The ALMA Front Ends; an Overview

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***Abstract*— The Atacama Large Millimeter / submillimeter Array will be an astronomical facility operating in the millimetre and sub-millimetre range (31 GHz – 950 GHz) currently under construction on a plateau in the Chilean Andes. The array will consist of at least 66 Cassegrain type reflector antennas, total collecting area nearly 6000 m^2, operating as a synthesis aperture interferometer. This article provides an overview of the receiver system design, including key performance parameters, project organization, and current project status.**

I. Introduction

The Atacama Large Millimeter / submillimeter Array (ALMA) is a new radio observatory operating in the millimetre and sub-millimetre wavelength range currently under construction. The realization of this novel facility of unprecedented size is only possible by a well concerted collaboration between the existing leading institutes in this field and industry from countries within the three regions, Europe, East Asia and North America, represented in this global partnership. This collaboration is also well demonstrated in the development and construction of receivers needed for ALMA. More than ten organizations, mostly R&D or academic institutions, united in the ALMA Front End Integrated Project Team (FE IPT) are undertaking this activity. The FE IPT faces the challenge to develop and produce the largest number so far of identical sub-millimetre receivers in the world. The performance of these receivers will set new standards in this wavelength range. In addition special care in design and production of these receivers has to be given to manufacturability and reliability.

II. Atacama Large Millimeter Array

This section provides background information on the organization of the ALMA Project and a description of the complete instrument.

A. An International Endeavour

The Atacama Large Millimeter / submillimeter Array (ALMA), an international astronomy facility, is a partnership between Europe, East Asia and North America 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 Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

B. System Configuration and Site

ALMA will be a single instrument composed of 1) a main

Fig. 1: A panoramic view of the 5000-meter high Llano de Chajnantor in the Atacama Desert of northern Chile

array of 50 high-precision Cassegrain antennas, each having a diameter of 12 m, operating in exclusively in interferometer mode and 2) a closely packed array (called ALMA Compact Array - ACA) consisting of 12 Cassegrain antennas, each having a diameter of 7 m, operating in interferometric mode and four Cassegrain antennas, each having a diameter of 12 m, operating in so called single dish total power mode. The instrument is located in the II Region of Chile, in the District of San Pedro de Atacama, at the Chajnantor altiplano, more than 5000 metres above sea level (Fig. 1).

ALMA's primary function will be to observe and image with unprecedented clarity the enigmatic cold regions of the Universe, which are optically dark, yet shine brightly in the millimetre portion of the electromagnetic spectrum.

TABLE I

ALMA KEY SYSTEM PARAMETERS

Telescope principle	Aperture synthesis (interferometers) complemented by 4 total power antennas
Number of Antennas	54 Cassegrain antennas of 12-meter diameter 12 Cassegrain antennas of 7-meter diameter
Number of baselines	1225 main array 66 ALMA Compact Array
Number of configurations	Continuous with maximum baselines from 150 to 14000 meters
Number of antenna stations	Approx. 220, antennas transportable between them
Site	Chajnantor, Northern Chile, 5000-meter altitude
Frequency coverage	31 - 950 GHz, except atmospheric absorption regions
Receiver complement	One cryogenically cooled unit accommodating 10 frequency band cartridges (7 installed initially) plus water vapour radiometer operating at 183 GHz
Signal transport	In digital format over optical fibres
Correlator	Reconfigurable digital correlator with 12 configurations and 1024 spectral channels
Software	Control and data handling, data pipeline, image production, remote control and remote observation
Operation	Service observing with Operations Centre near San Pedro de Atacama, 30 km from site at 2500-3000 -meter altitude

The array of antennas will be reconfigurable, giving ALMA a zoom-lens capability. The highest resolution images will come from the most extended configuration, and lower resolution images of high surface brightness sensitivity will be provided by a compact configuration in which all antennas are placed close to each other. The instrument thus combines the imaging clarity of detail provided by a large interferometric array together with the brightness sensitivity of a large single dish. The large number of antennas in the main array provides over 1200 independent interferometer baselines, making possible excellent imaging quality with “snapshot” observations of very high fidelity. The antennas in the ACA complete the main array in terms of wide field imaging. The receivers will cover the atmospheric windows at wavelengths from 0.3 to 10 millimetres.

