The ALMA Back-End

Alain Baudry[1]
Fabio Biancat Marchet[2]
Hervé Kurlandcyk[2]
Silvio Rossi[2]

[1] Observatoire Aquitain des Sciences de l'Univers de Bordeaux, Floirac, France
[2] ESO

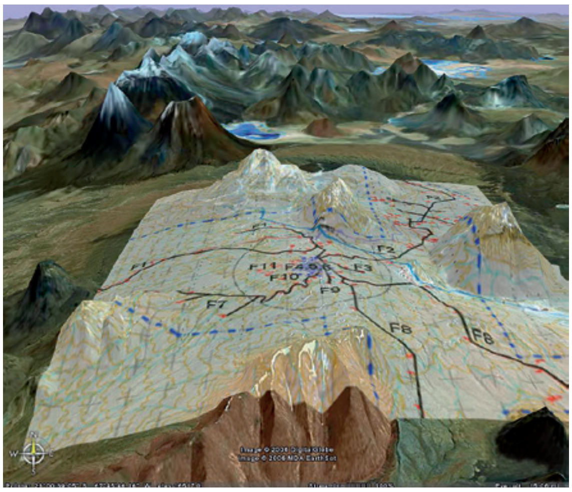

Figure 1: The fibre network on the Chajnantor site. The fibre network is an essential part of the Back-End allowing the data transfer from each antenna to the technical building. The distance of the farthest stations to the technical building is approximately 15 km. The network will encompass more than 100 km of multi-fibre cables for a total of installed fiber length exceeding 10000 km. In order to attain the thermal insulation required by the photonic local oscillator the cables will be directly buried at a depth of 0.6–1 m.

The Atacama Large Millimeter Array is designed to produce excellent images in spectral lines and continuum, to detect distant galaxies like our Milky Way and to image proto-stellar discs in the nearest molecular clouds. To accomplish these goals, signals from the ALMA antennas must be processed and transmitted to the technical building in a format ready to be accepted by the correlator. The ALMA Back-End provides this in a loss-free, reliable and flexible way. In the following an overview is given of the ALMA Back-End subsystems developed in various European Institutes under ESO coordination.

The signal of frequency up to 950 GHz captured by each antenna of the array is converted to a pair of Intermediate Frequency (IF) signals, one for each polarisation, in the range of 4–12 GHz by the Front-End cryogenic receivers, digitized and transferred to the technical building as a 120 Gbit/second raw data stream through one single optical fibre. A sketch of the fibre network at Chajnantor is shown in Figure 1.

In the technical building (right side of Figure 2) a custom processor, the correlator, cross-correlates the signals from all antennas and pre-processes the data flow before passing it to the computing system for further processing. The IF signal processing and digitization in the antenna as well as the data transmission system that transfers the signal to the correlator are part of the ALMA Back-End subsystem (left side of Figure 2).

The severe environment deserves special attention: at 5000 m altitude the heat dissipation capability is greatly reduced, in addition the remote location and the lack of oxygen heavily impact the possibility of performing maintenance on site. This calls for low power dissipation, high reliability and easy maintenance equipment.

Although the most advanced information and communication applications are fast approaching the ALMA needs, meeting the ALMA requirements was only possible by pushing the technology beyond the state of the art and Application Specific Integrated Circuits (ASICs) were developed where commercial solutions are not yet available.

