The ALMA Correlators
Technical details, Performance and Status of the Main Array Correlator
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Two Correlator sub-systems have been constructed for the ALMA project, one for the Main Array of 12-m antennas and one for the ALMA Compact Array (ACA). Both sub-systems combine the astronomical signals captured by the ALMA antennas to form the images which will be interpreted and modeled by the astronomers. These Correlators also have the ability to analyze the spectral content of the incoming radiation; in particular, they allow us to identify or discover the molecular and atomic species present in the nearby or distant cold Universe where new generations of stars are being formed. The ALMA Correlators can be seen as highly specialized ‘super-computing’ machines operated with no hard disks at the highest site ever used for astronomical programs. The 17 peta-operations per second performed by the Main Array Correlator may be compared with the fastest and latest generation of super computers operating in the petaflop domain. In this article we briefly introduce the basic principles of correlation and outline some of the architectural differences between the Main Array and ACA Correlators. We present the main technical characteristics of the Main Array Correlator and give some details on its observing modes and performance. Finally, we summarize the present status of these two powerful Correlator sub-systems and recall that several groups across the world were involved in their construction.
ALMA In-depth

ALMA is a highly sensitive and flexible imaging array, which combines the millimetre/submillimetre signals captured by all antennas deployed on the Chajnantor plateau in two correlator sub-systems. The ALMA correlators are powerful digital machines whose flexibility make them key elements of all future ALMA science programs, including Early Science projects. They process a total bandwidth of 8 GHz in each of two different senses of polarization and combine the signals from up to NA antennas (where \( N_A = 64 \) or 16) movable across the ALMA site within a diameter of about 18 km to 150 m (or even less for the most compact array, the ALMA Compact Array or ACA). Once the input signal voltages have been digitized in specific analog-to-digital converter circuits and combined in the ALMA correlators we obtain: (a) the amplitude and phase information contained in the interferometric fringe pattern of \( N_A(N_A-1)/2 \) independent antenna pairs, and (b) the received power for all \( N_A \) antennas. These data are first appropriately calibrated then processed further to produce the ALMA astronomical images in several spectral channels of the input bandwidth. The spectral images represent the ultimate products required by the astronomers to understand the structure and physical processes at work in the observed sources.

A first ALMA correlator, the main array or baseline correlator, was constructed by an NRAO/European team to process up to \( N_A = 64 \) antennas. (50 12-m antennas are being constructed for the main array but 64 antennas was the initial number in the ALMA project.) The main array correlator combines data from \( 64 \times 63/2 = 2016 \) independent antenna pairs. A second correlator, the ALMA Compact Array (ACA) correlator was constructed by a Japanese consortium to process 16 antennas and produce interferometric patterns for 120 antenna pair combinations. (The ACA consists of twelve 7-m diameter dishes to which four other 12-m diameter dishes—the ACA total power sub-array—have been added.)

These two correlators are run as stand-alone machines, but the calibrated images produced at the post-correlation stage for similar frequency profiles will be merged in several projects to deliver a complete picture of the extended and compact spatial structure present in many astronomical sources. In addition, to maximize sensitivity we expect that for a number of projects the main array correlator will process the data collected by both the main array and several antennas of the ACA. This is feasible because all ALMA antennas have identical data formats and because the patch-panel sub-system connecting with optic fibers the antennas to the main array correlator room can be configured in several different ways.

To understand the basic principles of signal correlation it is useful to derive the interferometer response of a single antenna pair, the basic element of any array of antennas. The wave signals from a celestial source, or voltage signals, collected by the antennas are first converted to a frequency range that allows to amplify these input signals. This operation, named heterodyne detection, is performed in the Front-End receivers except for ALMA bands 1 and 2 for which the signal is directly amplified. The amplified signals are later combined in a multiplier and
integrated over short periods of time. Signal multiplication and time averaging form the core of the correlation process. This is schematically shown in Fig. 1 where, as usual in all modern correlators, the analog signal is converted into a limited number of digits (signal digitization) prior to multiplication.

The high frequency component resulting from multiplication of the two signal voltages is filtered out whereas the low frequency product is the 2-antenna interferometer response at the correlator output. This response shows a sinusoidal pattern, the interferometer fringes, whose frequency depends on the observing frequency and the scalar product of the 2-antenna baseline vector with the unit vector to the source direction; the fringe frequency varies slowly with the source hour angle and the response is not distorted by short integrations. The interferometer amplitude is proportional to the power received by the two antennas. In the 2-dimension treatment of the basic 2-element interferometer response the amplitude and phase of the fringe pattern at the correlator output allow to derive the complex source visibility and hence to know the source brightness distribution on the sky.