ALMA will be a millimetre / sub-millimetre counterpart of the optical Very Large Telescope (VLT) and Hubble Space Telescope, with similar angular resolution and sensitivity but unhindered by dust opacity. It will be the largest ground-based astronomy project after the VLT/VLTI, and, together with the Next Generation Space Telescope (NGST), one of the two major new facilities for world astronomy coming into operation at the end of this decade.

III. RECEIVER SUB-SYSTEM

The ALMA receivers are located, at the interface to the antenna secondary focal plane, inside the receiver cabin at each antenna. ALMA will observe over the frequency region from approximately 31 GHz to 950 GHz. For technical reasons this frequency coverage has been split into 10 separate bands as is shown in Table II. There will be two identical receiver channels for each band, enabling observation of the full polarization state of the received radiation, in order to maximize the system’s sensitivity, and to allow polarization-sensitive observations to be performed. Fig. 2 provides a simplified block diagram of the front end and analogue back end electronic sub-systems mounted in each antenna

ALMA will observe in only one band at any given time. In the baseline construction project, only the seven frequency ranges of highest scientific priority, designated Bands 3, 4, 6, 7, 8, 9, and 10, will be fully implemented. Band 5 is being designed and six units will be built with additional funding by the European Commission under the 6th Framework Program.

C. RF Device Technologies

In the frequency ranges covered by ALMA, current technology provides direct amplification of the received radiation only in the lowest two bands, where a few radio astronomy groups have developed state of the art HEMT amplifiers. The remainder of the receivers will use SIS (superconductor-insulator-superconductor) junctions, either Niobium or Niobium-Titanium-Nitrate based, to convert the received signal to an intermediate frequency (IF) in the range of 4 to 12 GHz, where it can be readily amplified.

A great challenge for ALMA is to obtain proper control of the SIS junction fabrication processes needed to reach satisfactory performance that will also be reliable and suitable for series fabrication.

D. Heterodyne Local Oscillator Concept

The local oscillators used in these heterodyne receivers are fully electronically tuneable, no mechanical tuners are used as was common with existing technology so far. Each local oscillator uses a phase locked YIG tuned oscillator operating in the frequency range of approximately 14... 20 GHz and is multiplied using active, room temperature, multipliers and passive, varistor type, cooled multipliers for the final frequency multiplication stage. Cooling of these passive

TABLE VIII
ALMA FRONT END KEY SPECIFICATIONS

ALMA Band	Frequency Range	Receiver noise temperature		Mixing scheme	Receiver technology	Responsible organization	Country
		T_{Rx} over 80% of the RF band	T_{Rx} at any frequency				
1	31.3 – 45 GHz	17 K	28 K	USB	HEMT	Not assigned	-
2	67 – 90 GHz	30 K	50 K	LSB	HEMT	Not assigned	-
3	84 – 116 GHz	37 K	62 K	2SB	SIS	Herzberg Institute of Astronomy (HIA)	Canada
4	125 – 169 GHz	51 K	85 K	2SB	SIS	National Astronomy Observatory of Japan (NAOJ)	Japan
5	163 - 211 GHz	65 K	108 K	2SB	SIS	Chalmers University (6 units)	Sweden
6	211 – 275 GHz	83 K	138 K	2SB	SIS	National Radio Astronomy Observatory (NRAO)	USA
7	275 – 373 GHz	147 K	221 K	2SB	SIS	Institut de Radioastronomie Millimétrique (IRAM)	France
8	385 – 500 GHz	196	294 K	2SB	SIS	National Astronomy Observatory of Japan (NAOJ)	Japan
9	602 – 720 GHz	175 K	263 K	DSB	SIS	Netherlands Research School For Astronomy (NOVA)	Netherlands
10	787 – 950 GHz	230 K	345 K	DSB	SIS	National Astronomy Observatory of Japan (NAOJ)	Japan

multipliers improves the conversion efficiency compared to room temperature operation.

