ALMA Receivers Invading Chile

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The ALMA Project has moved into the production phase, perhaps most notably for the advanced receiver systems, or Front Ends that are required by the project. This article provides a summary of the technical and production status of the various Front End subassemblies and some of their recent deliveries. The fist complete Front End has been delivered by the European Front End Integration Centre to the ALMA Observatory in Chile.

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organisation for Astronomical Research in the Southern Hemisphere (ESO), in North America by the US National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA. The recent status and progress of the project was reported by Haupt & Rykaczewski (2007).

Since the previous article in 2004 dedicated to the ALMA receivers and published in this magazine (Tan et al., 2004), major progress has been made. In the past five years the baseline design has been largely completed, a pre-production phase of crucial Front End subassemblies has been successfully achieved and the project has now embarked on the final production run of receiver systems. The other noteworthy news is that the scope of this essential ALMA subproject has been substantially expanded with the entrance of Japan into the ALMA Project. This important event has allowed a further expansion of the Front Ends by the addition of another three receiver cartridges for Bands 4 (125–169 GHz), 8 (38–500 GHz) and 10 (787–950 GHz) in addition to the four baseline receiver bands. Funding has also been made available by the European Commission under the 6th Framework Programme for the development and pre-production (six units) of Band 5 (163–211 GHz) receivers as part of the project for the Enhancement of ALMA Early Science. The design and construction of the cold cartridges, including superconductor insulator semiconductor (SIS) mixers and intermediate frequency (IF) amplifiers, has been undertaken by Chalmers University in Gothenburg, Sweden. The matching local oscillator needed for this heterodyne receiver is being designed and built by the Rutherford Appleton Laboratory in the UK. Programme and system management of this activity is undertaken by the Front End Integrated Product Team (FE IPT) within the ALMA Division at ESO.

ALMA receiver status

The performance goals initially set by the project for the ALMA receivers were considered as challenging and at the very edge of what had so far been demonstrated (Tan et al., 2004). Over the past few years all groups involved in the development and construction of these receivers have worked very hard and demonstrated that it is possible to achieve this performance. It is also very rewarding to note that, for example, a key performance parameter like receiver temperature, a fundamental measure of the sensitivity of the receiver, is maintained over a broad frequency range and is repeatable from one receiver system to another (Barkhof et al., 2009), as shown in Figure 1. Table 1 provides a summary of the ALMA receiver bands, including achieved sensitivity performance (values in parentheses) where available.

Table 1 also shows that work is ongoing on four additional frequency bands as well as to the four baseline bands — Bands 3, 6, 7 and 9 — with which the bilateral project started. NAOJ took responsibility for Bands 4, 8 and the most recently approved in 2008, Band 10. The European Community has funded the development and preproduction of six units for the Band 5 receivers. More recently, informal discussions between various institutes in the ALMA partner regions have started on a collaboration for the development and production of the ALMA Band 1 receivers.

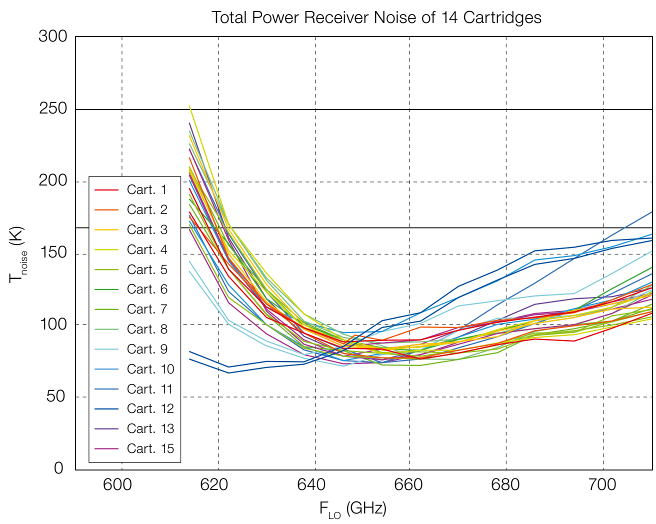

Figure 1. Receiver noise performance as a function of frequency as measured on 14 different Band 9 cartridges. The two blue curves deviating from the other curves, for Cartridge#12, are due to the use of a different type of SIS junction.

