Series Production of State-of-the-Art 602-720 GHz SIS Receivers for Band 9 of ALMA

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Abstract—**The Atacama Large Millimeter/Sub-millimeter Array (ALMA) requires the development and production of 73 state-of-the-art receivers for the 602-720 GHz range – the ALMA Band 9 cartridges. Development and "pre-production" of the first 8 cartridges was completed between 2003 and 2008, resulting in a cartridge design that meets the project's challenging requirements. The cartridge design remains essentially unchanged for production, while the production and test processes developed during pre-production have been fine-tuned to address the biggest new challenge for this phase – ramping up production to a rate of ~ 2 cartridges per month over 2009-2012.**

Index Terms—**submillimeter wave receivers, radio astronomy, superconductor-insulator-superconductor mixers.**

I. INTRODUCTION

The Atacama Large Millimeter / Sub-millimeter Array project is a collaboration between Europe, North America, Asia, and Chile, to build an aperture synthesis telescope consisting of at least 66 antennas at 5000 m altitude in Chile [1]. When complete, ALMA will observe in 10 frequency bands between 30 and 950 GHz, with maximum baselines of up to 14 km, offering unprecedented sensitivity and spatial resolution at millimeter and sub-millimeter wavelengths. As the highest frequency band in the baseline project, the 602-720 GHz Band 9 receivers will provide the observatory's highest spatial resolutions and probe higher temperature scales to complement observations in the lower-frequency bands in the baseline project (between 84 and 500 GHz).

The Band 9 cartridge design [2] combines a compact focal-plane optics assembly; fixed-tuned superconductor-insulator-superconductor (SIS) mixers with state-of-the-art sensitivities across the 602-720 GHz signal frequency range; a wide-band, low-noise 4-12 GHz IF chain; and an electronically tunable solid-state local oscillator (developed at NRAO). Given the large number of receivers that ALMA requires (73 cartridges, including spares), two essential elements of the design are that the implementation of these critical elements takes advantage of the capabilities of commercial sub-contractors wherever possible, and that cartridge assembly remains as clean and simple as possible.

The Band 9 cartridge design was validated by producing eight "pre-production" units between 2005 and 2007 – effectively one prototype, followed by a series of seven identical units that incorporated lessons learned from the prototype. While ongoing development may yet offer improved performance in the future (for example, by implementing next-generation Band 9 mixers incorporating AlN SIS junctions), at this time, it is critical to ALMA that cartridge production meets the aggressive schedule required by plans for higher-level system integration and testing. With this in mind, production of the next 65 Band 9 cartridges started in late 2007. Following a start-up phase in 2008, during which additional assembly and test capacity was added and cartridge components were sub-contracted, assembly and testing of the production cartridges has started, and is ramping up towards the required delivery rate of roughly 2 per month.

This paper describes the development and production of the Band 9 cartridges, including conclusions from development and pre-production and plans for production. These plans have been developed to address the unique challenge of the ALMA project – in particular, the need to produce 73 receivers, all with excellent performance and high reliability, in a short period of time, and with a reasonable amount of effort.

II. CARTRIDGE TECHNICAL REQUIREMENTS AND DESIGN

The Band 9 cartridge is a double side-band, dual-polarization SIS receiver with state-of-the-art performance, including low noise, high optical efficiency, wide IF and RF bandwidth, and high output power and phase stability. The mechanical design of the cartridge is driven by the design of the blank cartridge body (a cylinder 17 cm in diameter and 28 cm tall, with plates at each of the temperature levels: 300, 110, 15, and 4 K) and the available 20 cm of space above the 4 K plate. Table 1 summarizes the main technical requirements placed upon the Band 9 cartridge.

