The European Receivers for ALMA

To a large extent the scientific capabilities of the Atacama Large Millimeter Array (ALMA) will depend on the receivers mounted on each of the 64 antennas. In the last year, substantial progress has been made in the design of these receivers and currently a transition towards production is underway. Two out of the four initial baseline frequency bands funded under the bi-lateral project between Europe and North America are a European responsibility. This European contribution will be for the shortest wavelength ALMA Bands designated 7 and 9, covering the frequency ranges 275 GHz to 373 GHz and 602 GHz to 720 GHz.

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The Atacama Large Millimeter Array (ALMA) is an international astronomy facility. ALMA is an equal partnership between Europe and North America, in cooperation with the Republic of Chile, and is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC), and in Europe by the European Southern Observatory (ESO) and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), and on behalf of Europe by ESO.

ALMA will be a single instrument composed of 64 high-precision antennas located in the II Region of Chile, in the District of San Pedro de Atacama, at the Chajnantor altiplano, 5,000 metres above sea level. 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.

ALMA will initially be equipped with four out of the total of ten possible frequency bands. The two highest baseline frequency bands, making ALMA a true sub-millimeter instrument, are a European responsibility. These sub-millimeter receiver bands make full use of the high altitude location of the ALMA instrument where the disturbing influence of the atmosphere is minimal. The exceptional receiver performance at Bands 7 and 9 in terms of sensitivity are a prime justification for locating the ALMA instrument at this high altitude.

The ALMA Band 7 receiver cartridge, covering the frequency range 275 GHz to 373 GHz, is developed and produced by Institut de Radio Astronomie Millimétrique (IRAM) in France, while the Band 9 receiver cartridge, covering the frequency range 620 GHz to 702 GHz, is developed and produced by a Dutch consortium led by the Nederlandse Onderzoeksschool voor Astronomie (NOVA).

ALMA 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

Table 1: ALMA frequency bands and associated noise performance.

ALMA Band	Frequency Range	Receiver noise temperature: T_{Rx} over 80% of the RF band	Receiver noise temperature: T_{Rx} at any RF frequency	Receiver technology
1	31.3 – 45 GHz	17 K	28 K	HEMT
2	67 – 90 GHz	30 K	50 K	HEMT
3	84 – 116 GHz	37 K	62 K	SIS
4	125 – 169 GHz	51 K	85 K	SIS
5	163 – 211 GHz	65 K	108 K	SIS
6	211 – 275 GHz	83 K	138 K	SIS
7	275 – 373 GHz*	147 K	221 K	SIS
8	385 – 500 GHz	98 K	147 K	SIS
9	602 – 720 GHz	175 K	263 K	SIS
10	787 – 950 GHz	230 K	345 K	SIS

* - between 370 – 373 GHz T_{rx} is less then 300 K

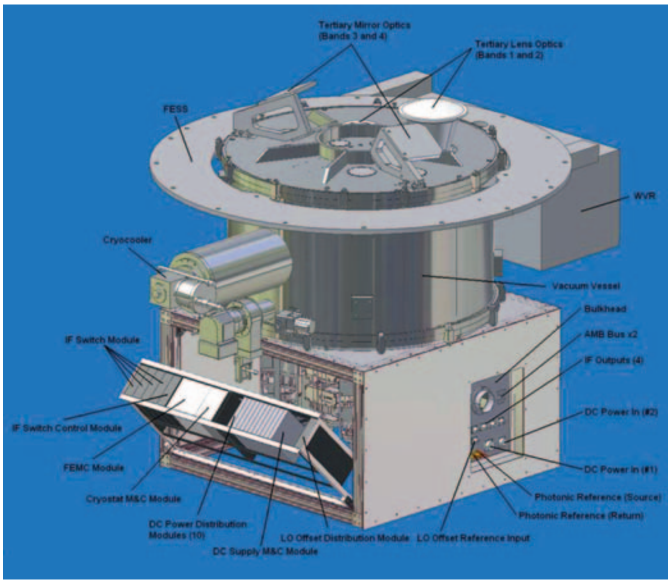


Figure 1: Top side view of the ALMA front end assembly.

