ALMA Band 9 Cartridge Automated Test System

J. Barkhof, B. D. Jackson, A. M. Baryshev, and R. Hesper

***Abstract*— The Atacama Large Millimeter/Sub-millimeter Array (ALMA) requires 73 state-of-the-art receivers for the 602-720 GHz range – the ALMA Band 9 cartridges. 65 cartridges are due between 2009 and 2012, with each undergoing thorough acceptance testing to verify its operation and performance prior to delivery. This is enabled by an automated test system developed during the project's pre-production phase in 2004-2008. The core of this system are a single-cartridge test cryostat, a dual-channel intermediate frequency signal processor, a phase-and-amplitude near-field test system, and script-based measurement and control software that enables automated cartridge tuning and unattended execution of time-consuming tests. Two test systems are operated in parallel to allow a delivery rate of at least 2 cartridges per month to be achieved.**

***Index Terms*—submillimeter wave receivers, automatic test equipment, superconductor-insulator-superconductor mixers, radio astronomy**

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 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 a maximum baseline 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 (see Fig. 1) will provide the observatory's highest spatial resolutions and probe higher temperatures to complement observations in the lower-frequency bands in the baseline project (between 84 and 500 GHz).

ALMA's aggressive integration and commissioning plans call for the delivery of up to two Band 9 cartridges per month to the Front End Integration Centers during the coming years. Prior to delivery, each of these cartridges will be thoroughly tested to ensure that the project's performance and interface requirements are met. Included in the list of properties that are to be tested are: heterodyne sensitivity and cartridge output power as a function of local oscillator (LO) frequency and intermediate frequency (IF), aperture and polarization efficiency, output power and signal path phase stability, and gain compression.

In order to realize these critical tests in a timely and reliable manner, a semi-automated test system has been developed for the Band 9 cartridges. Core elements of this test system include a cryo-cooled single-cartridge test cryostat (developed at NAOJ, Japan) [2], an ALMA Band 9 room-temperature LO [3] and cartridge bias electronics (both developed at NRAO, USA), a dual-channel IF processor, and a near-field phase-and-amplitude test system. These and other elements of the

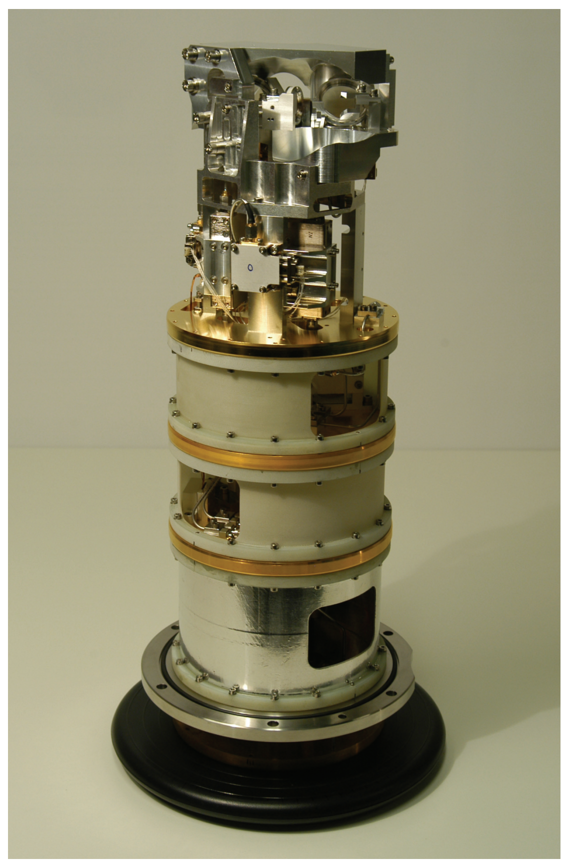

Fig. 1 – An ALMA Band 9 cold cartridge (i.e. not including the cartridge's warm electronics units). The cartridge is roughly 50 cm tall and 20 cm in diameter.