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TABLE 1 PRIMARY TECHNICAL REQUIREMENTS

Property	Required Performance
mixer configuration	linearly polarized, double side-band
RF bandwidth	614-708 GHz (LO range) 602-720 GHz (signal rnage)
IF bandwidth	4-12 GHz
total power receiver noise	< 169 K over 80% of the LO range < 250 K over 100% of the LO range
total power output power	-32 dBm < P_{out} < -22 dBm
output power variations	< 7 dB p-p over 4-12 GHz IF band < 5 dB p-p within 2 GHz sub-bands of the IF band
output power Allen variance	< 4 x 10^{-7} for 0.05-100 s delay < 3 x 10^{-6} for 300 s delay
signal path phase stability	7.1 fs for 20-300 s delay
aperture efficiency	80% for an ideal / unblocked telescope
polarization efficiency	> 97.5%
beam squint	polarization beam co-alignment better than 10% of FWHM
strength and stiffness	lowest eigenfrequency > 70 Hz, survival of "minimum integrity test" random vibration test plus aircraft and road transport
lifetime	15 years
mean time between failure	20 years

Fig. 1 contains an image of the cryogenic portion of the cartridge design that was developed to meet these requirements. The core components of this design are low-noise, broadband SIS mixers [3]; a low-noise 4-12 GHz IF chain including a cryogenic isolator [4] and low-noise amplifier [5], plus a 2nd stage room-temperature amplifier; a cold optics assembly [6] including polarization splitting grid, LO injection beamsplitters, and LO and signal path mirrors; and a tunable solid-state local oscillator (from NRAO) [7] based upon a high-power mm-wave (68-79 GHz) power amplifier [8] and a cryogenic frequency multiplier [9]. The warm components of the cartridge (bias module, warm IF amplifiers, and room-temperature LO components) are not shown.

Additional details regarding the cartridge design can be found in [2].

III. CARTRIDGE DEVELOPMENT CYCLE

The development and production of the Band 9 cartridges followed the same basic sequence as the other ALMA cartridges. Initial efforts (to 2003) addressed critical components (esp. the Band 9 mixers) and the conceptual design of the cartridge. The development and pre-production phase followed between 2003 and 2008, and resulted in both the preliminary and detailed design, plus the first 8 Band 9 cartridges. Cartridge manufacturing, assembly, and test procedures were also developed and verified during this phase. Finally, based upon the detailed design and procedures developed in pre-production, the project's production phase will yield the remaining 65 cartridges needed to complete the ALMA array between 2009 and 2012.

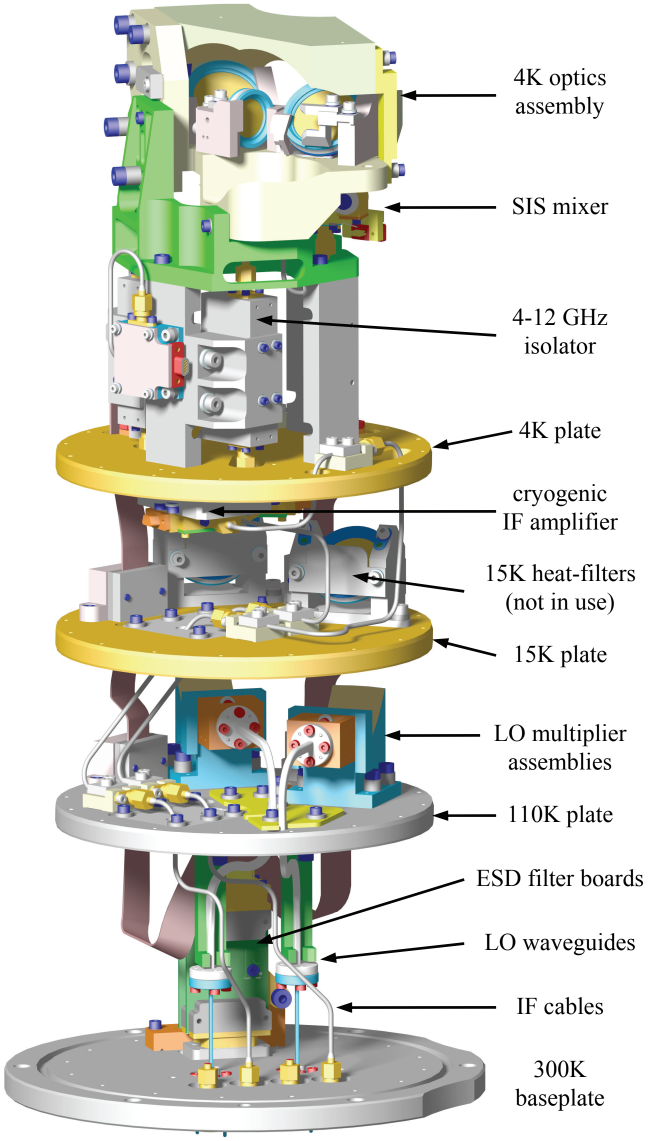

Fig. 1 – The cryogenic portion of the ALMA Band 9 cartridge. The fibre-glass cylinders that separate the temperature levels are not shown. Also not shown is the warm electronics assembly, including bias module and warm LO components (from NRAO) and warm IF amplifiers. From [2]