Highly phase stable reference signals are provided to each antenna over fibre optical cable. The optical carrier provides various microwave signals that are used in phase locking the local oscillator. Fine tuning of frequency and phase of the local oscillator signal is feasible due to the use of a direct digital synthesizer (DDS). Phase switching, both 90° and 180° as is commonly used in interferometers to suppress internal interfering signals, is implemented through this DDS.

E. Modular Cryogenic Receiver Concept

The complete front end unit will have a diameter of 1 m, be about 1-m high and have a mass of about 750 kg. Fig. 3 and Fig. 4 show respectively top and bottom side views of the front end assembly. The cryostat will be cooled down to approximately 4 Kelvin by a 3-stage commercial closed-cycle cryo-cooler based on the Gifford – McMahon cooling cycle. The individual frequency bands are implemented in the form of modular cartridges that will be inserted in a large common cryostat. This cartridge concept allows for a great flexibility in construction and operation of the array. Fig. 5 shows an example of such a receiver cartridge. Another advantage of the cartridge layout with well-defined interfaces is the fact that different cartridges can be developed and built by different groups within the ALMA Project with a large degree of independence but without the risk of incompatibility between them.

F. 183 GHz Water Vapour Radiometer

Because interferometric observations at (sub-)millimetre wavelengths are extremely sensitive to changes in the amount of water vapour in the earth's atmosphere, causing a variation in electrical path length, every 12-m antenna will be equipped with a water vapour radiometer (WVR), which is essentially a separate, dedicated receiver tuned to the frequency of a water vapour absorption line at about 183 GHz. The WVR will be an uncooled receiver and will take atmospheric data continuously, while the astronomical observations at other frequencies are underway. The WVR will enable these observations to be corrected for the influence of water vapour in the lines of sight between each antenna and the observed source.

G. Amplitude Calibration Device

ALMA has exceptionally challenging requirements for the accurate measurement of power flux. The objective is to obtain an accuracy of better than 1% below 300 GHz and less than 3 % for higher frequencies. For achieving this