The above description of an interferometer is valid for a given frequency and for a narrow bandwidth. If this assumption is not fulfilled, i.e. if the passband of each antenna Front-End receiver is broad, it can be divided into independent narrow band channels providing as many independent interferometers. Broad band or multi-channel analysis is required to understand the physics at the origin of the radiation mechanisms of many astronomical sources, and also to provide better sensitivity. In the case of the molecular or atomic radiation emitted by interstellar or circumstellar clouds in very specific frequency ranges, interferometry is required in several

More exactly, the visibility function is defined as the Fourier transform in the space frequency domain of the source brightness modified by the antenna power pattern. The visibility amplitude is directly related to the source extent with respect to the fringe spacing. For a point like source the phase information contains the source position once the array baselines have been calibrated (i.e. once the baseline extents and the baseline orientations with respect to the exact positions of distant quasars are known).
relatively narrow frequency channels to image these clouds and understand their kinematics. As explained later, spectral capability is relatively easy to implement in digital correlators and we do not have to build as many independent interferometers as we wish to have spectral channels.

In the early days of radio astronomy, combination of the signals from an antenna pair was achieved by summing the two signals in a square law detector. The ‘adding interferometer’ is the equivalent in the radio domain of the Michelson interferometer. The low frequency output of the square law detector contains the interferometer fringe pattern whose frequency varies slowly with time while the fringe amplitude is related to the source size. The major drawback of the adding interferometer is the presence of a constant term or response offset which drifts with time and cannot be easily eliminated. Instead of adding and detecting the captured signals, all modern radio interferometers provide the cross correlation i.e. multiplication of the input signals, thus eliminating all incoherent sources of noise along the two arms of each 2-antenna interferometer (electronics noise) and above each antenna (sky noise).

Spectral correlation and XF-FX architectures

Cross correlation is accomplished in a digital multiplier and integrator as schematically shown in Fig. 1 after the voltages collected at all antennas have been digitized. Formally, cross correlation for an antenna pair \((i,j)\) providing the signal voltages \(V_i(k t_s)\) and \(V_j(k t_s)\) sampled at time \(t = k t_s\) over a large number of samples, varies as the sum:

\[
P_{ij}(p t_s) = \sum_{k} V_i(k t_s) V_j(k t_s + p t_s)
\]

where \(t_s\) is the discrete time interval between samples and \(k\) and \(p\) are integers. The integer \(p\) which varies in discrete steps up to an adopted maximum value \(p_{\text{Max}}\) (where \(p_{\text{Max}}\) remains always very small compared to the total number of processed samples) is introduced to define a time offset \(p t_s\) (or time lag) and its associated Fourier transform to the frequency domain a frequency ‘channel’. There are as many values of \(P_{ij}\) as we have values of the time offsets and, in the associated Fourier space, the frequency separation between channels can be specified once \(p_{\text{Max}}\) and \(t_s\) are known (see below). The summed products \(P_{ij}\) when they have been properly normalized and calibrated in terms of the broad band noise standard deviation are also called the cross correlation coefficients².

The time interval between two digitized signal samples, \(t_s\), is derived from the sampling frequency which is directly related to the ALMA basic frequency interval, or ALMA baseband \(B= 2 \text{ GHz}\). (The ALMA baseband is defined as the fourth of the total instantaneous bandwidth, 8 GHz, in each of two polarizations.) In the Nyquist sampling case \(t_s = 1/2B\) which implies a high data rate of \(4 \times 10^9\) samples per second in the ALMA case (\(t_s = 250\) psec). If the cross correlation measurements are made for \(2p_{\text{Max}}\) time offsets, i.e. \(-p_{\text{Max}} t_s, \ldots, 0, \ldots, (p_{\text{Max}} - 1) t_s\), then the Fourier transform of the discretized cross correlation function provides the cross correlation coefficients².