IV. CONCLUSIONS OF THE DEVELOPMENT AND PRE-PRODUCTION PHASE

During development and pre-production, the detailed cartridge design was verified by producing and testing eight cartridges – one deliverable prototype plus a series of seven built based upon lessons learned from the prototype. The series of seven are largely identical, and were produced as a test case for larger scale production, allowing the production and test procedures to be evaluated and fine-tuned.

A. Cartridge Performance and Design

The pre-production cartridges offer state-of-the-art performance – see Fig. 2 for noise temperature test results of a typical pre-production cartridge. The cartridges' total power DSB receiver noise temperatures reach their minima in the center of the band below 100 K, remain < 150 K in the upper portion of the band, and drop somewhat more sharply towards the lower frequency end of the band (remaining within the 250 K requirement).

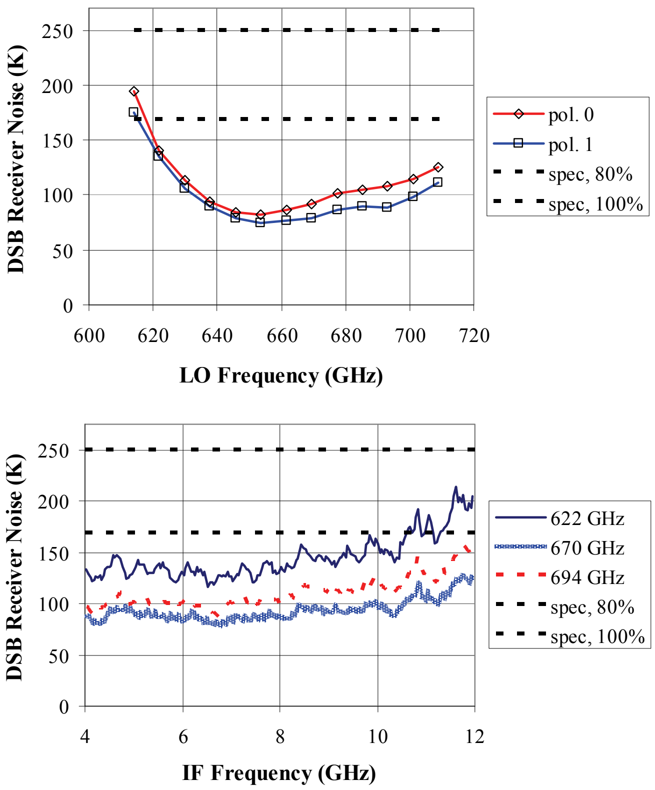

Fig. 2. DSB noise performance of cartridge #1 (a typical cartridge). (top) Total power noise temperature as a function of LO frequency. (bottom) Noise temperature as a function of IF frequency for three LO frequencies. In both plots, the dashed horizontal lines indicate the total power noise temperature required over 80% and 100% of the 614-708 GHz LO frequency range.

Acceptance testing of the pre-production cartridges covered all major requirements, including 2-dimensional near-field scans of the cartridge's beam-pattern, polarization efficiency, output power stability and phase drift measurements, gain compression for a 100°C input load, and output power flatness. Polarization efficiency and output power variations within 2 GHz sub-bands of the 4-12 GHz IF band were critical in the pre-production cartridges. With regards to the output power variations within 2 GHz sub-bands of the 4-12 GHz IF band, the measured peak-to-peak variations of up to 5 dB (and typically 3 dB) are low given the broad 4-12 GHz IF band and the state-of-the-art performance of individual IF components (in particular, the mixer's IF output coupling circuit, 4-12 GHz cryogenic isolators, and low-noise amplifiers).