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test system are combined and controlled by script-based control software that enables automated optimization of the mixer and LO bias parameters and unattended execution of time consuming tests such as amplitude and phase stability tests and near-field beam-pattern measurements.

II. Cartridge Technical Requirements

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 20 cm of space available above the 4 K plate. Fig. 1 contains a photograph of the cryogenic portion of the Band 9 cartridge. Additional details regarding the cartridge design and production can be found in [4,5].

Table 1 summarizes the main performance requirements for the Band 9 cartridge. Effectively, these also specify the test system that is used for cartridge acceptance testing, as every cartridge is tested to verify compliance with each of these requirements.

TABLE 1 Main Performance Requirements

Property	Required Performance
mixer configuration	linearly polarized, double side-band
RF bandwidth	614-708 GHz (LO) 602-720 GHz (signal)
IF)bandwidth	4-12 GHz
total power receiver noise temperature	< 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

III. Cartridge Test System Design and Sample Test Results

A. System Design

The Band 9 cartridge test system was developed in parallel with the development of the cartridge design and the production of the first 8 cartridges. Design verification and acceptance tests of the first cartridge in 2005-2006 were used to demonstrate all of the required tests, while acceptance tests of the remainder of the first 8 units were used to further refine and streamline the test equipment and test procedures.

The test system is built up around 4 main components:

- a single-cartridge test cryostat developed by the National Astronomical Observatory of Japan [2];
- a dual-channel IF processor that includes 4-12 GHz band-pass filters, two amplification stages, computer-controlled YIG filters to sample the 4-12 GHz IF band at ~ 50 MHz resolution, and switches that select measurements in total-power or narrow-band mode;
- a phase-and-amplitude near-field system that includes a superlattice harmonic generator [6] as a tunable 602-720 GHz signal source, a 3-D scanning stage mounted on top of the cartridge test cryostat, and a phase-detection system; and
- measurement and control software that is used to operate (and optimize) the cartridge bias and control all associated test equipment.

Additional important components include a hot-cold chopper for heterodyne sensitivity testing with 77 and 295 K blackbody loads, a rotatable polarizing grid for cross-polarization measurements, and a 373 K heated load that is used for linearity testing. Both the hot-cold load and the polarizer are computer-controlled to facilitate automated measurements.

Fig. 2 includes a photograph of the cartridge test system configured for cross-polarization tests – the rotatable polarizer in the cartridge beam between the cryostat window and the hot-cold load allows the receiver sensitivity to be measured as a function of source polarization.

Fig. 2 – The Band 9 cartridge test system configured for polarization efficiency measurements, with a rotating polarizing grid placed between the receiver and the hot-cold load (both computer-controlled).

B. Monitor and Control Software Design

The cartridge and cartridge test system are operated via custom-built control software written in LabWindows. This software is designed to allow cartridge tests to be performed reliably and efficiently. Test execution generally requires manual intervention to reconfigure the test hardware and initialize some test parameters, but once initialized, time-consuming tests are performed with a minimum of operator intervention (such as refilling liquid nitrogen loads).

Key elements of the test system control software are:

- a script-based user interface that facilitates test standardization (acceptance tests are executed from standard scripts centrally stored in text files) and allows every test command to be logged;
- a "nested loop" functionality that allows complex measurements to be built up as multi-dimensional scans, both for standard tests (i.e. receiver sensitivity vs. LO and IF frequency) and one-time exploratory tests (i.e. output power stability as a function of SIS junction bias);
- semi-automated optimization of cartridge operating parameters (mixer magnet tuning and SIS junction bias voltage and pump level optimization); and
- a modular structure that aids in maintainability, and eases the incorporation of new test equipment and portability to ALMA partner institutes.

C. Semi-Automated SIS Mixer Tuning

Band 9 cartridge operation requires tuning of the SIS mixers' electromagnets and optimization of the (LO frequency dependent) SIS bias voltage and current.