ALMA Band	Frequency Range	Receiver noise temperature		Mixing scheme	Supplier
		T_{rx} over 80% of the RF band	T_{rx} at any RF frequency		
1	31.3–45 GHz	17 K	28 K	USB	Not assigned
2	67–90 GHz	30 K	50 K	LSB	Not assigned
3	84–116 GHz	37 K (40K)	62 K (50K)	2SB	Hertzberg Institute of Astrophysics
4	125–169 GHz	51 K (45K)	85 K (55K)	2SB	National Astronomy Observatory of Japan
5	163–211 GHz	65 K	108 K	2SB	Onsala Space Observatory**
6	211–275 GHz	83 K (40K)	138 K (60K)	2SB	National Radio Astronomy Observatory
7	275–373 GHz*	147 K (75K)	221 K (100K)	2SB	Institut de Radio Astronomie Millimétrique
8	385–500 GHz	196 K (160K)	294 K (270K)	2SB	National Astronomy Observatory of Japan
9	602–720 GHz	175 K (120K)	263 K (150K)	DSB	Netherlands Research School for Astronomy (NOVA)
10	787–950 GHz	230 K	345 K	DSB	National Astronomy Observatory of Japan

* Between 370 – 373 GHz T_{rx} is less than 300 K
** Limited to 6 units, funded by the EC under FP6

Table 1. ALMA frequency bands and associated noise performance requirements. The values within brackets indicate actual measured performance. In column 5, USB = Upper Sideband, LSB = Lower Sideband, 2SB = Sideband separating and DSB = Double Sideband.

For all of the four baseline receiver cartridges, the design, after successfully passing a Critical Design Review (CDR), went into preproduction phase, and eight units have been completed. The final production phase of these baseline receivers has started and covers the production and delivery of another 65 units to equip the whole ALMA array and provides sufficient spare units (Jackson et al., 2009b).

Amplitude Calibration Device

One of the important science requirements for the ALMA instrument is that it should be able to measure the strength of the incoming astronomical signal accurately. The objective is to achieve an accuracy of better than 3% below 300 GHz and better than 5% above this frequency. In order to enable this high precision in power measurements each antenna, including all ACA antennas, will be equipped with a so-called Amplitude Calibration Device (ACD). This ACD consists of two loads, both blackbody radiators, which have different accurately known physical and radiometric temperatures, and which are used as a power reference (see Murk et al., 2008). One load is at an ambient temperature of about 293 K, while the other is actively kept at a well-stabilised temperature of between approximately 343 K and 353 K. By inserting the loads in front of one of the receiver inputs, the amplitude scale of each receiver can be calibrated. The loads are moved by a robotic arm in front of one of the ten receiver inputs (see Figure 2).

In addition to these calibration loads, the ACD can carry two so-called “widgets”. One of these widgets is a solar filter enabling observations of the Sun. This is basically a broadband attenuator, operating across the 30 to 950 GHz range, which reduces the radio frequency (RF) signal from the Sun, which has a brightness temperature of approximately 6000 K, to a lower level that does not saturate the sensitive ALMA receivers. The other widget consists of an optional Quarter Wave Plate (QWP), optimised for operation in Band 7 (275–373 GHz). This device converts an incoming circularly polarised signal into a linearly polarised signal very accurately. The QWP might be required to enhance high fidelity observations of polarised sources. The ACD concept using the robotic arm was conceived by Matt Carter from the Institut de Radio Astronomie Millimétrique (IRAM) in Grenoble. The actual design has been done through a collaboration between ESO, IRAM, the Institute of Applied Physics (IAP) at the University of Bern, STFC/RAL in the UK and NTE SA near Barcelona.

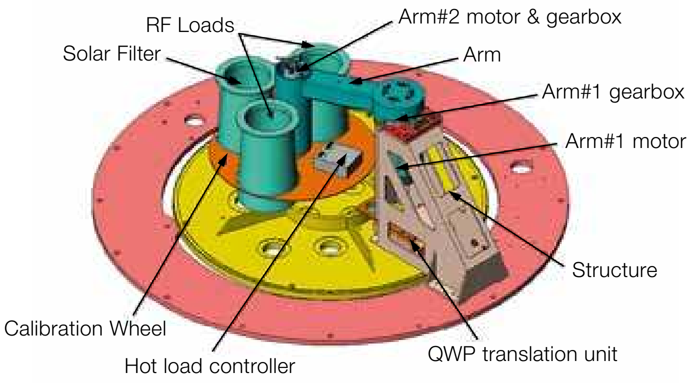

Figure 2. CAD overview drawing of the Amplitude Calibration Device.

In 2008 the development activities led to the completion of two prototype ACDs. In August 2008 the first prototype ACD, #1, successfully passed the Test Readiness Review and Preliminary Acceptance In-house (PAI) at ESO Garching. Subsequently the unit was shipped to the Operations Support Facility (OSF) in Chile where it passed the Provisional Acceptance on-Site (PAS) in mid-September 2008. A support team from the ALMA Division at ESO travelled to the OSF to assist the local Assembly, Integration and

Figure 3. ACD#1 during installation in the antenna receiver cabin.