B. *Manufacturing and Assembly*

In addition to verifying the cartridge design and performance, the second major goal of pre-production was to establish and validate manufacturing, assembly, and test procedures in advance of production. In this respect, this phase was a success – following the assembly and test of the first (prototype) cartridge, a broad redesign was implemented with the primary goal of easing manufacturing and assembly. This revised design was used for cartridges #2-8, with only minor modifications thereafter.

With only a few exceptions (such as the absorbing coatings used as beamdumps in the 4 K optics assembly, and the SIS junctions), component manufacturing was sub-contracted in pre-production – for all critical components, one or more sub-contractors were identified and evaluated. Because of the attention paid to ease-of-assembly during the design phase, the cartridge assembly effort was minimized once the second half of the pre-production series was reached. In fact, the work to inspect and clean parts and prepare sub-assemblies, dominated the assembly effort – assembly of the cartridge structure and integration of the optics and mixers is relatively straightforward. Ultimately, even though the time-consuming preparatory work of inspection, cleaning, and sub-assembly was performed as part of assembly, a throughput of 1 per month was achieved. Fig. 3 shows a photograph of production cartridges #3-8 prior to their deliveries to the project.

Fig. 3. Six Band 9 pre-production cartridges (#3-8) assembled, tested, and awaiting acceptance and delivery to the ALMA project in Aug. 2007.

C. *Acceptance Testing and Delivery*

Cartridge acceptance testing during pre-production showed similar experience – tests of the first cartridges took longer, as test procedures were developed and fine-tuned. However, once the 2nd half of the pre-production phase was reached, a test throughput of one per 3-4 weeks was realized. This was largely thanks to the development of a test system that allows both the semi-automated execution of mixer bias optimization and magnet tuning, plus unattended execution of time consuming tests such as near-field beam scans and output power and phase stability testing. Ref. [10] describes this semi-automated test system in more detail.

V. PRODUCTION PLANS AND STATUS

A. *Production Phase Requirements*

Moving into the project's production phase, the technical requirements have remained largely unchanged. New requirements on aperture efficiency and the co-alignment of the cartridge's two polarization beams were introduced, the cross-polarization requirement has been confirmed, and a number of other requirements have been clarified. However, the core technical requirements, including sensitivity and RF and IF bandwidth, have not changed.

With only minimal changes in the technical requirements, the biggest change is in the increased scope of the production effort – in place of eight cartridges in 1 year, the production phase requires 65 cartridges in 4.5 years, including an eventual delivery rate of about 2 per months. This increased scope has required revised procedures and processes when compared with the earlier development and pre-production phase.

B. Component Procurement

The cartridge design was developed with the goal of sub-contracting as much manufacturing as possible to commercial suppliers – as reported above; this was already accomplished in pre-production. In this respect, the biggest change going into production is in the size of the orders – with the larger orders for production come additional formalities in the contracting process, and thus much longer lead-times. Because of these long lead-times, it was essential to freeze the design for production early, and the design for the production phase was frozen in late 2007, allowing procurement to start in mid-to-late 2007.

Orders for the full production quantities were placed between late 2007 and mid-2008. As a result, where single-batch production was most efficient (including mechanical parts and off-the-shelf components), full production quantities have already been inspected, cleaned, and placed in storage. For components that are produced in smaller batches, the goal is to receive components half a year or more before they are needed, to minimize risks to the cartridge deliveries. This was not feasible for the first production component deliveries, but every effort is being made to reach this goal by mid-2009. Particular attention is paid to components that are critical to cartridge performance and reliability, including corrugated mixer horns, SIS junction mounts, 4 K mirror blocks, polarizing grids, 4-12 GHz isolators, cryogenic semi-rigid cables, and LO waveguides and horns.

Three critical cold cartridge components come from ALMA partners (cryogenic amplifiers from CAY, Spain; cold LO multipliers from NRAO and VDI, USA; and the blank cartridge bodies from RAL, UK). The warm LO assembly and cartridge bias modules also come from NRAO.

C. Cartridge Test System Expansion and Upgrade

Provided that components are available well before they are needed for assembly, the critical item in the production project schedule is cartridge testing (including trouble-shooting, if needed).