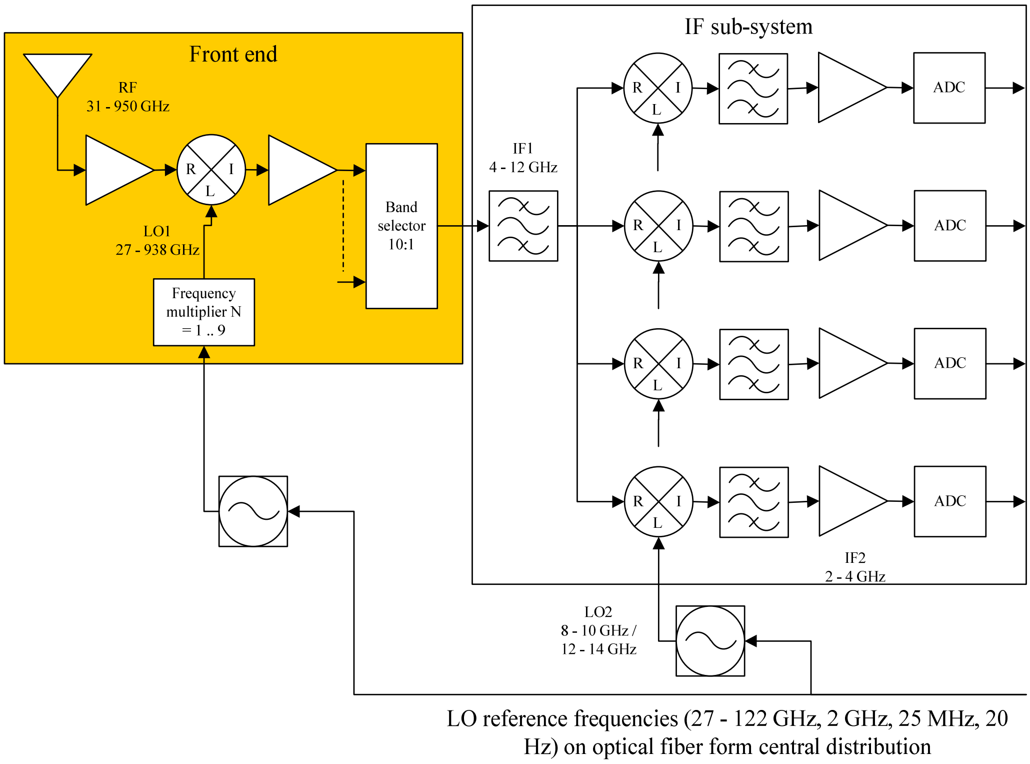

Fig. 2: Simplified antenna based block diagram of front end (orange highlighted) and analogue back end electronics

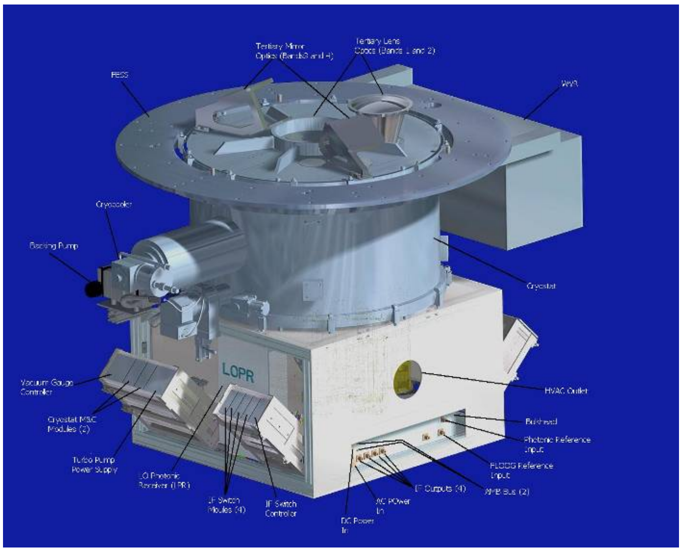

Fig. 3: Top – side view of Front End Assembly

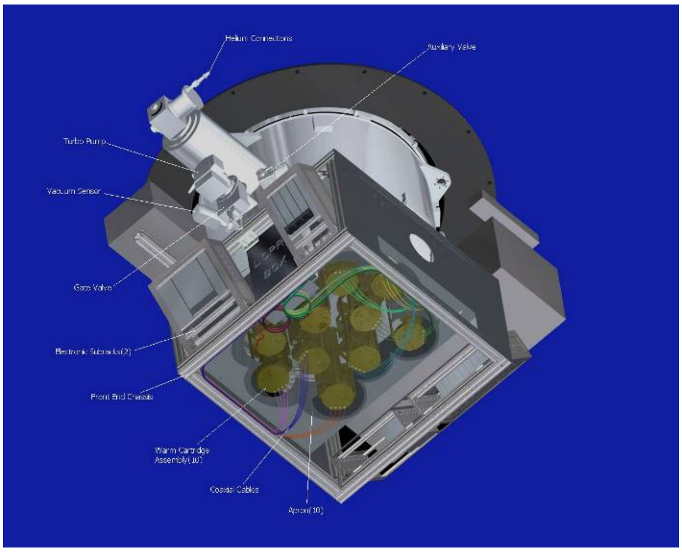

Fig. 4: Bottom – side view of Front End Assembly

requirement each receiver channel inside an ALMA Front End can be calibrated against a well characterised hot load, having a temperature in the range of 340 – 360 K, (only Bands 3 – 10) and a precision ambient load, having a temperature of approximately 295 K. Fig. 6 shows a CAD drawing of the Amplitude Calibration Device (ACD).