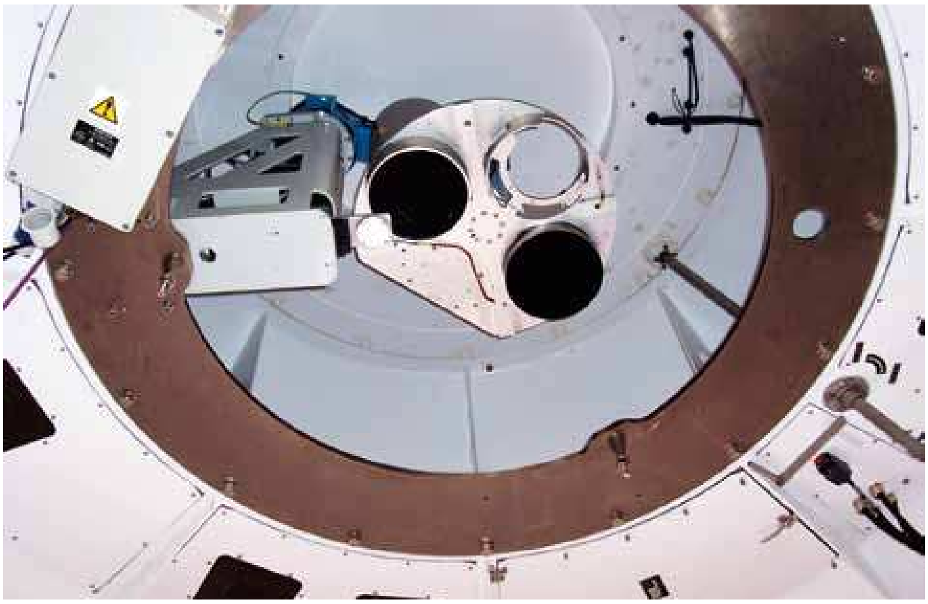

Figure 4. ACD#1 installed in a MELCO antenna.

Verification (AIV) team with these activities, as well as for the first installation of the ALMA calibration device into a 12-metre antenna, manufactured by Mitsubishi Electrical Company (MELCO), on 29 September 2008. Figure 3 shows the ACD mounted on an *xy*-translation stage during installation in the receiver cabin. The installation equipment was designed by the ESO team, who also provided the procedure for a safe and smooth installation. Figure 4 shows ACD#1 after installation in the MELCO antenna. The calibration device itself is installed on top of an annular ring, the Front End Support Structure (FESS), which acts as the mechanical interface between the antenna and the Front End subassemblies. Below the FESS, a box containing the control and power electronics for the ACD is mounted.

The second prototype, ACD#2, passed PAI in November 2008 and was shipped to the OSF. ESO assisted the AIV team with the PAS in February 2009. The calibration device was installed in a Vertex 12-metre antenna shortly afterwards. Following the successful delivery of these two prototype ACDs a preproduction run of five units, still using loads based on an interim design, has started. ACD#3 and #4 passed PAI on 8 April 2009. Figure 5 shows ACD#3, with the calibration wheel and interim calibration loads, during PAI testing in the ESO ALMA Laboratory. Final production of the robotic arms was contracted to NTE AS in Spain. These will be initially integrated into complete ACDs by the ALMA Division at ESO. Development of the final load design, meeting all the demanding technical requirements, is still underway at ESO with support from IAP, University of Bern and industry, and is scheduled to be completed by summer 2009.

European Front End Integration Centre

The ALMA European Front End Integration Centre (EU FEIC) is located at the Rutherford Appleton Laboratory within the Space Science and Technology Department (SSTD). The Centre is nearing completion of its Phase 1 infrastructure preparation and much of the receiver assembly and test equipment is in place, and a key item — the receiver tilt-table (Figure 6) — was recently installed and commissioned. The

Figure 5. ACD#3 during PAI testing in the ESO ALMA laboratory.

