Hunt for Molecules
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A GLIMPSE OF TECHNOLOGY ADVANCES FOR THE *ALMA* PROJECT. THE *ALMA* CORRELATOR

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Abstract. The Atacama Large Millimeter Array (ALMA) consists of up to 64x12-m antennas and a Compact Array of 16 antennas. The antenna array has a variety of configurations for imaging astronomical sources at a 5000-m high site in the Chilean Atacama desert. The ALMA science and technical specifications are very ambitious and require innovative developments in order to build the most sensitive imaging interferometer for mm/submm-wave astronomy. We briefly describe selected instrumental areas: high speed digitization (4 GHz clock) of the incoming signal; the photomixing system used for the interferometer local oscillator; the correlator system with emphasis on a new digital filtering concept. The correlator combines the signals of up to 64 antennas and produces all combined interferometer pairs required to image astronomical sources with highly flexible spectral (a few kHz to 2 GHz) and time resolutions (a few millisec to seconds or more) in various polarization products.

1 Introduction

The Atacama Large Millimeter Array (ALMA) is an equal partnership between Europe and North America to construct and operate a mm/submm-wave array of up to 64x12-m antennas. In order to meet the imaging re-

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quirements, the ALMA antennas are movable within a diameter of 150 m to an expanded configuration of 18.5 km maximum separation. The 5000-m high ALMA site is located in the Chilean Atacama desert to offer optimum sky transparency in the mm/submm domain and thus optimize the sensitivity. Japan has joined this new international astronomy facility and will add a Compact Array of 12x7-m along with 4x12-m antennas.

The main science objectives are the formation of galaxies in the distant Universe and the formation of stars and planets throughout the Galaxy. These primary goals and the more general ALMA science drivers allowing astronomers to precisely image a huge variety of objects require a large collecting area, high angular and spectral resolutions, and high sensitivity (for the ALMA science case see e.g. Wootten, 2001 and http://www.alma.info). Such requirements resulted in the selection of a high-elevation and flat site. The top level technical specifications are listed below:

Antennas: up to 64 x 12-m, along with the Japanese Compact Array (12 x 7-m + 4 x 12-m); surface accuracy better than 25 μm r.m. s.

Baseline extent: 150 m up to 18.5 km

Frequency coverage and bands: 30 to 950 GHz; 10 bands with 4K-cooled receivers and photonic Local Oscillator

Intermediate frequency bandwidth: 8 GHz x 2 polarizations per antenna

Digitization, Signal transport: Digitization at antennas, Optical fiber link

Correlator: Up to 2016 baselines processed; flexible digital filtering; thousands of spectral channels, etc.

The technical specifications above required intensive discussions in several groups throughout North America and Europe; one may cite in particular many exchanges on photonic local oscillator generation in the receivers, digitization at the antenna or not, digital or analog signal transport in optical fibers and many discussions on digital filtering and the correlator structure.

In this paper we briefly highlight some technical advances (Section 2). In Sections 3 and 4 we concentrate on specific European designs: the analog signal digitization subsystem, the local oscillator photomixers, and the digital filters developed for the correlator system. In Section 4 we also give general information on the correlator performances.

2 Technical challenges and innovations

Because of the ambitious ALMA science objectives the technical specifications are difficult to meet and have required specific design and development programs. In addition, ALMA will be remotely operated in difficult environmental conditions over many years and this constraint sometimes resulted in difficult compromises between innovation, long-term reliability and affordable costs. Industrial partnership early in the project development was mandatory in several cases, especially for those subsystems to be produced in large quantities (thousands of units) with repeatable performances.

It is important to note that, as of today, temporary or production ALMA systems and subsystems have been successfully tested in *all* areas of the project. We mention here 7 technically challenging areas which required innovative designs: *(1)* High quality 12-m antennas will be produced in quantity. The reflector surface accuracy goal is 25 μm r.m.s. and accurate pointing and fast switching must be achieved ($0.''6$ and $1.5°$ in 1.5 s, respectively). *(2)* The Front-End receiver noise must be as low as a few times the quantum limits at the observing frequencies and the instantaneous intermediate frequency (IF) bandwidth is wide (8 GHz per polarization). *(3)* Enough power must be generated at the photomixers to drive the Front-End receiver local oscillators. In addition, the optical fiber stability must be as high as a few 10^{-10} over the longest baselines to achieve the required 'up-link' phase coherence (e.g. a few degrees around 300 GHz). *(4)* The 4 GHz clock digitizers of the analog signal must support 8-comparison levels and accept IF frequencies up to 4 GHz. *(5)* 96 Gbits/s per antenna must be transmitted through a highly stable optical fiber to the central electronics laboratory. *(6)* The array phase fluctuations will be diminished with 183 GHz water vapor radiometers at all antennas to allow very high frequency and long baseline observations. *(7)* The correlator requires innovative digital filtering and architecture and the design of a new correlator chip.