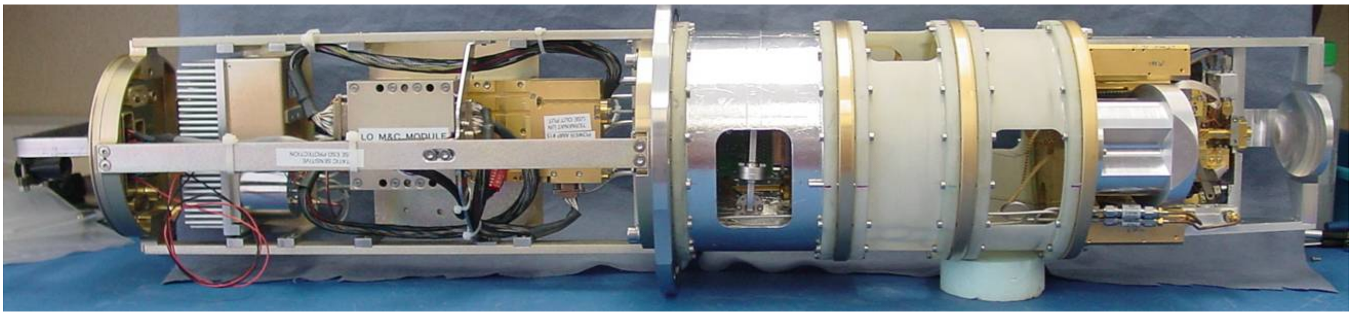

Fig. 5: Example of a, Band 6, receiver cartridge. The larger diameter metal plate in the middle is the boundary between cooled receiver electronics inside the cryostat (right hand side) and the room temperature electronics (left hand side).

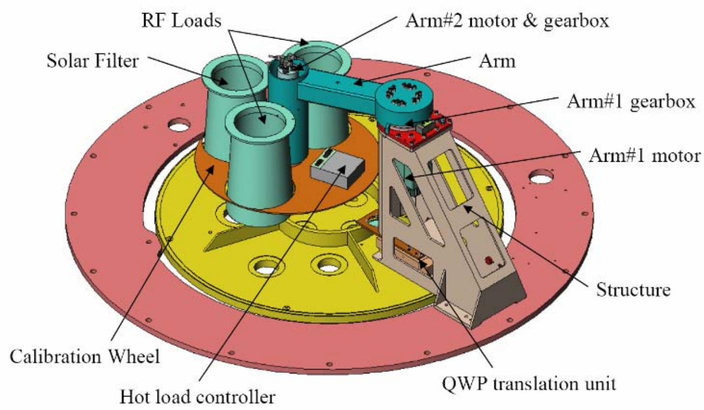

Fig. 6: CAD drawing of the Amplitude Calibration Device (top – side view)

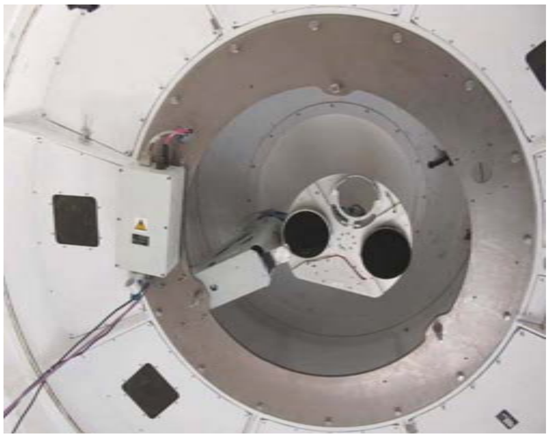

Fig. 7: Amplitude Calibration Device mounted in antenna (bottom view)

The ACD is mounted on the Front End Support Structure (FESS) a circuar, metal ring providing the interface between Front End Assembly and antenna structure. The ACD consists of a robotic arm which moves the calibration loads in front of one of the ten receiver windows. In addition to the calibration loads it carries a so called solar filter. This solar filter acts as an attenuator for the RF signal and reduces the IR heat load when observing the sun. The ACD has the option for installing a Quarter Wave Plate (QWP) in front of the Band 7 receiver. The QWP provides an enhanced accuracy for polarization measurements. Fig. 7 is a picture showing the actual ACD mounted in one of the ALMA antennas. The, black, calibration loads are clearly visible while the solar filter is not mounted.