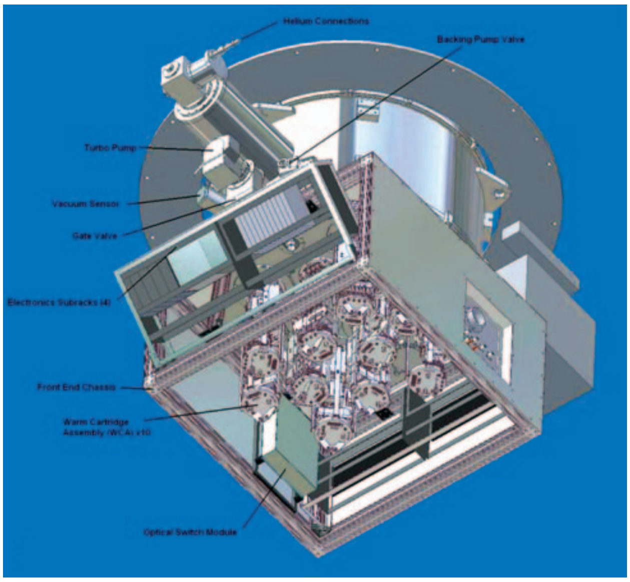


Figure 2: Bottom side view of the ALMA front end assembly.

region from approximately 30 GHz to 950 GHz. For technical reasons this frequency coverage has been split into 10 bands that are shown in Table 1. There will be two identical receiver channels for each band, observing 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.

ALMA will observe in only one band at any given time. In the baseline construction project, only the four frequency ranges of highest scientific priority, designated Bands 3, 6, 7, and 9, will be implemented.

At the extremely high frequencies of 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 front-ends will use SIS (superconductor-insulator-superconductor) junctions, either Niobium or Niobium-Titanium-Nitrogen based, to mix 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 good control of the processes needed to reach good performance that will also be reliable and suitable for series fabrication.

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. Figures 1 and 2 show respectively top and bottom side views of the front end assembly. The cryostat will be cooled down to 4 Kelvin by a closed-cycle cryo-cooler driven by a compressor. The individual frequency bands will be made in the form of cartridges that will be inserted in a large common cryostat. The cartridge concept allows for great flexibility in operation of the array. Another advantage of the cartridge layout with well-defined interfaces is the fact that different cartridges can be developed and built by different groups among the ALMA participants without the risk of incompatibility between them.

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 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.

Programmatic overview

The early project development, including the design and development Phase 1, is summarized in a previous *Messenger* article (Kurz et al., 2002).

The 10-year construction phase of the project (Phase 2) began in 2002 with approval by the ESO Council on behalf of its 10 member states, and the National Science Board in the U.S. The ESO/NSF Bilateral Agreement was signed in February 2003. Spain participates in Phase 2 of ALMA through an ESO-Spain Agreement signed in January 2003. The total estimated cost for Phase 2 of the bilateral project is 552.5 million (year 2000 US$), to be shared equally between Europe and North America.

After approval of ALMA Phase 2 by the ESO Council, a Call for Tender for development and prototyping, including the Band 7 and 9 cartridges, was issued by ESO in August 2002. At the request of the Joint ALMA Office the original development proposals were amended to include a pre-production run of 8 units. The aim of this approach was to gain more experience with series production early on in the project and expedite the transition from development to series production. Contracts with both IRAM and NOVA for the development and a pre-production series were placed covering a contract period running from the start of 2003 until early 2006.

Spread out over the first half of 2004 individual Preliminary Design Reviews were held for all four ALMA cartridges, including Bands 7 and 9. Currently both groups are working towards the production and delivery of the pre-production cartridges. Delivery of the first pre-production units is imminent and scheduled for early 2005, well in time to be integrated with the rest of the front end assembly at the ALMA front end integration centres.

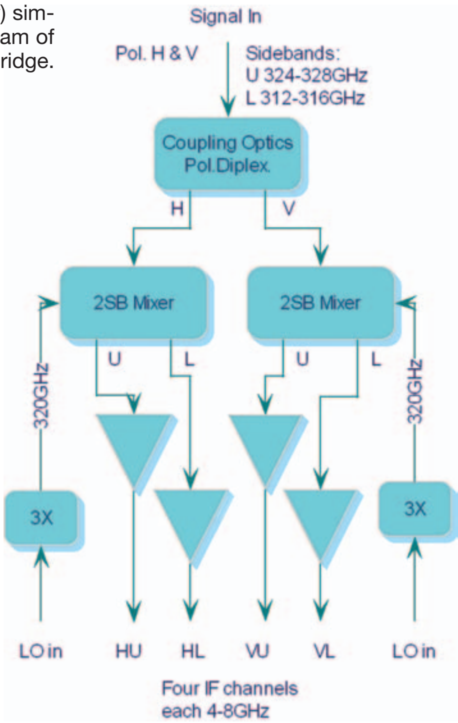
Critical Design Reviews (CDR) for both cartridge bands are planned shortly after the delivery of these first pre-production units. The CDR will formally conclude the design phase of these cartridges and release the production design. Delivery of the remaining seven pre-production units of the Band 7 and 9 cartridges is distributed over 2005 and early 2006.