The above list is not exhaustive and does not mention for example that new non-linear imaging algorithms are needed for the broad user community or that there are several managerial challenges (in particular, the large antenna budget must necessarily be limited without compromising the science and antenna technical requirements).

In the next two Sections we give further details on selected, but innovative, subsystems developed by the European teams.

3 On Back-End specific technology advances

The Back-End subsystem converts the 4 to 12 GHz IF signal into 8 baseband channels (in each of 2 polarizations), digitizes these 8 basebands at 4 Gsamples/s and transmits 96 Gbits/s of data (along with transmission protocol data) from each array antenna to the correlator using fiber optic cables. Another main Back-End function is to provide the Local Oscillator (LO) reference to the high frequency cooled mixers in the Front-End subsystem for conversion to lower IF frequencies. We concentrate below on tasks concerning the fast digitizers and the photonic LO but do not describe here the fiber optic system proposed by Jodrell Bank Observatory to transport the digitized signal from the antennas to the correlator in the central building (see McCool 2001).

3.1 High speed Analog-to-Digital Converters

Digitization of the ALMA signal is performed by a 2-4 GHz bandpass analog-to-digital converter (ADC) which was designed by Université de Bordeaux because there was no commercial device meeting all of the ALMA specifications (in particular, input high frequencies up to 4 GHz and low power dissipation). Low power dissipation is an important goal to maximize the lifetime in a difficult environment with minimum maintenance on site. We have adopted a flash ADC architecture which is well suited to the conversion of wide bandwidths and to high frequency operation with a limited number of bits. The ADC integrates an input amplifier, 7 comparators (8 levels), an encoder matrix and 3 output buffers (3 bits).

Our design uses the Si-Ge technology and BiCMOS 0.25 micrometer process from ST Microelectronics with 2.5 V supply. Our final design exhibits the main following features: *(a)* 1.4 W dissipation per chip on average (to be compared to several watts for commercial, lower frequency ADCs but with many bits); *(b)* 3-bit, Gray-encoded, low swing, differential signal outputs; *(c)* high stability from Allan Variance tests (up to and above 100 s); *(d)* good sampling performances verified with clock signals up to 5 GHz. The ALMA digitizer specifications and results are summarized in Baudry et al (2002) and Recoquillon et al (2005).

In order to lower the data rate to the correlator another chip was developed to demultiplex the 4 Gbits/s serial stream out of the ALMA ADC into 16-bit words at 250 MHz rate. There are 3 such demultiplexing chips

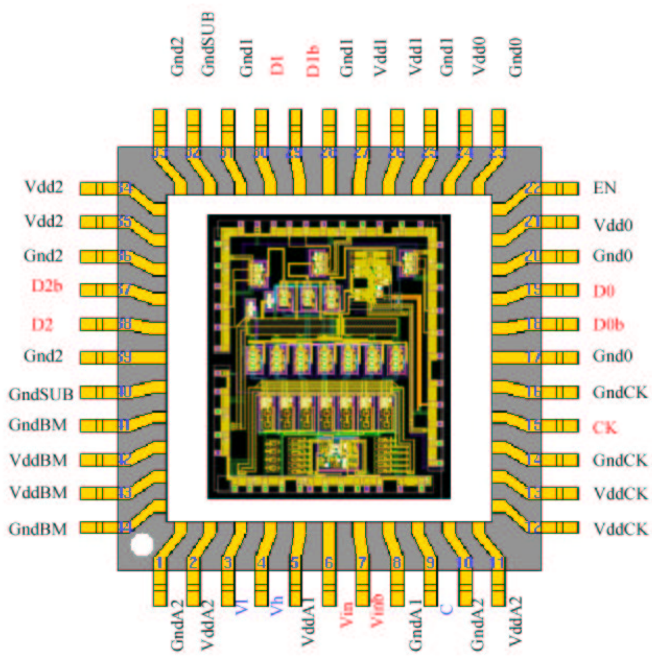

Fig. 1. Photograph of the 8-level ALMA sampler. The Silicon surface is 7mm x 7mm; the chip is assembled in an ESD-protected, 44-pin package

per ADC (one chip per ADC bit) which deliver 250 MHz differential signals to the 'formatter' of the fiber optic transmission subsystem. Each demultiplexing chip dissipates around 650 mW only and includes a built-in-self-test circuit to verify that the chip is properly working. Decoupling the demultplexing function from the ADC was adopted early in the design because of highly complex packaging and pin count issues and to minimize any coupling between the high frequency digitized outputs and the ADC analog inputs. Technical Data Sheets are available for these new chips.