The input signals are both sampled and quantized in the digitizers, and the actual cross correlation coefficient is slightly different from the formal or ‘true’ cross correlation defined above. In practice the products \(V_i(k t_s) V_j(k t_s + p t_s)\) are obtained from a look-up table (Read-Only Memory or ROM) whose values correspond to the expected cross correlation products; in this process the input digitized signals are used to determine the address of the products stored in ROMs. The multiplication table is implemented in the correlator circuit.
power spectrum at the discrete spectral intervals $1/(2p_{\text{Max}}^3)$. Therefore, for Nyquist sampling, the spectral interval or frequency channel separation is $B/p_{\text{Max}}^3$.

The cross correlation measurements are performed in the ‘baseline electronics’ part of the spectral correlator schematically represented in Fig. 2. The correlation products are derived in multipliers and accumulators, the MAC cells, where MAC stands for data multiplication and accumulation. Each arm of the 2-element interferometer processing the input signals for the (i,j) antenna pair is delayed with respect to the other one by $1\,t_S$, $2\,t_S$, etc. (see Fig. 2). All cross products are then sent to a Long Term Accumulator (LTA) which accumulates the correlation functions. Finally, the cross power spectrum which contains the spectral information of interest to the astronomer is obtained in the Fourier Transform (FT) processor which performs a discrete Fourier transform of the correlation functions. The ‘antenna electronics’ and ‘baseline electronics’ together with the FT processor form the digital spectral correlator system. The final outputs of this large system are the source visibility functions for several narrow frequency channels across the input bandwidth and for all antenna pairs in the array. They allow the astronomers to build the 2-dimension spectral images of the observed sources as especially required for spectral line observations. If the astronomical sources do not exhibit rapid variations with frequency the astronomers can select a digital correlator configuration with less spectral channels which is then better suited to ‘continuum’ observations (as opposed to spectral line observations), and eventually measure the average cross correlation product across the entire signal bandwidth.

The digital spectral or continuum cross correlators used to image astronomical sources with relatively narrow or broad band spectra are designated as XF correlators, or lag correlators, where X represents the cross-correlation part of the signal processing and F stands for the Fourier transform. In terms of signal processing it is fully equivalent to construct correlators based on the XF or FX architecture. In the latter case conversion to the frequency domain would be

3 The total number of time offsets $2p_{\text{Max}}^3$ used to derive $P_{ij}(t_S)$ is very small compared to the number of samples processed in the cross correlator; this limitation degrades the spectral resolution to about 1.2 times the spectral interval between channels.
(F-part) is performed in a real time fast Fourier transform (FFT) circuit whose outputs are multiplied (X-part) to provide the cross power spectrum\(^4\).

With the XF architecture much complexity is embedded in the correlation part and increases in proportion with \(N_A(N_A - 1)/2\) (or roughly with the square of the number of antennas) whereas for the FX architecture, Fourier transformation is performed in proportion with the number of antennas. Both architectures have been adopted for the ALMA project. The FX correlator built by the Japanese team processes the signals captured by 16 antennas of the ACA. The main array correlator constructed by the NRAO/European team to process up to 64 antennas is not exactly an XF design but incorporates the European concept of Second Generation Correlator in which the input baseband is digitally split into several frequency-mobile subbands (this is performed in the Digital Processing box of Fig. 2 and, more precisely, in the Tunable Filter Bank Card box of Fig. 3); higher flexibility and higher spectral resolution are thus implemented in the main array correlator as described later (see sub-sections on Filtering and Modes). The main array correlator architecture is in fact a digital hybrid XF design or FXF. However, when frequency division of the input baseband is bypassed, then the main array correlator behaves as a pure XF system; both operating modes are offered to the users (see FDM and TDM modes below).

**ALMA main array correlator : technical details and performance**

The top level specifications of the main array correlator are gathered in Table 1. (Most of these specifications, baseband inputs/antenna, input sample format, 2-bit 4-level output sample format and number of polarization products are also common to the ACA correlator.) Among the difficulties met by the designers of the main array correlator one may highlight processing a very broad bandwidth (16 GHz in total) for each of 64 antennas and implementing spectral flexibility to provide high or low resolution and selectable spectral windows across the input baseband.

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

The main parts of the main array correlator are shown in Fig. 3 and briefly described below.