Starting in 2005, preparations will also be made by ESO leading to contracts for series production. This series production contract covers the delivery of the remaining 56 units to equip all 64 ALMA antennas with these unique receiver cartridges.

ALMA Band 7 cartridge

Band 7 of ALMA covers the signal frequency (RF) range 275 GHz to 373 GHz. Briefly

Figure 3: A (very) simplified block diagram of the Band 7 cartridge.



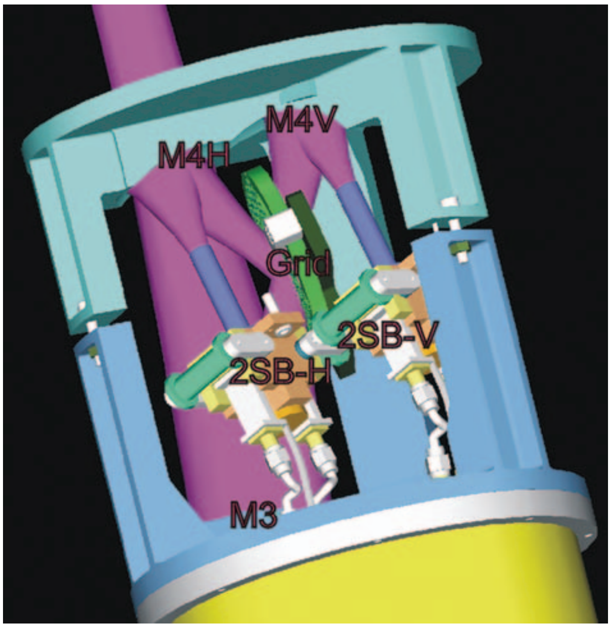


Figure 4: CAD rendering of the cold optics. The purple object is the incoming signal beam, undergoing two refocusing reflections on offset elliptical mirrors, and a polarization separation realized by the grid. The central support piece has been removed for clarity.

stated, the role of the Band 7 cartridge is to accept the cosmic signal that has been collected by the antenna and concentrated at its Cassegrain focus, transpose that signal to a lower frequency range (intermediate frequency, IF), and, after suitable amplification, deliver the IF to the rest of the signal processing chain.

A short tour of the block diagram (Fig. 3). *Optics*: The optics of the cartridge couples the f/D=8 beam supplied by the telescope to the two mixers. The optics comprises a first offset elliptical mirror M3, then a wire grid that separates the two linear polarizations (the grid acts as a near-perfect mirror when the E-field is parallel to the conducting wires, and is virtually transparent to the orthogonal polarization). Each of the two orthogonally polarized beams is refocused by twin elliptical mirrors M4H and M4V onto the apertures of the horns of the two mixers (see also Fig. 4 and Fig. 5).

Long wavelength optics: For millimetre and sub-millimetre systems, where λ is typically three orders of magnitude larger than in the optical domain, while the systems themselves are of comparable dimensions, ray optics is not a valid starting point for design. In fact, the mirrors of the Band 7 cartridge are always in the close vicinity of the beam's focal point. Instead Gaussian beam optics (originally developed in the 60's for laser beams) is the basic design tool.

Sideband separating (2SB) mixers: Their function is to convert a slice of the RF band to a fixed IF band: 4 – 8 GHz. This is done by making the RF signal beat with the local oscillator (LO) in a non-linear element: the SIS junction, a sandwich of an insulating layer of Aluminium oxide only a few molecular layers thick between two layers of superconducting Niobium. Such a device combines the two desirable properties of having a non-linear I-V characteristic on a scale of order one mV, well matched to the energy of the incoming photons, and of performing the down conversion with very low noise. The SIS junction operates at a temperature of 4K. The SIS junctions for the Band 7 mixers, together with superconducting impedance matching circuits, are fabricated by IRAM's SIS Group (see Fig. 6). For an "ordinary" (DSB) mixer, operating at an LO frequency of, say, 320 GHz, there are two RF frequencies that produce the same beat frequency, say 6 GHz, in the IF band, one in the upper side band, at 326 GHz, and the other in the lower side band, at 314 GHz. A sideband-separating mixer provides two separate IF outputs, each one carrying the conversion product from just one of the two RF side bands. This is accomplished by splitting the input signal, with appropriate phase shifts, before feeding two identical DSB mixers, and recombining their IF signals with again appropriate phase shifts. This is detailed in Fig. 7 and its caption.