The mixers' magnets are tuned after first demagnetizing the magnets (by applying a series of magnet currents of alternating sign and decreasing amplitude) and defluxing the junction (by applying a single pulse to the mixer's deflux heater, where a pulse is ~ 0.2 s in duration). Once the magnet has been demagnetized and defluxed, the mixer's zero-bias supercurrent is measured as a function of magnet current to locate the 2^{nd} minimum in the Franhofer pattern. Due to hysteresis, the magnet current is always tuned starting from 0 mA, after demagnetizing and defluxing.

The optimum bias voltage and pumped current of the cartridge's SIS mixers are determined by a nested set of 1-dimensional scans of cartridge hot and cold output power as a function of LO power and SIS junction bias voltage. The optimum bias is found from the minimum noise temperature versus LO power and maximum output power versus SIS bias voltage. To facilitate exchange of local oscillators and simplify retuning for new LO frequencies, the optimum LO power is defined in terms of the resulting SIS bias current. Thus, optimization is performed for 13 LO frequencies between 614 and 710 GHz, and a frequency-independent optimum bias current is defined as the average of the 13 optimum currents. The SIS bias voltage remains LO frequency dependent. In operation, the optimum bias is obtained by tuning the LO power amplifier to obtain the required SIS bias current at the optimum SIS bias voltage.

D. Heterodyne Sensitivity Testing

Cartridge sensitivity acceptance tests are performed at a standard set of 13 LO frequencies between 614 and 710 GHz, at optimum bias for each LO frequency. Measurements are taken in narrow-band mode (at 40-50 MHz IF resolution over the full 4-12 GHz IF band), with total power results obtained by off-line integration of the narrow-band results.

For diagnostic purposes, and to characterize the Band 9 LO in terms of excess noise, sensitivity measurements can also be performed at finer LO spacing (typically 1 GHz), fully sampling the IF band at ~ 50 MHz resolution. These measurements are performed at a fixed (LO-independent) SIS bias voltage and pumping level (tuning the LO power at each frequency to obtain a defined SIS bias current).

Fig. 3 presents total power noise temperature data for 14 cartridges and sample narrow-band data of noise temperature versus LO and IF frequency for one polarization channel of one cartridge.

