitting all 32 correlator planes into sub-units with different observing modes and thus different spectral resolutions. Multi-resolution and multi-window modes added to all basic modes widely increase the correlator flexibility which should be used in the future as a powerful tool to decipher the chemical complexity observed in many astrophysical environments; especially in those sources where complex pre-biotic molecules are searched for in line 'forests'. However, these 'new' observing modes still need software development and adequate users interfaces.

4. Acknowledgments

The authors wish to thank the large number of people involved in the ALMA Correlator Integrated Product Team (IPT) during the construction, assembly and testing of the 64-antenna correlator. Correlator IPT acknowledges continuous support from NRAO and ESO at Charlottesville and University of Bordeaux, respectively. We especially thank the ALMA Computing correlator subgroup in Charlottesville without which integrated testing of the correlator hardware and firmware would not have been possible at the integration site as well as at 5000 m in Chile.