In a combined effort of the Université de Bordeaux and ST Microelectronics all chips required for the project have been produced and packaged (Fig. 1). Several of the production chips have now been assembled in industrial modules processing two different polarization channels (two 2-4 GHz basebands per module). The digitizer modules have been successfully used in end-to-end experiments of the complete data transmission system at the ALMA integration center. Some laboratory performances of the digitizer modules are given in Recoquillon et al (2005).

3.2 Photomixing and Local Oscillator

The ALMA interferometer requires a high frequency, phase stabilized LO to all antennas across the array. A photomixing design has been adopted to generate the LO signal. The photomixer converts a small frequency difference between two optical waves into a $30 - 140$ GHz radio frequency signal. The optical waves (around 1550 nm) are generated from phase locked master and slave lasers and carried to the photomixer through a single mode optical fibre. The photomixer output is a standard mm waveguide whose signal (around $30 - 140$ GHz) is multiplied up to provide the Front-End first LO signal. Astronomical signals up to 950 GHz, the highest ALMA frequency, can thus be mixed with high frequency photonic LOs for IF down conversion and further processing. At this very high frequency the phase jitter specification is below $\approx 20°$ in order to remain well below the atmospheric phase fluctuations. A photomixing block with fibre input and waveguide output has been developed and pre-produced by the Rutherford Appleton Lab in the UK.

The connected array must remain phase coherent and any phase change in the LO propagation process must be compensated. Compensation is achieved by both passive means (thermal insulation of buried fibre) and an active control of the electrical length across the fiber. The complete LO system and cable wraps are being tested with the prototype interferometer at the VLA site in New Mexico (ALMA Test Facility).

4 The ALMA Correlator

The ALMA correlator is a highly specialized super-computer housing around 3000 printed circuit cards with more than 135 000 highly complex Integrated Circuits distributed in 32 main racks. When all correlator cards are used with all digitizers active in all antennas the calculation rate reaches 1.7 10^{16} multiply-and-add operations per second. This is to be compared with the most powerful super computer developed by IBM (Blue Gene/L) which reaches around 300 10^{12} operations/s or with the biggest supercomputers which should offer in perhaps 20 years from now around 10 petaflops (or 10^{16} operations/s) in a sustained mode.

4.1 The Correlator System

The ALMA correlator system combines the astronomical signals from up to 64 remote antennas using a bandwidth of 8 GHz in each of two distinct polarizations per antenna to measure the cross-correlation coefficients of up to 2016 antenna pairings in both wide bandwidth and narrow, multi-channel spectral modes. Further processing of the correlation coefficients gives the continuum or spectral line intensity maps of the sources. The system is highly flexible and supports: *(a)* various polarization options (all Stokes parameters or not); *(b)* single or double Nyquist sampling and 2- or 4-bit options to improve sensitivity; *(c)* spectral resolutions from 2 GHz to 8192 spectral elements each 3.8 kHz wide; *(d)* various dump times (from millisecs to any integration time) according to the selected observing modes.

The correlator flexibility results from the merging of a standard correlator 'time lag-architecture' with a frequency division scheme implemented in digital filters. This system and performances are described in Escoffier et al. (2005, 2006). The correlator is operated and controlled at the Array Operation Site (500-m elevation) and the 'raw' correlation coefficients are processed into spectra in a dedicated computer.

The first quadrant of the correlator has been built, assembled and verified. The operating modes of the correlator are being verified in close cooperation with the ALMA computing team. The overall correlator project is on schedule and remains within the limits of the original budget.

4.2 Correlator and Filter cards

The correlation card and the digital filter card which narrow in a flexible manner the input signal band before correlation are two main building elements of the correlator system. Each correlation card includes 64 big chips each with 4096 time 'lags' (each lag performs 2-bit by 2-bit multiplication). These low power (< 2 W) chips process the data stream at 125 MHz; they have been developed by NRAO, Charlottesville. The associated Long Term Accumulator (LTA) delivers the 1 msec or 16 msec minimum integration time data required for further processing.