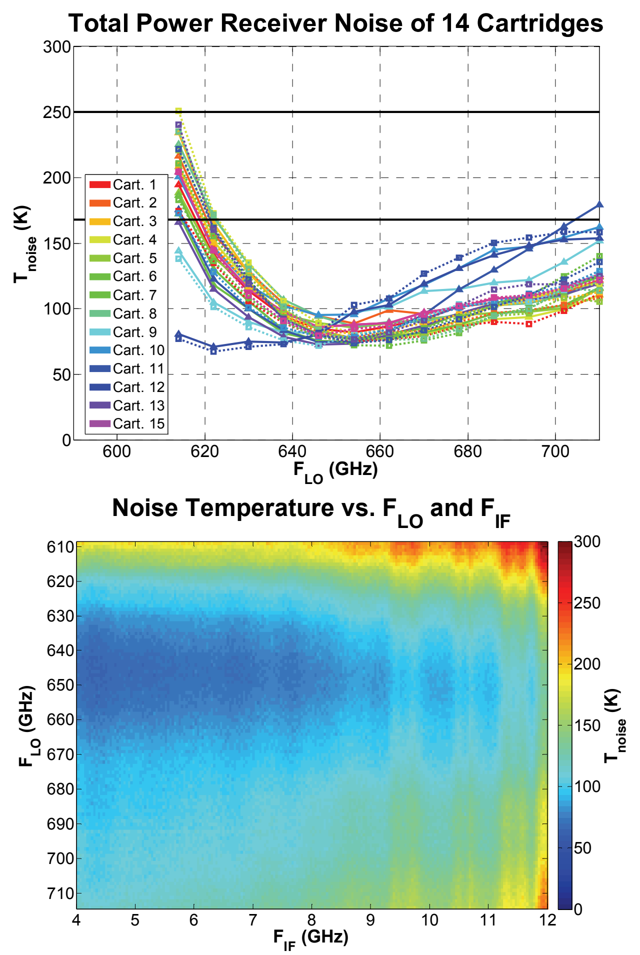

Fig. 3 – Sample receiver noise temperature test results. (top) Total power receiver noise for 14 cartridges at 13 LO frequencies, measured at optimum bias for each frequency. (bottom) Narrow-band receiver noise at 1 GHz LO spacing and 50 MHz IF spacing, for a fixed LO-independent mixer bias point. The automated control system allows this 2-D noise temperature scan to be completed in less than 1 hour.

E. Near-Field Testing

Near-field phase-sensitive tests are used for two purposes in cartridge acceptance testing – phase-and-amplitude beam-pattern measurements and long-term phase drift measurements.

The basic elements of the near-field test system are:

- a signal source – a superlattice diode harmonic generator [6] driven by a microwave signal generator (SG1);
- a 2^{nd} microwave signal generator (SG2) that replaces the YIG oscillator in the Band 9 LO;
- a microwave circuit that mixes harmonics of the outputs of SG1 and SG2 to create a reference signal;
- a phase detection system that uses a vector network analyzer to compare the amplitude and phase of the cartridge's response to the signal source with the reference signal; and
- a 3-D scanning stage that is mounted on the cartridge test cryostat, allowing the signal source to be scanned in a plane above the cryostat's optical window.

Beam-pattern measurements are performed at standard test frequencies across Band 9. Measurements are performed in two planes, separated by ¼-wavelength, to allow standing waves between the receiver and the probe to be removed [7]. The near-field data is Fourier transformed to the far-field and corrected for the far-field pattern of the corrugated probe horn. The angular size and position of the corrected far-field pattern are then compared with those of the antenna's secondary mirror. The far-field data is also analyzed to determine the receiver's aperture efficiency and phase center. Finally, the phase centers of the cartridge's two polarization beams are compared to determine their co-alignment in the focal plane. (The signal source's polarization is manually rotated to allow the cartridge's two polarization beams to be sampled.)

Fig. 4 shows the cartridge test system configured for near-field measurements. The off-axis mirror that normally focuses the cartridge beam into the hot-cold load (see Fig. 2) is removed and the 3-D scanning stage is mounted on the cryostat with the signal source above the cryostat window.

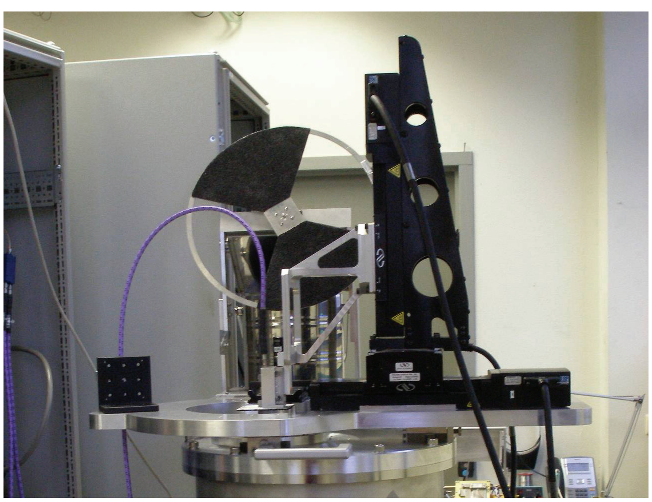

Fig. 4 – The Band 9 cartridge test system configured for near-field phase-and-amplitude beam-pattern measurements. A harmonic source is scanned in a plane directly above the cryostat window and can be rotated without disturbing its lateral alignment to allow the relative alignment of the cartridge's two polarization beams to be verified.