Although cartridge acceptance testing is extensive (most performance requirements are verified on all cartridges), the semi-automated Band 9 cartridge test system [10] allows this to be done efficiently. Taking into account the time required for cartridge bias optimization and performance testing, plus the inevitable need to repeat some tests and rework some cartridges, a throughput of one cartridge per three weeks is realistic. Thus, two test systems are needed to keep up with the required production rate of up to two cartridges per month. Built around a single-cartridge test cryostat developed at NAOJ [11] and using the same cryo-cooler as in the ALMA cryostat [12], the 2nd cartridge test system (see Fig. 4) was built in 2007 and 2008.

Fig. 4. Two cartridge test cryostats (from NAOJ, Japan). With a test throughput of 1 cartridge per 3 weeks, a 2nd test system was built in 2007-2008 to allow a delivery rate of 2 cartridges per month to be realized.

D. Manufacturing and Assembly

As discussed above, assembly typically required one month per cartridge in pre-production. However, a significant contributor to this rate was the time required to inspect and prepare parts and sub-assemblies, as assembly proceeded one cartridge at a time. For production, these preparatory activities have been removed from the assembly process, and are being performed in large batches in advance, allowing work to be more efficiently organized. In this approach, final assembly of the cartridge structure and its integration with the mixers and optics is feasible at the required rate of 2 cartridges per month, even with an increased level of inspection of incoming parts.

E. Optics and Mixer Testing

Plans for mixer testing in production do not deviate significantly from the approach followed during pre-production. Making use of a small liquid helium dewar that can be cycled 2-3 times per day, pre-selection of candidate mixers is done by Fourier Transform spectrometer tests of their direct detection responses. Potentially good mixers are then heterodyne tested in a two-mixer test dewar. The quick cycling times of both dewars, combined with test software that allows two mixers to be heterodyne tested in one day, allow sufficiently quick testing to meet the project's requirements.

The 4 K optics assemblies are receiving additional attention during the production phase. As in pre-production, room-temperature near-field beam-pattern measurements of all assemblies are used to verify that the cartridge's optical requirements are met. For production, these RF measurements are preceded by mechanical inspections of all 4 K mirror blocks by their manufacturer to verify that the manufacturing tolerances are achieved – these inspections were introduced to help ensure that the required co-alignment of the cartridge's two polarization beams is achieved. Verified optics assemblies are placed into storage as assemblies (minus the mixers).

F. Cartridge Testing and Delivery

The cartridge test program for production is largely based upon that used in pre-production, with some fine-tuning to improve test accuracy and/or to address requirements that were revised since for production. With two cartridge test systems operating in parallel, if reworking or retesting of a cartridge is required, work on the following units can proceed, allowing cartridge deliveries to continue.

VI. ONGOING DEVELOPMENTS

Although the production of cartridges meeting the project's requirements is the clear top priority at this phase of the project, ongoing development continues with the goal of improving Band 9 cartridge performance in both the near and longer term.

In the near-term, efforts continue towards the application of AlN SIS junction technology [13-15]. When compared with the baseline AlO_x SIS junctions AlN junctions offer good junction qualities for much higher junction current-densities. Because the fixed-tuned bandwidth of AlO_x SIS junctions in Band 9 is largely limited by the *RC* product of the SIS junction's tunnel barrier, the potential to use much higher current-density junctions (with correspondingly lower values of *RC*) offers a substantial increase in the fixed-tuned bandwidth of the Band 9 mixers. Ref. [15] describes the evaluation of prototype AlN mixers in a Band 9 cartridge during 2007-2008. Since that demonstration, work has continued to optimize AlN mixer performance in Band 9 [16]. Although development is not yet complete, implementing AlN SIS junctions in the Band 9 cartridge requires only a change of the junction chip in the mixer – this potentially allows a design change to be implemented mid-way through production, without significantly affecting the production process.

In the longer term, development of a side-band separating mixer for ALMA Band 9 continues. A side-band separating configuration offers the potential for substantial improvements in receiver sensitivity by eliminating the noise contribution of the atmosphere in the image side-band, in particular for line observations. See [17] for more information.

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