IV. Organization

A. Integrated Project Team

More than ten different organizations, both academic institutes and industry scattered among three continents, play a key role in the design and production of the ALMA receivers. Each of these organizations has several, in general commercial, sub-contractors involved for production work. Fig. 10 provides an overview where the various organizations contributing to the ALMA front ends are located. Each of these organizations has the responsibility for delivering front end sub-assemblies. All these entities are organized in a so called Integrated Product Team (IPT) which carries the overall responsibility of providing front ends to the ALMA Observatory in Chile. The IPT management is formed by a two-headed team located at ESO in Garching bei München, Germany, and the NRAO in Charlottesville / Virginia, U.S.A. The FE IPT management is supported by system engineers and project schedulers.

B. Front End Integration Centres

Integration and final verification before delivery to Chile of all ALMA Front Ends is a major activity and three Front End Integration Centres (FEIC) have been established for this work. This is both a technical as well as a logistical challenge as one can conclude from the simplified ALMA Front End integration flow diagram shown in Fig. 8

The FEICs are located at different locations across three continents:

- Chung Shan Institute of Science and Technology / Aeronautical Systems Research Division in Tai-Chung, Taiwan
- National Radio Astronomy Observatory in Charlottesville / Virginia, U.S.A.
- Rutherford Appleton Laboratory near Didcot, United Kingdom