IF amplification: Four low-noise amplifiers (one for each combination of polarization and sideband) amplify the outputs of the 2SB mixers by approximately 35 dB. These amplifiers are supplied within the ALMA project by Centro Astronomico de Yebes in Spain. Outside the vacuum enclosure, the IF signal is further amplified by another 35 dB by room-temperature amplifiers.

LO system: The local oscillator signal is tuneable in the range 283 – 365GHz. This is obtained from a microwave oscillator operating in the range from 15,7 GHz to 20,3 GHz, followed by a chain of solid-state frequency multipliers and amplifiers; the final stage, a tripler, is located within the cryogenic enclosure and operates at 80K. The LO system is supplied within the ALMA project by the National Radio Astronomy Observatory in the U.S.

All the cryogenically cooled components are mounted in/on and cooled by a cylindrical structure (the so-called blank cartridge), supplied within the ALMA project by our colleagues of Rutherford Appleton Laboratory in the UK.

Several design challenges had to be met in the design and prototyping of the Band 7 cartridge. The first one is common to all SIS mixers: due to the capacitance of the S-I-S sandwich (typically 80fF), the junction's impedance is highly reactive, while it must be matched to the real source impedance over the RF band; Band 7 has the largest relative bandwidth (f_{max}/f_{min} = 1.356) of all ALMA bands implemented with SIS mixers. Another major challenge is the actual fabrication of the junctions. The junction area must be within 10% of its nominal value of 1 μm^2, corresponding to linear tolerances of 0.05 µm. This is made possible by electron beam lithography. As already stated, the thickness of the insulating layer of the junction is only a few molecular layers, and is especially critical because of the exponential dependence of the junction's resistance on its thickness. The pair of DSB mixers that enter the fabrication of the sideband separating (2SB) mixers must be well matched in amplitude and phase to maintain the properties of the 2SB scheme. The optical assembly must be aligned with the telescope optics, without any adjustment, requiring tight fabrication tolerances; this has led to the fabrication of the optical assembly (see

Figure 5: Photo of the cold optics assembly, with the two 2SB mixers.

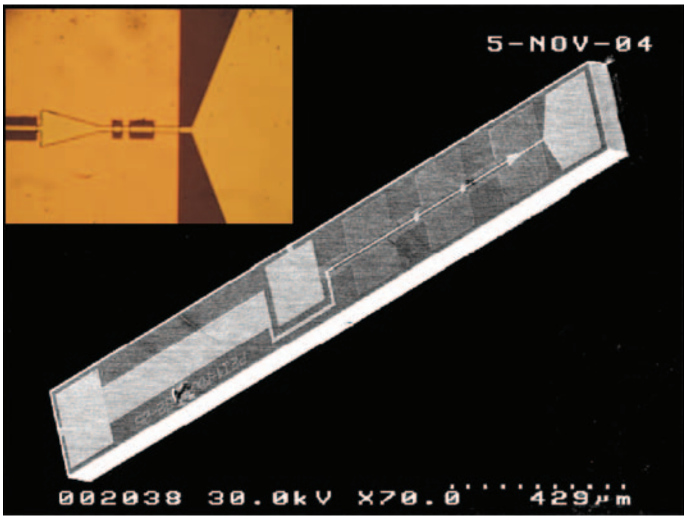


Figure 6: A SEM picture of the Band 7 SIS junction with RF tuning circuits.

Fig. 4, 5) by machining from just three metal blocks, with suitable heat treatment for stabilization.

Results achieved with one of the 2SB mixers produced so far are shown on Fig. 8. Similar results are obtained when the mixer is integrated in the cartridge. As can be seen, the noise specifications that were set at the outset of the project several years ago (and had never been realized at that time) are met or exceeded.

ALMA Band 9 cartridge

The ALMA Band 9 cartridges are state-of-the-art heterodyne receivers that cover the 602 GHz to 720 GHz atmospheric window with a unique combination of high sensitivity and a broad instantaneous bandwidth (8 GHz per side-band of this double side-band receiver). The Band 9 receivers are the highest-frequency receivers in the baseline plan of the joint European – North American ALMA project. As such, the observatory's maximum spatial resolution will be obtained with these receivers (as the maximum spatial resolution scales with the ratio of the telescope separation to the operating wavelength). Furthermore, when combined with lower-frequency observations, the higher temperature scales that high-frequency molecular line observations probe will be important to allow the observatory to probe warm, dense gas close to protostars and galactic nuclei. Similarly, continuum observations are needed over a wide frequency range in order to fully characterize the emission of dust, especially for nearby sources, whose emission spectra peak in the 60–200 µm range.