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\(^4\) One way to implement the FX correlator consists in sending input data streams of \(2n_x\) samples to the FFT circuit of each antenna which then provides \(n_s\) complex signal amplitudes (cosine and sine outputs). The sample length, \(2n_x\), is chosen to optimize the FFT algorithm. The FFT complex amplitudes are later multiplied with the amplitudes from all other antennas in the array to form \(n_s\) values of cross power spectrum. After FFT transformation the discrete frequency interval is given by \(1/2n_x\) or \(B/n_s\) in the Nyquist sampling case.
Digitization and Filtering

Digitization, that is to say sampling and quantization of the input signal to convert the analog voltage into a digital data flow is a critical step in the ALMA processing chain because it is performed at the antennas soon after the Front-End receivers and for a broad bandwidth (2 to 4 GHz). Digitization of the ALMA baseband requires 4 Gsamples/second digitizers and, according to the ALMA specification, each sample is 3-bit encoded (8 quantization levels). Correlation cannot be performed at the 4 GHz clock rate of the ALMA digitizers, therefore the data flow is demultiplexed to provide much lower frequency signals allowing to ultimately process the data at 250/125 MHz clock rates; this is achieved in a specific 1:16 demultiplexing stage provided in the digitizer assemblies. The resulting lower frequency parallel bit stream is transmitted from each antenna to the correlator room through optical fibers.
ALMA In-depth

Baseband frequency division is accomplished in the Tunable Filter Bank (TFB) cards which divide the 2 GHz input bandwidth into 32 frequency-agile subbands of 62.5 MHz. Subband extraction is the result of a digital 3-stage digital filter design implemented in a programmable logic device (a Field Programmable Gate Array or FPGA). The last stage of the digital filter strongly determines the filter properties (passband ripple, stopband rejection, use or not of pre-calculated digital weights to narrow the subband further). A commercial large FPGA device using 90 nanometer technology (i.e. the smallest circuit prints in the FPGA are around 90 nanometers) has been selected for the TFB cards. 16 FPGA's are required to implement all 32 subbands in a single card. There are as many as 8 TFB cards per antenna (see Station Electronics TFB blocks in Fig. 3), and 512 cards are required for the full 64-antenna system. It is important to stress that digital filtering offers many advantages in terms of flexibility or performance reproducibility (e.g. stability with respect to thermal drifts).

Correlation

All cross products for the full array of 64 antennas are derived in 32 correlator ‘planes’ shown in the ‘Correlator Array’ of Fig. 3. A correlator plane is a 64x64 matrix in which a total of 256 specific integrated circuits (the correlator chips) are used to multiply the signal by its time shifted version (time lag) for all independent antenna pairs in the array. One correlator plane processes one baseband in two different polarizations and places the 64x64 matrix in four correlator printed circuit cards. These four cards are the ‘lags’ and ‘leads’ cards (each providing 64x63/2 cross correlation products) and two other cards providing the auto-correlation coefficients for all 64 antennas. There are 64 correlator chips per correlator card in order to keep a reasonable physical size for the correlator card and also to facilitate power dissipation and thus the cooling. The basic element in one correlator chip is a 256-lag block in which one lag corresponds to the MAC cell shown in Fig. 2. Each 256-lag block can be configured to support single or double polarization observations or to produce all 4 cross products for full Stokes parameters analysis.

Each of the 32 digital subbands extracted in the TFB cards is assigned to one of the 32 correlator planes for signal correlation in the widest bandwidth mode. The resulting spectra are stitched together at a later stage to reconstruct a global spectrum with now 32 times more spectral channels across the baseband. To further enhance the spectral resolution one can assign all correlator plane resources to fewer than 32 subbands. In that case the total input bandwidth is less than the original 2 GHz baseband and can be narrowed in powers of two down to 62.5 MHz (or even to 31.25 MHz with special digital weights but with some restrictions).

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5 One MAC cell or lag circuit includes a 2-bit x 2-bit multiplier, a multi-bits accumulator and an output register. The basic element being a 256-lag block, there are 16 x 256-lag blocks in one correlator chip for a total of 4096 lags per chip. When the elemental 256-lag block is configured to produce all four cross products for full polarization analysis there are only 64 lags available per cross product; there are twice more lags for double polarization without cross products.
Data transmission and rack architecture

Communication of antenna-based electronics with baseline-based electronics is a very difficult problem. The whole system with 64 possible antennas, 8 basebands per antenna and 32 demultiplexed signals (at 125 MHz clock rate) per baseband requires a total of 32768 rack-to-rack interfaces for 2-bit correlation per sample. In the ALMA correlator we multiplex the digital filter card outputs and use twice less cables, 16384, carrying 250 MHz signals. The output phase of each cable is remotely controlled and adjusted for error-free data transmission.