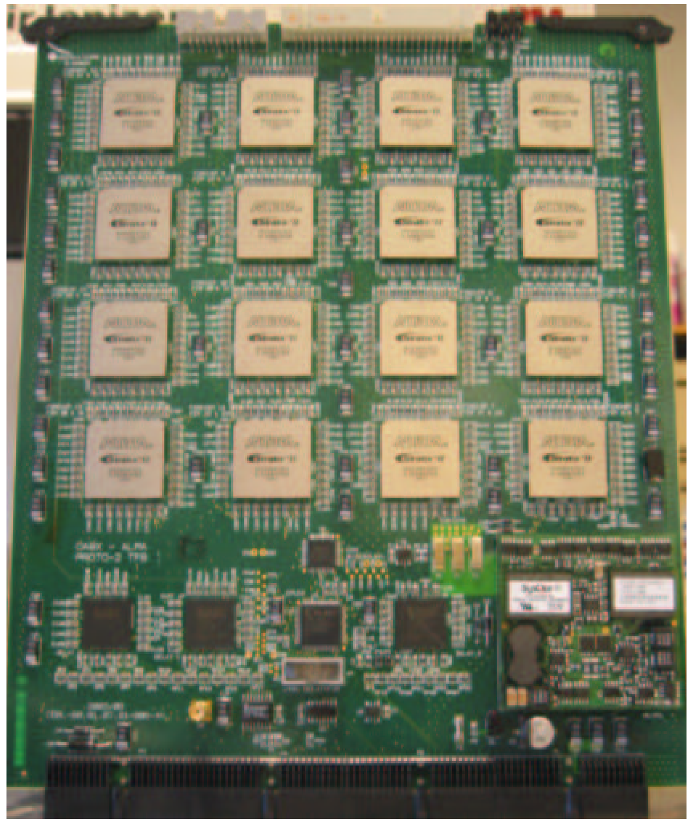

Fig. 2. Photograph of a single correlator digital filter card. There are 32 digital tunable filters implemented in 16 large programmable FPGAs. The filter bandwidth (from 2 GHz to 31.25 MHz), filter shape, and spectral resolution can be selected by the users (see text). The correlator system includes 512 such cards

The digital filter cards are the result of a European study for an ALMA Second Generation Correlator including a Tunable Filter Bank (TFB) which performs the frequency division of the 2 GHz wide input signal into 32 subchannels each 62.5 MHz wide (Quertier et al. 2003, Escoffier, Webber and Baudry 2005). The TFB is highly flexible and all subchannels are independently programmable and may be overlapped to diminish aliasing effects. The TFB card is a plug-in replacement of an earlier filter design; it provides a 32-fold spectral improvement in the wide band mode. The core of the TFB card is a Real/Imaginary 2-stage digital filter which optimizes the logical resources available in large commercial Field Programmable Gate Array (FPGA) chips. The first stage is a low pass decimation filter and, for the second stage, pre-calculated filter tap weights allow the users to select the desired filter shape and bandwidth. Two such 2-stage filters are implemented in one FPGA and 16 FPGAs are assembled on each TFB card (Fig. 2). The complete TFB subsystem consists of 512 filter cards. There are additional key elements, in particular, 'delay' chips are used as signal buffers and distribute the data through the array of FPGAs; these chips are also used to derive part of the geometric delay of the interferometer.

Power dissipation in the TFB cards is a main issue not only because it must remain low to maximize the FPGAs lifetime but also because the cooling capabilities at 5000 m are much reduced. To achieve this goal we have used the most recent firmware tools to implement the digital filters and we have used the most recent hardware technology (90 nm technology). The net dissipation per TFB card is around 80 W well below our initial goal. The overall power dissipation of all 32 operational correlator racks including all 1024 correlator and filter cards is around 170 kW.

5 Conclusion

We have briefly presented some of the ALMA technological advances and have emphasized the European contributions to the project in selected areas (signal digitization, local oscillator photomixers and digital filtering in the correlator). We have outlined the potential of the ALMA correlator which will allow the astronomers to analyze various spectral windows with a great variety of spectral resolutions and to combine simultaneous observations in the continuum and in the spectral lines. The correlator system combined with imaging capabilities will be ideal, for example, to investigate complex 'line forest' sources or to determine unknown redshifts of distant galaxies.

Prototype and production systems or subsystems have been fabricated and tested for the complete ALMA project. When completed, around 2012, ALMA will offer an unrivalled sensitivity (a few micro-Jy in one hour in the continuum mode) and spectral resolution (a few kHz in the spectral mode) along with a huge imaging potential in the mm/submm domain. ALMA will also nicely complement other existing or future large instruments in the visible and IR domains such as the VLT on earth and Herschel and James Webb Space Telescope in space.

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