Critical components in the Band 9 cartridge

In order to achieve the desired combination of high sensitivity, full 602 GHz to 720 GHz frequency coverage, and a broad instantaneous bandwidth, state-of-the-art technologies are needed in three areas: the mixers which form the "eyes" of the receiver, the local oscillator that "pumps" the mixers at the operating frequency, and the cryogenic "intermediate frequency" (IF) amplifier chains that are needed to amplify the mixer's weak output signal before it leaves the cryostat.

The superconductor-insulator-superconductor (SIS) mixers used in the ALMA Band 9 cartridge (the "eyes" of the system) are the product of a 15-year collaboration between the National Institute for Space Research (in Dutch: Stichting Ruimteonderzoek in Nederland (SRON)) and the SIS junction group at Delft University of Technology (formerly at the University of Groningen). In particular, the Band 9 mixers are descendents of the design of 600-700 GHz mixers that were developed by SRON and the University of Groningen for use at the James Clerk Maxwell Telescope, in Hawaii (Baryshev et al., 2001). More recently, advances in mixer design and SIS junction fabrication have yielded substantial improvements in mixer performance, such that the ALMA project's sensitivity requirement (T_{rx} = 175 K across 80% of the band) can now be met, as is seen in Figure 9. Figure 10 includes pictures of the Band 9 mixer, including its two critical mechanical components – a corrugated horn antenna (from Radiometer Physics GmbH, in Germany) and a waveguide device mount (produced by a local company using high-precision machining techniques). Note that

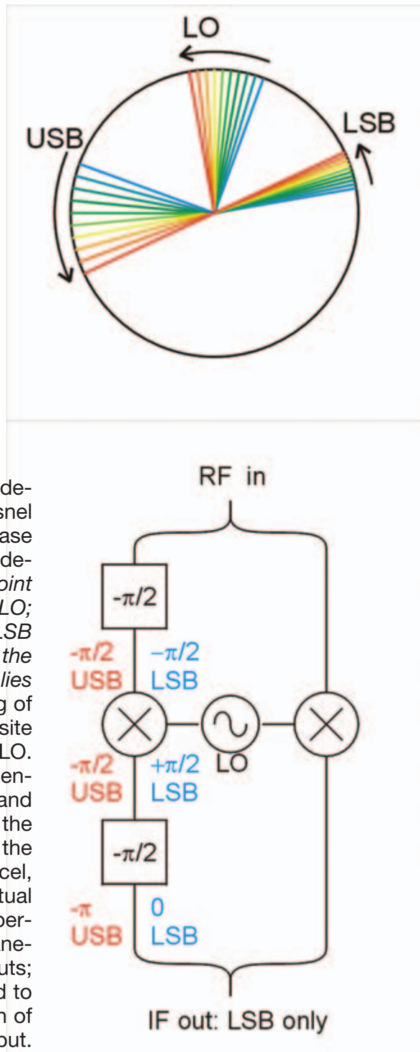


Figure 7: A pictorial explanation of the sideband separation mechanism. Top: a Fresnel diagram illustrating the frequency and phase relationships between the two signal sidebands and the LO frequency. *The key point is that the LSB is lagging behind the LO; therefore, a phase lag applied to the LSB increases the phase difference between the LO and the LSB, while the converse applies to the USB.* Bottom: The same phase lag of π/2 applied to the RF results in opposite phase offsets after mixing with the LO. Another phase lag, applied at the IF frequency, results in zero net phase for the LSB, and in a phase lag of π for the USB. When the left-hand signal path is combined with the right-hand path, the USB signals cancel, while the LSB signals add up. In the actual mixer, two different summations are performed at the output, providing simultaneously the USB and LSB on separate outputs; the diagram shown has been simplified to focus the explanation on the production of the LSB output.

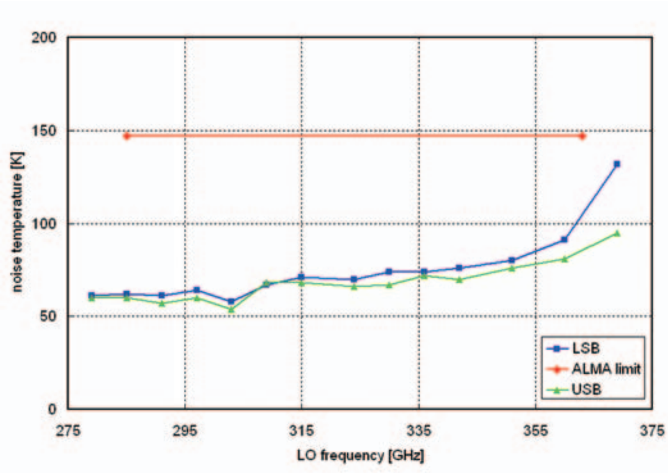


Figure 8: Results achieved with one of the first 2SB mixer assemblies produced. Note: the horizontal scale applies to the LO frequency; therefore, the RF signal range extends an extra 8 GHz on either side. The red line is the ALMA specification for receiver noise.