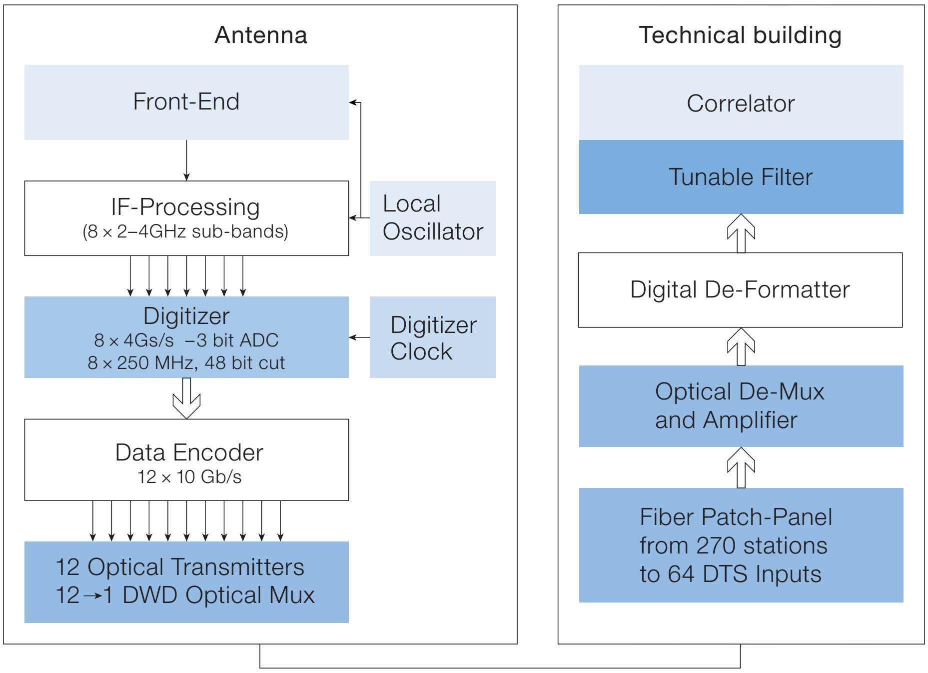

Figure 2: A schematic view of the ALMA system, showing the location of the Back-End subsystems between the Front-End receivers and the correlator. The Data Transmission System within the Back-End in the antenna processes, digitizes at 4 Gsamples/s and converts the 'low' frequency (4–12 GHz) signals output by the Front-End receivers in a multi-colour light beam that through one single fibre is transferred at the rate of 120 Gbit/s to the technical building where it is converted back to an electrical signal and fed into the correlator. The Back-End also includes the photonics Local Oscillator that provides an extremely phase accurate signal to all antennas.

Data Transmission System

The Data Transmission System (DTS) in the antenna performs two main tasks: it digitizes the processed IF frequency signals and converts them to a format suitable for digital transmission along one single optical fibre. In the DTS the scientific signal is converted into 12 10 Gbit/s digital serial streams each one driving a laser emitter with slightly different colour. The 12 light beams are optically mixed together and injected into one single optical fibre (Dense Wavelength Division Modulation).

In the technical building the incoming light beam is optically de-multiplexed to separate the 12 original beams. These are converted to electrical signals and fed into the correlator. In order to reliably operate at the required light frequency and with the proper power and sensitivity throughout their whole lifetime both the laser emitters and receivers need a sophisticated control system for current and temperature.

The Digitizer Assembly

The ALMA Digitizer Assembly is part of the Data Transmission System. It digitizes the two incoming signals, one for each polarisation, at a rate of 4 G samples/s and parallelises them into six 16-bit words at a rate of 250 MHz. These words are sent to the Data Encoder that formats them for the optical transmission.

The heart of the Digitizer Assembly is the digitizer chip, VEGA (see Figures 3 and 4), a band-pass 2–4 GHz 3-bit flash analog to digital converter operating at the sampling rate of 4 G samples/s. Although at present the market offers components that nominally meet some of the requirements, the suitable combination of sampling rate, resolution, maximum input frequency (4 GHz) and power consumption is not available. Therefore, an Application Specific custom device (ASIC) needed to be developed. The power dissipation represents an additional constraint as the low air density at the operating altitude makes the ventilation rather inefficient, especially considering that the Digitizer Assembly needs to be enclosed in a sealed case to reduce radio frequency interference.

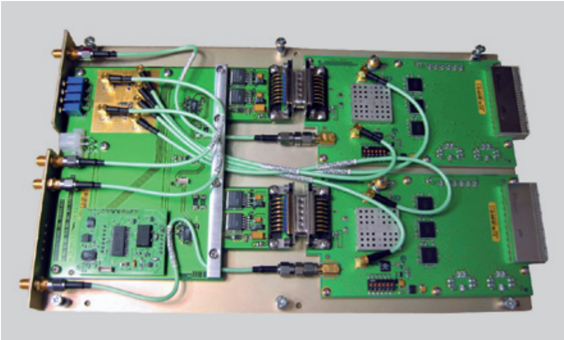

Figure 3: The Digitizer Assembly contains two VEGA digitizer chips (enclosed in the small metal boxes) and six PHOBOS de-multiplexer chips (the square black devices on the right side). The Digitizer Assembly converts two 2–4 GHz pass-band signals sampled at 4 G sample/s into six 16-bit parallel streams at 250 MHz. The left side of the assembly contains the power supplies, the clocks distribution circuits and the low frequency circuits for communication and remote control.