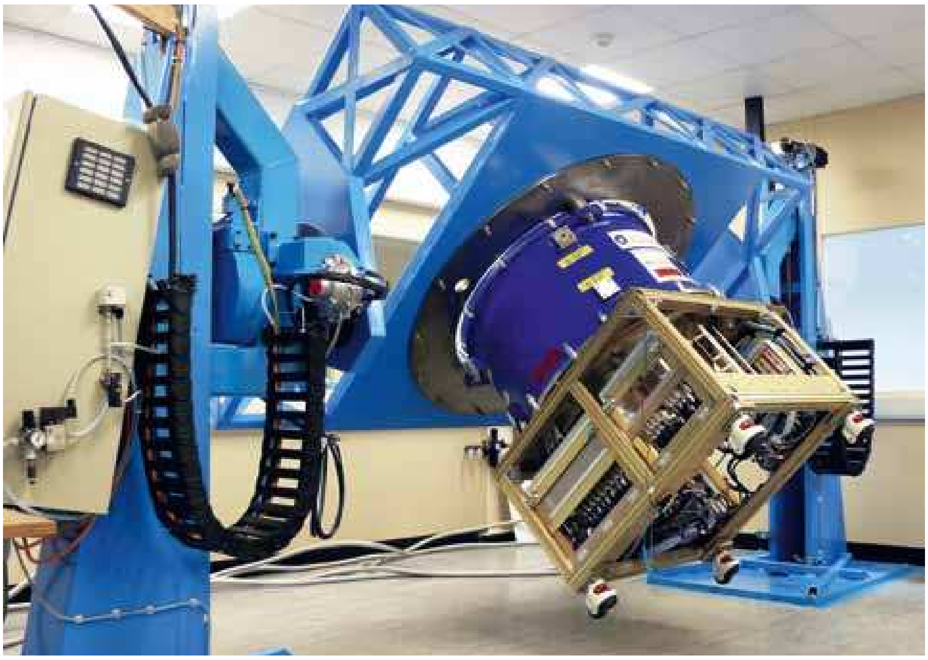

Figure 6. Receiver tilt-table installed at the European Front End Integration Centre. The table emulates an ALMA antenna interface.

remaining test infrastructure, particularly the critical millimetre and submillimetre wave beam scanner, is at an advanced stage of development and the EU FEIC is able to perform essential tests on receiver Front Ends that demonstrate receiver functionality and operation. By the end of 2009, the EU FEIC will be completely ready for the full integration and verification of ALMA Front Ends when the Operational Readiness Review (ORR) will be held. This ORR is a formal validation by the ALMA Project that a Front End Integration Centre meets the requirements to perform its tasks as defined by the project. At this ORR, not only a technical evaluation of the test equipment and integration tools will be made, but also much attention will be paid to aspects related to product assurance, to assure that the integration and verification activities are performed in a consistent and controlled manner. This ORR is held for all three ALMA FEICs and ensures that the Front Ends delivered, irrespective where they have been integrated and verified, are built in an identical way and fulfil the same project requirements.

In fact, the state of readiness is such that the European ALMA Executive recommended to the Joint ALMA Office management that the first European integrated Front End, as a partially qualified engineering model, should be shipped to the project in spring 2009 — some six months earlier than originally anticipated for a first fully qualified Front End. The ALMA management accepted this recommendation and plans were initiated at ESO and RAL to bring forward the delivery schedule. Technical and administrative teams at RAL and ESO — and with the support of groups within the ESO member states, especially the Band 7 and 9 cartridge groups from IRAM and the Netherlands Research School for Astronomy (NOVA), North America and East Asia — worked hard to provide appropriate subassemblies, perform integration, and complete testing, all in the required timescale. The fully assembled and verified receiver system, a first for an FEIC, was duly dispatched from RAL in March 2009 and successfully completed its journey to the OSF in Chile, where it arrived on 2 April (Figure 7). Since then it has successfully undergone PAS verification, performed by a joint team from the ALMA Observatory, ESO, NOVA, NRAO and RAL (see Figure 8) and currently preparations for deployment on one of the ALMA antennas are underway.

The delivery of this receiver represents a major milestone, not only for the European element of ALMA, but also the ALMA observatory itself, as once the receiver is installed on a telescope then interferometry becomes possible. In addition, a pioneering step was taken with regard to the methodology of shipping that demonstrated the feasibility of safe delivery of a single fully integrated system to Chile — this improves the efficiency of delivery and substantially eases the test and installation process at the observatory. This success was also appreciated by the

Figure 7. Arrival of the first ALMA Front End from the European Front End Integration Centre at the temporary assembly integration and verification laboratory at the ALMA Operations Support Facility.

Joint ALMA Observatory, which now would also like to apply this shipment method to the other two FEICs in East Asia and North America.