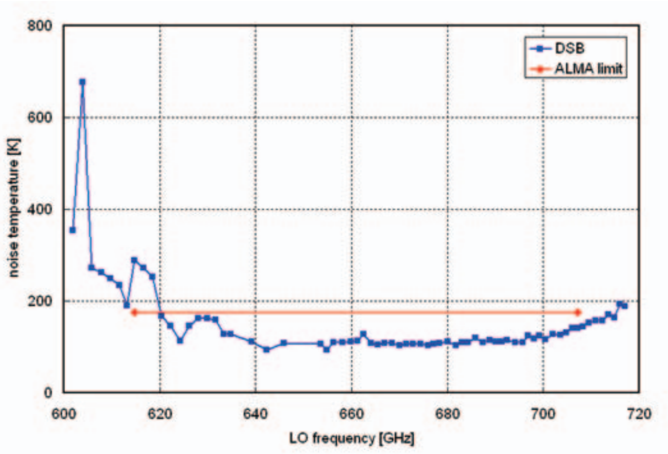


Figure 9: 600 GHz – 720 GHz SIS mixer noise performance.

the relatively short wavelength of 650 GHz radiation (~ 0,5 mm) results in these components having critical dimensions of ~100 µm, which requires machining tolerances of ~ 5 µm.

The local oscillators and IF amplifiers in the Band 9 cartridge are being developed and produced by partners in the ALMA project. In particular, the local oscillator (LO) chains are being developed at the National Radio Astronomy Observatory (NRAO), based upon state-of-the-art millimetre-wave power amplifiers from NRAO and solid-state frequency multipliers (from Virginia Diodes, Inc., in the United States). The low-noise 4 – 12 GHz cryogenic amplifiers that are being used in the Band 9 cartridge are being developed by the Centro Astronomico de Yebes, in Spain (Lopez-Fernandez et al. 2001).

On top of the need for these unique development items, the development of the Band 9 cartridge has been further complicated by the ALMA project's unique need to produce, operate, and maintain 64 state-of-the-art cartridges for each frequency band. This has required eliminating moving parts (such as the mechanical tuners that have traditionally been used in solid-state local oscillator chains and SIS mixers) to improve the system's reliability, and simplifying the manufacturing and assembly of the cartridge to as great an extent as possible (including taking advantage of commercial manufacturing capabilities where possible).

4K Optics Assembly Design and Development

A key element of this "design for manufacturing" has been in the design of the cooled (down to 4 Kelvin) optical assembly that will combine the astronomical signal from the telescope with the local oscillator signals (two) and focus the combined beam into the cartridge's two mixers. Beyond the "usual" requirements for low optical coupling losses and high image quality, the design of this system has been further complicated by the limited volume available (the cartridge is only 17 cm in diameter), and the need to manufacture and assemble 64 of these assemblies at the rate of one per month, or faster. This has pushed the development of a design in which no alignment is needed (or possible). Instead, high-precision CNC machining is used to machine four of the system's five mirrors into a single metal block (in a single machining step, to ensure that they are correctly aligned with respect to each other). The fifth mirror is then machined into a second part and the absolute accuracy of a well-controlled CNC machine is used to ensure that the two mirror blocks can be assembled with sufficient accuracy that the desired optical alignment and imaging quality is achieved by machining tolerances alone. This "alignment-by-machining-accuracy" philosophy is also applied to the mounting of two LO-combining beam splitters and a polarization-splitting grid in the space between the two mirror blocks.

Preliminary verification of this design principle was provided by manufacturing and testing a two-mirror prototype of the 4 K mirror assembly (Baryshev et al., 2004), while recent measurements of the first full 4K optical assembly have provided further design verification. Figure 11 shows a picture of the first 4 K optical assembly. In addition to the two mirror blocks, the polarization-splitting grid and the LO combining beam splitters can also be seen, together with absorbing beam-dumps that are used to absorb stray light in the system.

Cartridge Design and Development Overview

The assembly of the first complete Band 9 cartridge has started, and Figure 12 shows pictures of the integrated 4K opto-mechanical structure mounted on a prototype of the cartridge body.