The main array correlator is organised by quadrants each quadrant processing one baseband pair for the two different polarizations captured by each antenna. There are 8 racks per quadrant (4 Station Electronics and 4 Baseline Electronics racks) and a total of 32 racks for all 4 quadrants to which one must add the power supply racks, the Correlator Data Processor (where Fourier transformation to the frequency domain is performed) and the Correlator Control Computer racks. All racks are installed in the correlator room at the AOS (ALMA Operations Support) technical building (Fig. 4). One of the main concerns to operate the full system is power dissipation which directly impacts long term reliability. Because the air density at the AOS is about half that at sea level air circulation is forced under the correlator room floor. In addition, several fans are installed at the top of the station racks to improve heat dissipation at the level of the printed circuit cards and components. Temperature is remotely controlled throughout the racks and in the correlator room; correlator shutdown is programmed in case of emergency. The full system including all computers dissipates around 130 kW; air circulation in the correlator room is thus a critical question.
Observing Modes

Broadly speaking the ALMA main array correlator supports two categories of observing modes the Time Division Modes (TDM) and the Frequency Division Modes (FDM). In the first case the correlator behaves as a pure XF system. 32 ‘time bins’ are first sent from the ‘Station Card’ (see Fig. 3) to the 32 correlator planes (each processing 1/32 of the digitizer samples). Then all time packet outputs from all 32 planes are summed at a later stage to keep up with the 4 Gsample rate of the antenna digitizers. TDM modes are adequate for relatively low spectral resolution (less lags available) and fast dump times (16 msec for cross correlation). In the FDM operation mode each of the 32 TFB card outputs (there are 32 subbands each 62.5 MHz for the 2 GHz input baseband) is processed in one of the 32 correlator planes. Narrower total bandwidths are obtained if not all subband outputs are processed. Higher spectral resolutions are then possible by sending the active filter outputs to all correlator lag resources; this is activated by appropriate addressing of the microcontroller in the ‘Station Card’ shown in Fig. 3. FDM modes are best suited to high spectral resolution and spectroscopic observations. A large number of FDM modes is offered to the user when one includes the ‘higher sensitivity’ double Nyquist and 4-bit x 4-bit correlation modes for which digitization efficiency is increased to 94% and 99%, respectively. The latter modes require more lag resources per input bandwidth and the
spectral resolution is lowered. The 64-antenna correlator supports a total of 63 FDM and 4 TDM modes including the polarization options (one single polarization baseband and 2 basebands per quadrant with or without cross products). The highest spectral resolution, 3.8 kHz, is obtained for one baseband processed with specific digital weights downloaded in the last stage of the digital filter.

Examples of bandwidths and channel separation are given in Table 2 for two basebands (both polarizations) and 2-bit correlation.

**Table 2**: Effective bandwidth per baseband and spacing of spectral points for 2-bit correlation in frequency division mode (FDM) with 2 basebands processed (both polarizations). Spectral resolution is twice less for double Nyquist sampling but sensitivity is improved by 7%.

<table>
<thead>
<tr>
<th>Effective bandwidth* (MHz)</th>
<th>Channel separation (kHz) Nyquist sampling</th>
<th>Channel separation (kHz) Double Nyquist</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>488</td>
<td>-</td>
</tr>
<tr>
<td>938</td>
<td>244</td>
<td>488</td>
</tr>
<tr>
<td>469</td>
<td>122</td>
<td>244</td>
</tr>
<tr>
<td>234</td>
<td>61</td>
<td>122</td>
</tr>
<tr>
<td>117</td>
<td>30.5</td>
<td>61</td>
</tr>
<tr>
<td>62.5</td>
<td>15.3</td>
<td>30.5</td>
</tr>
<tr>
<td>31.25**</td>
<td>-</td>
<td>7.6</td>
</tr>
</tbody>
</table>

* The effective bandwidth is determined by the properties of the anti-aliasing analog bandpass filter placed in front of the digitizers and by the slight subband channel overlap required for optimum subband stitching when 2 or more subbands are used.