Fig. 5 presents sample near- and far-field data for one polarization of one Band 9 cartridge. The far-field amplitude plot includes an outline and marker indicating the angular size and position of the antenna's secondary mirror (which is nominally offset by 0.95° from the vertical). The data shown (with 201x201 points sampling a 40 mm x 40 mm scan region) is obtained in ~ 1 hour per frequency and polarization.

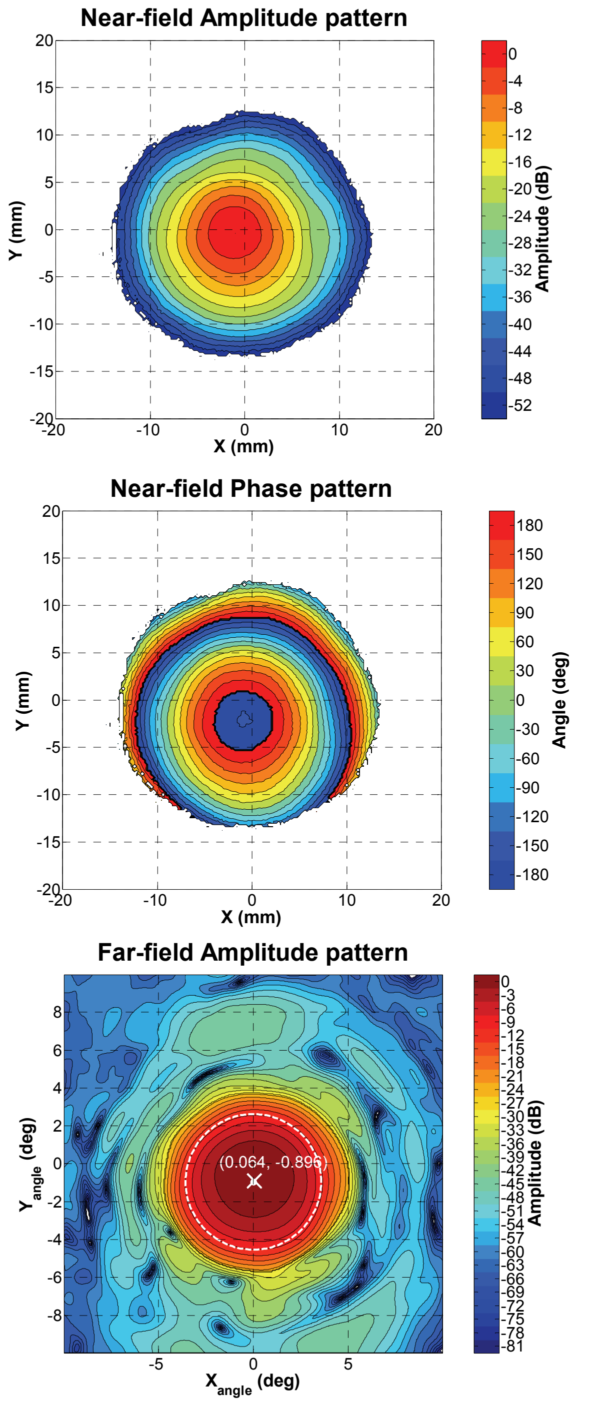

Fig. 5 – Antenna beam-pattern test results. (top and middle) near-field amplitude and phase patterns. (b) far-field amplitude pattern obtained from the measured near-field data (corrected for the far-field pattern of the corrugated probe horn).

F. Stability Testing

Two forms of stability test are performed on each cartridge – Allen variance measurements of the total power output power when observing a room-temperature blackbody, and phase drift measurements. Both measurements are performed for 3 standard frequencies and both cartridge polarizations.