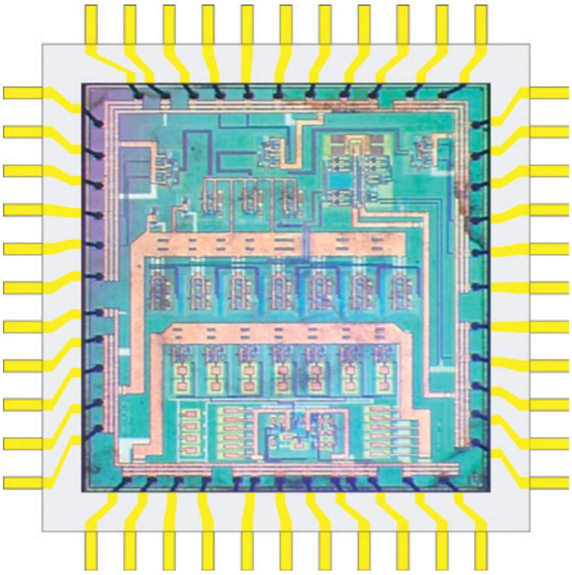

Figure 4: This microphotography shows the internal layout of the VEGA digitizer chip a 4 G sample/s 3-bit analog to digital converter. A second chip, PHOBOS, de-multiplexes (i.e. parallelises) the VEGA serial stream output. Both devices are custom developments and are operated at clock frequencies as high as 4 GHz. They are implemented in the Silicon-Germanium BiCMOS technology that allows to design transistors with transition frequency as high as 75 GHz, but with power dissipation significantly lower than other high frequency technologies (InP, GaAs). The power consumption for the two devices is in the range of 1 W, which allows enclosing the whole Digitizer Assembly into a RF tight box without any special heat sink.

In order to meet the high speed and low power requirements, the digitizer uses the Silicon-Germanium technology and BiCMOS 0.25 µm process. This technology allows the fabrication of high speed and low dissipation hybrid analog/digital devices. The nominal voltage supply is 2.5 V and the average power consumption is 1.5 W. The device has a high temporal stability, a key requirement for radio astronomy. A self-diagnostic block is included in the chip in order to verify after the production or during maintenance that the device exhibits toggling outputs.

A companion demultiplexing chip, PHOBOS, was also developed. It parallelises an incoming 4 Gbit/s serial stream in 16-bit words at a rate of 250 MHz. Three of these devices are connected to each one of the three VEGA output lines. Despite the higher pin-out and complexity and even lower power dissipation constraints (less than 1 W per chip), the development of PHOBOS was less critical being a fully digital device with no analogue parts.

VEGA and PHOBOS are the result of a combined effort between the Observatoire de Bordeaux, the IXL Laboratory of the Université de Bordeaux and a commercial partner. All design, simulations and qualification tests have been performed by the two institutes while the commercial partner provided the software tools and the production facilities.

Local Oscillator

To operate the array in the interferometric mode the ALMA Front-End receivers require a phase-stabilised Local Oscillator (LO) coherent among all antennas to convert the incoming astronomical signal to lower frequencies. Receiving frequencies as high as 950 GHz and baselines up to 15 km set an extremely tight phase stability requirement for the LO.

To generate and effectively distribute such a stable reference all over the array, a photonic approach has been adopted. Two laser beams whose frequency difference equals the LO frequency (before multiplication in the Front-End) are injected in one single fibre that brings the signal from the technical building to the antenna. At the antenna the two beams are combined in a photomixer and the resulting electrical signal, whose frequency is the difference of the incoming beams frequency, is fed into the Front-End receiver.

The laser synthesizer is based on an extremely stable master laser to which a second laser, the slave, is phase locked with a frequency difference (the actual LO frequency) that is set by a tuneable microwave generator.

The tight requirements in terms of operating frequency and sensitivity of the photomixer are met by a custom device designed and produced at Rutherford Appleton Laboratory (UK), where a modified commercial photodiode has been integrated in a special package (Figure 5) providing fibre optic connection, bias connection, filtering and output waveguide.

Since the propagation time along the fibre affects the phase of the LO signal, to reduce the phase variations, the changes in length of the fibre must be kept as small as possible. In the LO system the fibre length variations are limited by both passive means and active control. The active control is based on an interferometric subsystem which measures the round trip length and acts on fibre stretching actuators to compensate for the length variations. The length of the link combined with the light speed in the fibre sets the bandwidth of the line length corrector which is constrained to about 1 kHz. Therefore, only disturbances (including acoustic ones) well below this frequency and of limited amplitude can effectively be compensated, the others must be kept low by passive means. Passive means include thermal-stable installation of the fibre, thermal insulation, and mechanical insulation. In order to keep the cost of the system affordable utilisation of special fibres (like low temperature coefficient) was not considered.