** Available with specific digital weights downloaded in last stage of the digital filter and for double Nyquist sampling only (3.8 kHz resolution requires the processing of only one baseband)

The bandwidth and resolution examples given in Table 2 are well suited to spectral line observations in a broad variety of astrophysical environments. The effective bandwidths cover most interesting cases for sources in our Galaxy and for nearby galaxies. This is illustrated in Table 3 in which we give (i) the typical velocity coverage observed in a number of sources and (ii) the total bandwidth required to perform observations around for instance 89 and 602 GHz; the spectral lines of abundant molecular species (HCO+ or HCN and methanol) are present near these two frequencies.
Table 3: Examples of total velocity coverage and total bandwidth required for line observations of galactic or extragalactic sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Typical total velocity coverage (km/s)</th>
<th>Total bandwidth required (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>89 GHz (Band 3)</td>
</tr>
<tr>
<td>Galaxy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energetic Outflows</td>
<td>300 – 600</td>
<td>90 – 180</td>
</tr>
<tr>
<td>Orion &amp; Galactic Center star forming regions</td>
<td>80 – 160</td>
<td>24 – 48</td>
</tr>
<tr>
<td>Compact HII regions</td>
<td>40</td>
<td>12</td>
</tr>
<tr>
<td>Interstellar Molecular Clouds</td>
<td>5 – 40</td>
<td>1.5 – 12</td>
</tr>
<tr>
<td>Extragalactic Sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nearby galaxies (≤ 200 Mpc)</td>
<td>≤ 2000</td>
<td>≤ 600</td>
</tr>
</tbody>
</table>

Supposing we need two polarizations, examples in Table 2 can be used to help select the total bandwidth and spectral resolution most appropriate to a given astrophysics environment. High resolution, say around 10 to 100 kHz, is well suited to the study of molecular line emission in protostellar discs, interstellar molecular clouds or Galactic masers. On the other hand, 1 MHz resolution is well adapted to the analysis for instance of the widespread CO lines emission observed in nearby galaxies or in Galactic outflows. Tables 2 and 3 suggest that this can achieved with effective bandwidths of 1.8 or 0.9 GHz and by binning spectral channels.

Coarser spectral resolution than shown in Table 2 is best suited to the observation of: (i) broad band continuum emission sources in the Galaxy or external galaxies, and (ii) spectral line sources in distant galaxies for which the total bandwidth must be broad. This is better achieved with the TDM operation mode. There are 3 TDM modes for 2-bit correlation providing 7.8, 15.6 or 31.3 MHz channel separation across 2 GHz (1.8 GHz effective bandwidth) if 1, 2 or 4 polarization products are selected, respectively. There is a fourth, higher sensitivity 3-bit correlation TDM mode, providing 31.25 MHz channel separation across 2 GHz; it is available if only one 2 GHz baseband polarization channel is processed.

The basic modes described above apply to a single region, 2 GHz in the TDM case and, in the FDM case, to a single region selected from 2 GHz to 62.5 MHz (or 31.25 MHz). But the main array correlator architecture and firmware allow us to support other FDM and correlator planes combinations which we briefly describe below. All of them require, however, new software development from Computing Integrated Product Team in order to offer adequate users interfaces. In addition, some possibilities may just be limited by too high data rates—and these limitations have not yet been fully explored.

- Because FDM allows us to move the 62.5 MHz subbands anywhere within one 2 GHz baseband it is possible to ‘break’ the total bandwidth associated with a selected mode into multiple disjoint spectral regions (up to 4 ‘windows’ are implemented in practice). We can thus analyze various spectral lines spread across the input bandwidth provided that all regions are multiples of 62.5 MHz and fit within 2 GHz.
ALMA In-depth

- Multi-spectral resolution across different bandwidths is another option allowing to zoom on some complex spectral features. Each quadrant can be split into sub-units and each sub-unit can be operated with a different observing mode (e.g. different resolutions or polarization modes are selectable). The correlator resources available in all sub-units are limited of course by those available in the full 32 planes. (Note that with a single quadrant configured to support 4 basebands it is also possible to select FDM modes with different bandwidths and spectral resolutions in order to achieve multi-resolution.)

Even more configurations are possible. For instance, one can broaden the total bandwidth beyond 2 GHz by combining basebands within a quadrant or by combining quadrants. 1, 2 or 4 basebands are available for each polarization and the aggregate maximum bandwidth is 8 GHz per polarization. One can also select FDM and TDM modes for simultaneous spectral line and continuum observations with two independent overlapping quadrants.