Output power stability measurements are performed with 25 ms sampling for 60 min., allowing the cartridge's Allen variance to be verified for delays of 0.05 to 300 s. Fig. 6 (top) presents data for 15 cartridges at 670 GHz LO frequency.

Phase drift measurements are performed using the near-field test system with the source fixed in position at the center of the cartridge beam. The cartridge phase is sampled with ~ 0.1 s sampling over a 70 min. duration. The measured data is then integrated to create 10 s samples, which are statistically analyzed to determine the standard deviation in the data for delay times up to 5 min..

Fig. 6 (bottom) presents sample phase drift data for one polarization of one cartridge. Also included in this plot is the variation in the temperature of the phase lock loop (PLL) in the Band 9 LO. This is used as an indicator of variations in the ambient temperature during the measurement. As the data indicates, these long-term phase drift measurements are sensitive to drifts in the ambient temperature on the order of 0.5° over a 1 hour period. In general, the requirement that the maximum standard deviation of phase be less that 1.6° is met with margin in all cartridges.

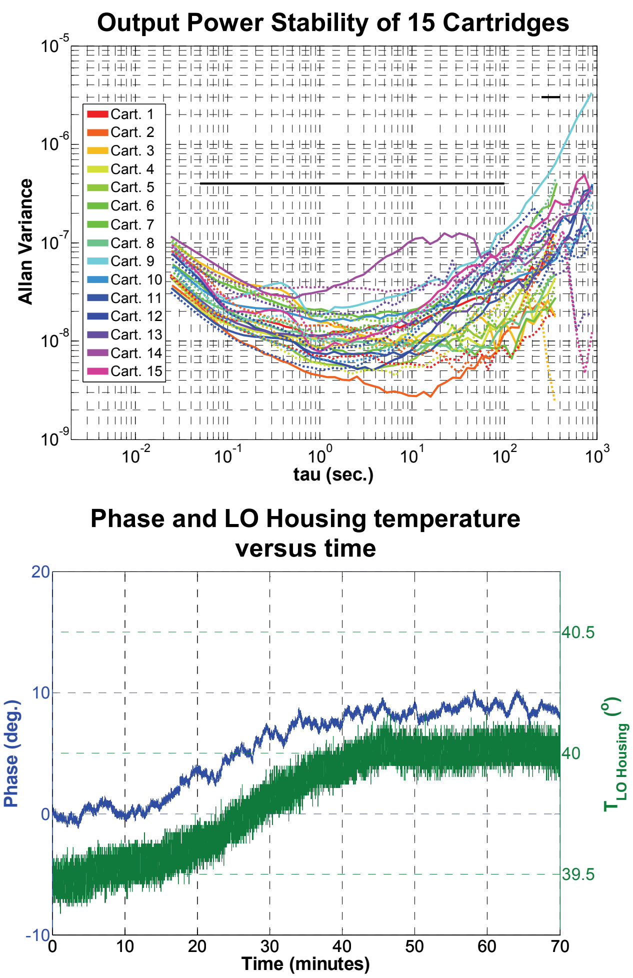

Fig. 6 – Receiver stability test results. (top) total power output power Allen variance of 15 cartridges at 670 GHz LO frequency. (bottom) signal path phase and LO housing temperature drift with time. Both stability tests are sensitive to the ambient environment. Optimal results are obtained from unattended overnight tests (3 frequencies can be tested in one night).

IV. Conclusion and Production Plans

An automated test system has been developed to allow each ALMA Band 9 cartridge to be thoroughly tested prior to delivery to the project. The system was fine-tuned while testing the first 8 cartridges between 2004 and 2008.

During the project's production phase, 65 cartridges are to be delivered to the project over 2009-2012, at a rate of up to 2 cartridges per month. Given a need for retesting and/or reworking of some cartridges, experience shows that the full acceptance test program can be completed in an average of 3 weeks. For this reason, a duplicate test system was built in 2008 – the use of two test systems in parallel is needed to allow the required delivery rate to be achieved.

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