The complete LO system has been tested in the lab (with the proper length of fibre) and is currently undergoing field tests at the Alma Test Facility (at the VLA Observatory, in New Mexico).

The fibre system

As mentioned above, the antennas will be connected to the technical building through a network of optical fibre cables. Each antenna will be reached by eight single-mode optical fibres, allocated as follows:
- one fibre for the Data Transmission System (the data resulting from observation)
- one fibre for the Photonics Local Oscillator reference signal
- two fibres for the monitoring and control signals (Ethernet network)
- four spare fibres

There will be approximately 200 possible locations (antenna pads) among which the antennas will be relocated. The fibres from each one of the antenna pads are connected at the technical building to a central patch panel (with up to 270 antenna connections, see Figure 2). Here, the through connections from the optical equipment at the antennas to the optical equipment in the technical building will be made. The maximum and minimum distances between antenna pads and technical building will be 15 km and 500 m respectively. The relatively long maximum distance calls for low attenuation and reduced amount of splices along the links and the topology of the network must be optimised in these respects. In addition, the design shall take into account the extreme sensitivity of the Local Oscillator to both temperature variations and vibrations. This sets tight requirements on the layout of the system where good thermal and mechanical insulation must be achieved. For this purpose the cable will be directly buried underground, including the fibre splices. This solution provides high thermal and mechanical insulation. In order to fully exploit the insulation characteristics of the soil, no ducts or other protections that could allow air flow around the cable are foreseen (with some possible exceptions at road crossings). Therefore, the cable needs to be suitable for direct burial. Similarly, the cable joints will be directly buried and the fibre splices as well as the terminations at the station vault will be properly protected against the environment by suitable enclosures.

Unlike the Local Oscillator and the Data Transmission System, the links carrying the monitor and control signals from all pads will be permanently connected to the equipment and the switching to the active pads will be performed automatically, not requiring a manual patching. Although currently under investigation, a similar automatic connection does not seem feasible for the LO and DTS links because of the tighter requirements and higher costs.

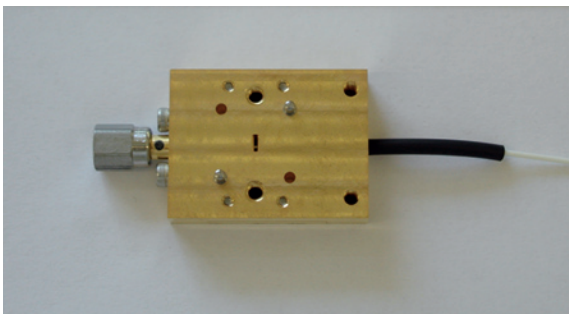

Figure 5: The photomixer is a tiny but fundamental component of the ALMA photonics LO. It converts the two icoming (through the fibre on the left side of the picture) light beams into an electrical signal whose frequency is the difference of the frequencies of the light beams. Pushing the performance close to the theoretical limit, Rutherford Appleton Laboratory managed to enclose a photodiode into a 'photomixer block' capable of delivering up to 1 mW at frequencies as high as 140 GHz.

Fibre splicing at 5000 m

Experience from the APEX project, which also operates at Llano de Chajnantor, suggests that the harsh operating environment (dust, strong wind, extreme temperatures and low air density) might prevent any contractor from reliably meeting the 0.15 dB splice loss (at the sea level) assumed as a standard in the industry and as a baseline for the optical budgets used in ALMA. As a matter of fact, no splicing equipment existed that was rated for that altitude.

For the LO link specifically, the quality of the splice is important because the Photonic LO signal is limited in terms of launch power by Brillouin backscattering (because of the extremely narrow line width) and in terms of received power because of the low saturation power of the photomixers. Poor splices may also result in other polarisation effects which may affect the LO signal phase.

In order to provide the technical teams involved in the project with a realistic expectation of the yield and quality of splices attainable at the Chajnantor site and to identify the most suitable splicing equipment, a splicing trial activity has been carried out at the site. The outcome of the splice trial showed that it is possible to make excellent splices at 5000 m and that the two industrial splicing machines tested on site are suitable for the fibre optic installation work once they are properly adjusted. It is confirmed that, provided that cleanliness precautions are taken during installation, the 'sea-level' splice loss can be adopted also for the ALMA site.

Acknowledgements

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The Irregular Galaxy NGC 1427A. Based on *U*, *V* and *H*-alpha observations with FORS1 obtained in service mode for Andreas Reisenegger and his colleagues in November 2002 and January 2003. North is on the left and West is up. Henri Boffin (ESO) did the final processing of the image. See ESO Press Photo 27c/06 for more details.