Figure 12 shows a cut-out view of the cryogenic portion of the cartridge design (with the fibre-glass cylinders that separate the cartridge's four temperature stages removed from the left-hand image to allow the internal components to be seen). The warm local oscillator (a high-power millimetre-wave source) and the cartridge's bias electronics will be mounted in a structure that bolts to the outside of the 300 K stage of this assembly (this structure is not seen in this figure). Inside the cartridge, waveguides run from the 300 K plate to the 90 K temperature level to feed the high-power millimetre-wave LO signal (at 100 – 120 GHz) to a cryogenic frequency multiplier on the 90 K stage that produces the 614 – 708 GHz LO power that is needed to pump the SIS mixers. The local oscillator power produced by the multiplier is coupled via an optical beam to the optics assembly on the cartridge's 4 K stage. Within this optical assembly, the LO beam is optically combined with the signal beam from the telescope and the combination is then focussed into the SIS mixer's horn-antenna. The 4 – 12 GHz IF output from the mixer passes through a 4 – 12 GHz isolator (from Passive Microwave Technologies) before being amplified in a low-noise amplifier that is mounted on the bottom side of the 4K stage. The IF signal is then coupled out of the cartridge and further amplified in room-temperature amplifiers that are located in the mechanical assembly that also contains the warm LO components and bias electronics.

The assembly of the first complete Band 9 cartridge has started with the integration of the 4 K opto-mechanical structure on a prototype of the cartridge body to allow a first cool down of the optics assembly. Further integration of the cartridge is now proceeding, including the other temperature levels and the inter-stage wiring harness is now proceeding. In parallel with this cartridge manufacturing and assembly effort, the

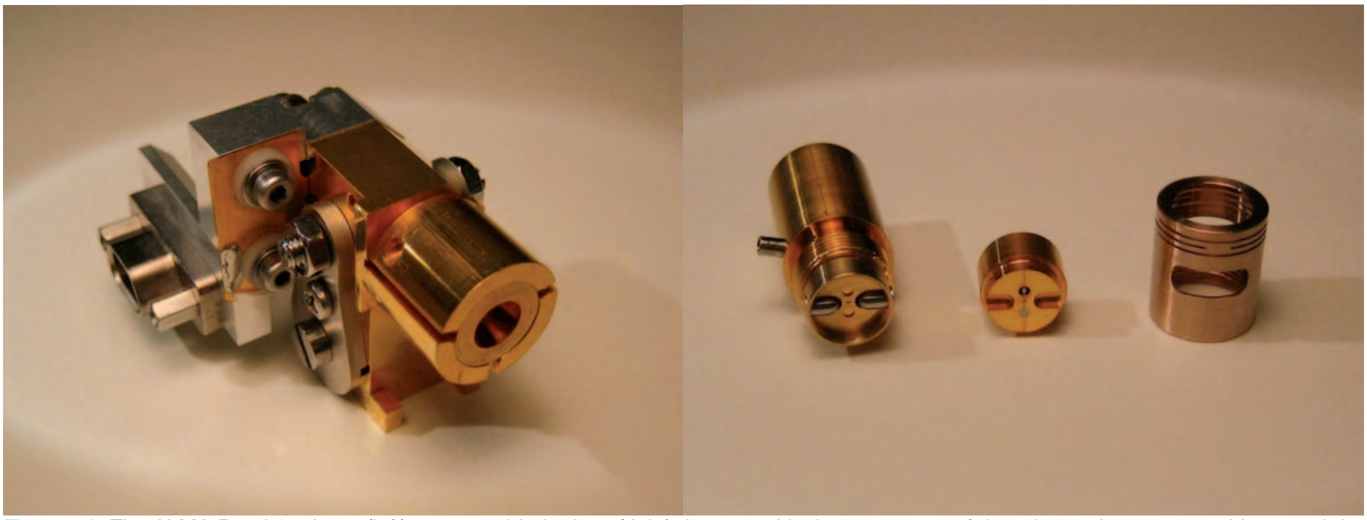


Figure 10: The ALMA Band 9 mixer: (left) an assembled mixer, (right) the two critical components of the mixer – the corrugated horn and the waveguide device mount in which the SIS mixer chip is mounted.