Water Vapour Radiometer

Another important milestone for the ALMA Project has recently been achieved with the delivery and successful provisional acceptance of the project's first Water Vapour Radiometer (WVR) system at the OSF. When fully commissioned, the WVR will provide near real-time measurements of the brightness temperature of the atmosphere at the Array Operations Site (AOS). These data will enable subsequent delay correction of the astronomical signal received by each antenna that is impaired by the continually fluctuating water vapour conditions present within the Earth's atmosphere (Nikolic et al., 2008). This delay correction procedure is important in achieving the overall performance specification for obtaining high dynamic range maps with the ALMA system. Each 12-metre diameter ALMA antenna, including the four so-called total power antennas within the ALMA Compact Array (ACA), will therefore be provided with its own dedicated WVR, operating as a passive receiver system at submillimetre frequencies, to monitor the sky temperature along each antenna's boresight. The smaller 7-metre diameter antennas within the ACA are grouped closely together, within a circle of diameter less than 300 m, and are thus less affected by the water vapour variations in the atmosphere above the site. For this reason these 7-metre antennas are not equipped with WVRs.

The WVR has been designed to an exacting and demanding technical specification that necessarily takes into account the harsh climatic and environmental conditions that exist at an altitude above 5000 m. The WVR has also been designed to operate continuously for extended periods in the field without routine maintenance. The design of the WVRs is based on an uncooled heterodyne receiver and incorporates precision quasi-optical mirror assemblies and RF components designed for operation at a centre frequency of 183 GHz, where one of the water emission lines is located. This RF signal is subsequently down-converted and filtered into four IF frequency bands from 0.5–8 GHz and the atmospheric water vapour content can be determined by comparing the power level in the four IF channels to each other. The WVR system design is based on a "Dicke-switched" radiometer configuration that includes a rotating chopper wheel subsystem and also features two highly accurate and thermally regulated blackbody internal calibration loads. The WVR system also includes sophisticated thermal management electronics, precision mechanical components and embedded monitoring and control software, all packaged and contained within a relatively lightweight and compact structure. Each WVR is then integrated and mounted into the antenna cabin alongside other ALMA subsystems.

Figure 8. The first ALMA Front End from the European Front End Integration Centre undergoing Provisional Acceptance on-Site verification with a subgroup of the international team supporting the delivery.

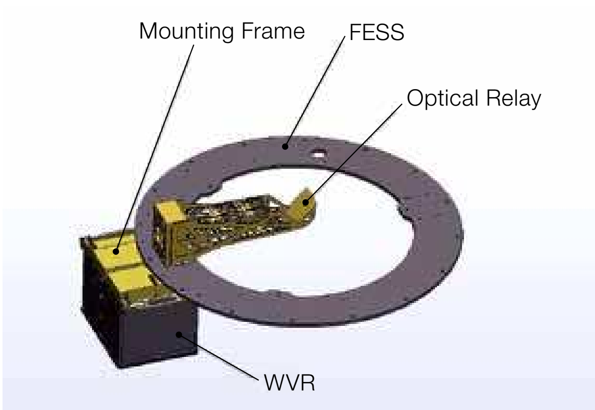

Figure 9. CAD overview drawing of the 183 GHz water vapour radiometer.

The first production water vapour radiometer was delivered to the OSF on the 1 April 2009 and underwent a successful on-site provisional acceptance test. This period of testing was followed by an initial installation check and sky-temperature test with the WVR integrated into a Vertex 12-metre antenna. This testing was accomplished smoothly and successfully, which bodes extremely well for future integration testing and operations at the AOS.

The WVR is a complex, multidisciplinary project that has been system-designed and developed by Omnisys Instruments AB based in Goteborg, Sweden. Omnisys AB has given serious attention to developing a receiver that can be effectively manufactured for series production and optimised for efficient operational use. This latter aim is achieved by avoiding the use of any cryogenic components, since the cooling system would need regular maintenance. It is easy to handle by maintenance staff because of the low mass and small size. See Emrich et al. (2008, 2009) for a description of the system. Omnisys AB has also provided personnel and extensive technical support to the WVR acceptance trial, carried out with close liaison and interaction between the ALMA AIV team, ESO Front End and science IPT personnel.

The WVR work package is managed and has been procured for ALMA by the ESO FE IPT of the ALMA Division in Garching and complements a range of Front End systems being procured and provided to the ALMA Project.

Successful delivery and acceptance of the first WVR is a fitting tribute to the dedication and work of all the personnel involved in this project, including staff and personnel from Omnisys AB, ESO and ALMA, as well as other supporting teams and organisations.

Acknowledgements

We would like to thank all our collaborators spread around many organisations within the three ALMA partner regions for supporting the work described in this article.

Figure 10. First production water vapour radiometer being unpacked after arrival at the ALMA Operations Support Facility.

Figure 11. First production water vapour radiometer mounted inside an ALMA antenna.

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