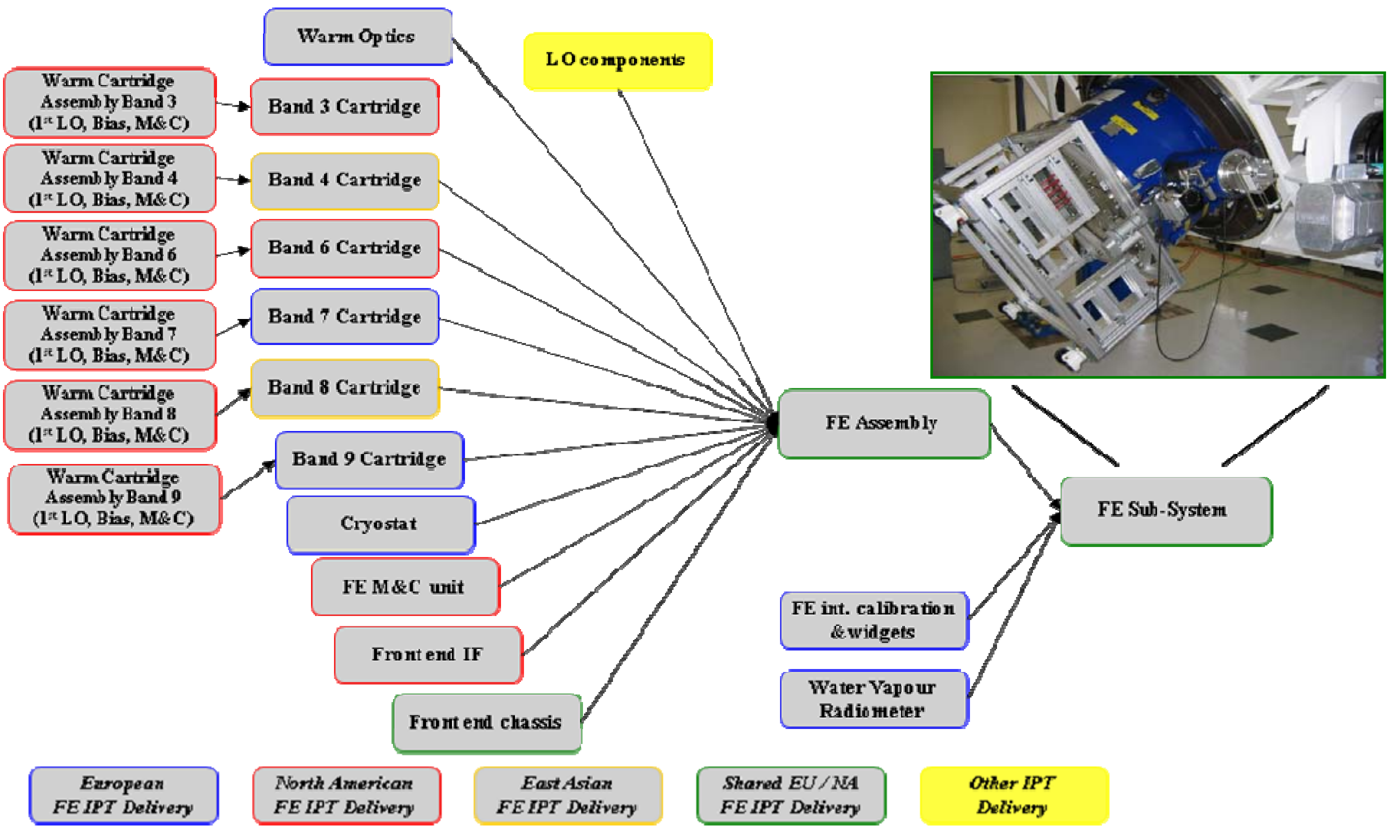

Fig. 8: Simplified integration flow of the ALMA Front End Sub-System

Operation of the FEICs is well synchronized to guarantee that the products, Front End Assemblies, delivered by each of the FEICs are identical in configuration and performance. All three FEICs work according to the same Front End Assembly technical specifications and verification procedures. Test equipment used at the different FEICs might vary but the performance of test sets used in verification of front ends meet identical minimum requirements.

C. *Acceptance Process*

Given the complexity of the integration process of ALMA Front Ends a clearly defined and rigorous acceptance process has been established to guarantee product quality. Fig. 9 provides a schematic model of the primary steps in accepting and delivering components to a FEIC and to the ALMA Observatory in Chile. Each step is clearly documented and agreed with the stake holders involved.