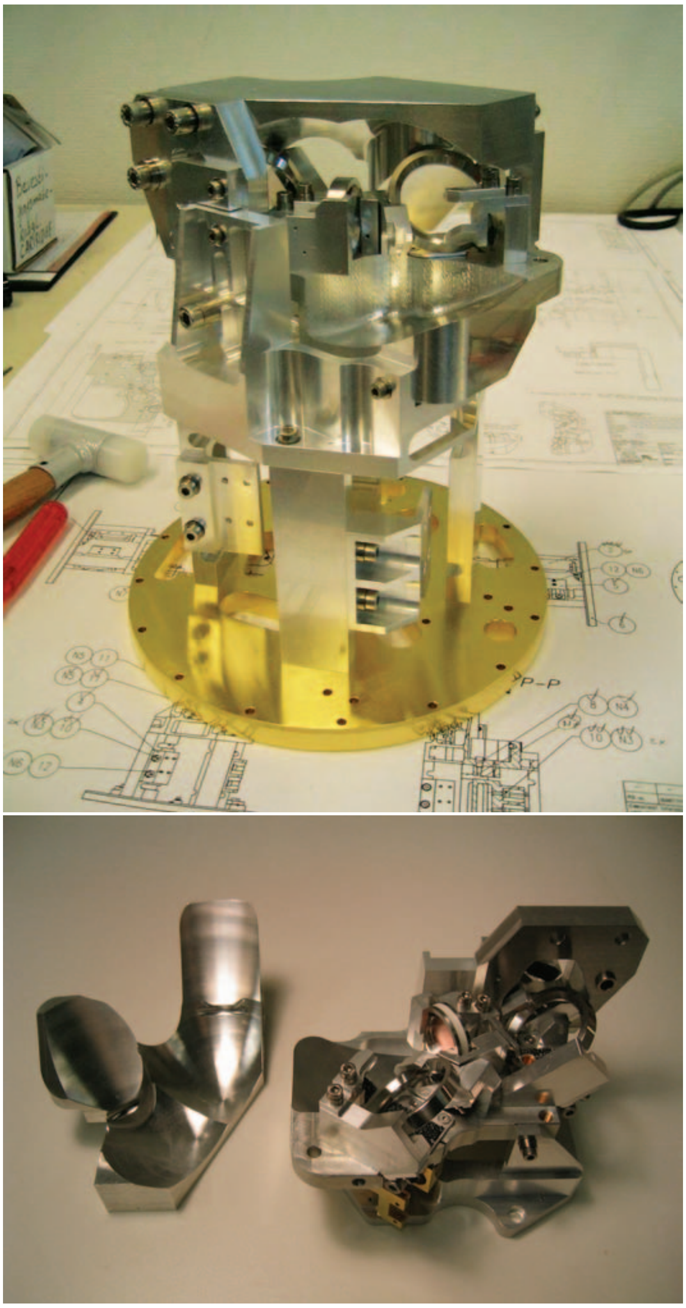


Figure 11: (top) The Band 9 4K optics assembly, (bottom) a disassembled view of the optics assembly in which the machined mirrors can be seen, as can the grids, beam splitters, and absorbing beam dumps.

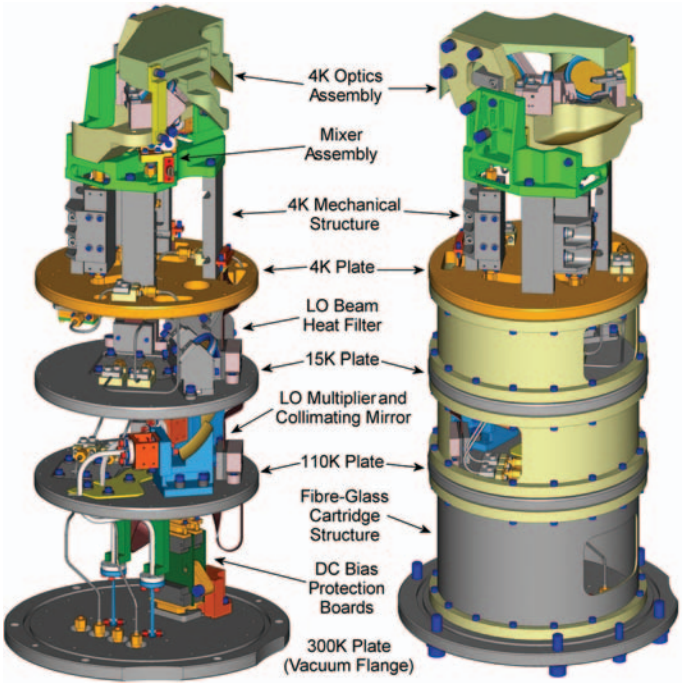


Figure 12: 3-D drawing of the mechanical design of the Band 9 cartridge.

development of test equipment is proceeding, with testing of the first cartridge expected to start this fall.

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