Finally, it is important to mention three other correlator configuration modes which will become available soon or in the near future: (a) Sideband separation mode in which the correlator, in conjunction with 0-90° phase switching, separates the Front-End receiver mixer sidebands. This is required for the double sideband receivers in ALMA bands 9 and 10 and in other ALMA bands when sideband rejection is thought to be inadequate. (b) Subarraying which is the ability to operate in different observing modes independent subsets of antennas. Each correlator quadrant can support 2 or more subarrays. (c) Very Long Baseline Interferometry (VLBI) observations involving the ALMA phased array (or a subset of the ALMA antennas) are possible with the main array correlator design because each correlator card can provide the summed outputs of up to 64 antennas. VLBI requires development of a specific phasing and control software and additional hardware, mainly an hydrogen maser to replace the ALMA rubidium master frequency standard and a specific data recorder to which the summed antenna outputs are sent.

Status of the ALMA correlators

To conclude, we give brief indications on the ALMA correlators status and installation schedule. Installation and testing at the AOS of quadrant 1 of the main array correlator were completed in October 2008. Quadrant 1 supports up to 16 antennas and 4 baseband pairs. It is being used routinely by the AIV/CSV teams especially for ALMA science verification. The second and third quadrants have been installed at the AOS in the fall and summer of 2009 and 2010, respectively. In October 2010, the 2-quadrant configuration was commissioned and operated from the Correlator Control Computer and the engineering port. 2-quadrant operation will be available soon in 2011. With 2-quadrant configuration and appropriate control software, up to 32 antennas in the array and up to 4 baseband pairs will be available for ALMA Early Science. Full delivery to the users community, however, still requires some software development from Computing IPT.

The fourth quadrant has been constructed and is being operated at the integration center in Charlottesville. Installation at the AOS has been delayed to the second semester of 2011 in order to continue firmware and software development. All 4 quadrants of the main array correlator are needed to support more than 32 antennas (up to 64) and all 4 baseband pairs.

In parallel with the fabrication and installation of the main array correlator, two scaled down models of the large machine have been fabricated with exactly the same production TFB and
correlator boards. These models are for 2-antenna operation; one has been installed at the Operation Support Facility site since 2008 and is used for antenna equipment testing before newly outfitted antennas are moved to the high site.

The ACA Correlator is also built in quadrants. Two quadrants (Fig. 5) have already been successfully connected to 2 antennas on the ACA pads at the AOS in August, 2010. It is expected that all 4 quadrants will be delivered in 2011. When the two ALMA correlators will be fully delivered to the project it would be useful to compare or cross-calibrate the digital efficiency and spectral properties of these two large machines for a subset of ALMA antennas (up to 16, the maximum processed by the ACA correlator). A first investigation of the expected difference between the frequency profiles of the XF and FX correlators has been made by the Japanese team; it shows that frequency profile compatibility is possible as required to combine the main array and ACA images.

Teams involved in the construction

Several teams and a large number of people were involved in the construction of the two large correlator sub-systems. The 64-antenna correlator has been constructed by a consortium of laboratories within the ALMA Correlator Integrated Product Team organization supported by the North American and European ALMA Executives. The key correlation and filtering cards of the 64-antenna correlator were designed, prototyped and functionally tested in Charlottesville (NRAO) and Université of Bordeaux (LAB), respectively. Production of the ALMA 64-antenna correlator cards involved several industrial partners selected after competitive bidding to manufacture the printed circuit cards or the application specific integrated circuits and to assemble all components on the printed circuit cards. Acceptance of the production key cards was supported by specific card test fixtures and test procedures were designed by the Correlator IPT team.

The correlator quadrants have been first assembled and tested in Charlottesville before delivery to Chile at the AOS. Integrated testing of the 64-antenna correlator hardware and firmware embedded in several correlator cards as well as final acceptance at the correlator quadrant level were made possible thanks to the software developed by the correlator sub-group of the ALMA Computing Integrated Product Team. The frequency division mode concept and frequency-agile TFB design emerged in Europe in the years 2001 to 2003 within the 2nd Generation Correlator team which, in addition to incorporating their design in the initial NRAO correlator design, compared their performance and costs with the Japanese correlator project.

The ACA correlator has been constructed by the ACA Correlator team in Japan. This team comprised astronomers and engineers at NAOJ and engineers at FUJITSU Ltd., the sub-contractor. The FX design of the ACA correlator was initially proposed by NAOJ. All details of the final design are the result of the cooperative work of NAOJ and FUJITSU Ltd.. The sub-contractor is also responsible for fabrication, shipment, and assembly on site. Functional and performance testing for acceptance has been conducted by the ACA Correlator team with support of the ACA Correlator sub-group of the ALMA Computing Integrated Product Team.