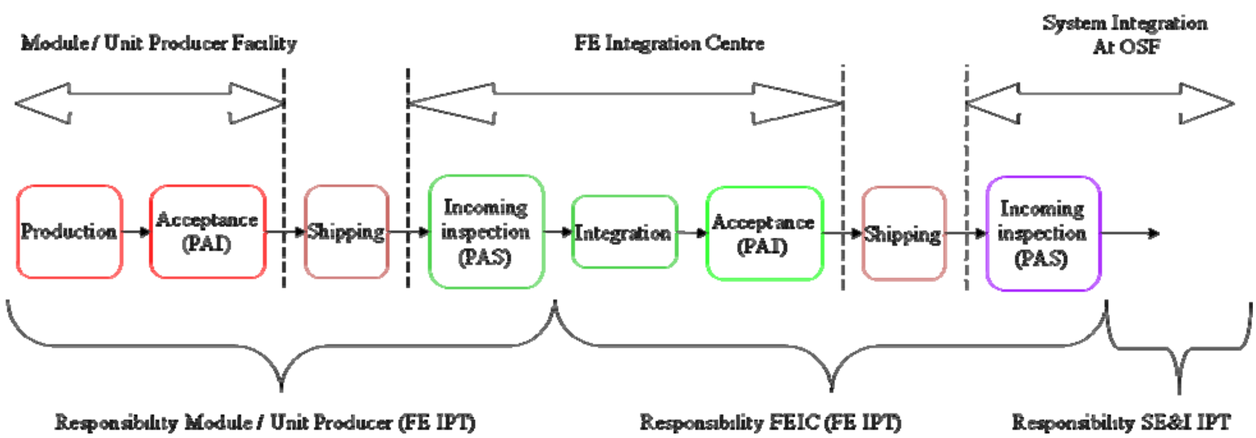

Fig. 9: Delivery and Acceptance model to / from Front End Integration Centres

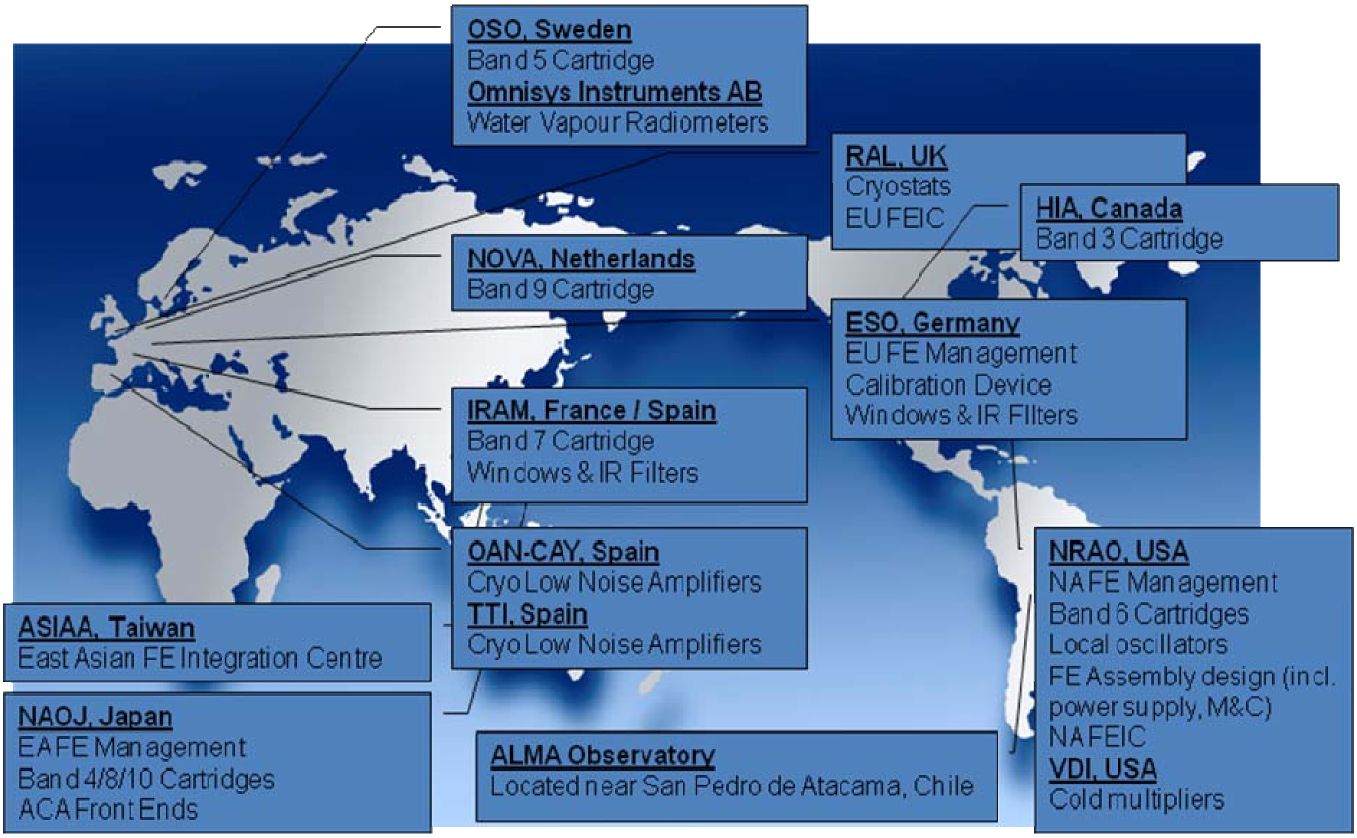

Fig. 10: Overview and location of key organizations contributing to the ALMA front ends.

CONCLUSIONS

This article summarizes the technical concept and requirements of the ALMA receivers. Organizational aspects how this project is organized, involving partners on three different continents, for development and production are presented as well.

ACKNOWLEDGMENT

The work reported in this article is the result of efforts made by many individuals both inside the ALMA Project as well as from other organizations. The author expresses his great appreciation to all who make this exceptional project reality.

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