Performance of ALMA band 9 receiver series

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***Abstract*—This article describes several aspects of ALMA band 9 cartridges: design, development and characterization. We give special attention to the characterization of the system. In this context, we present the noise measurements of the first eight cartridges with an emphasis on the extremely large IF bandwidth (4-12 GHz). The IF gain slope, receiver linearity and saturation, receiver beam pattern and cross polarization level measurements are also presented.**

***Index Terms* — Heterodyne detection, saturation, spurious signals, SIS mixer, Local Oscillator, sub millimeter wavelengths**

I. Introduction

The Atacama Large Millimiter Array (ALMA) project is a collaboration between Europe, North America, and Japan to build an aperture synthesis telescope consisting of at least 64 12-m antennas located at 5000 m altitude in Chile in its full configuration, ALMA will observe in 10 frequency bands between 30 and 950 GHz, and will provide astronomers with unprecedented sensitivity and spatial resolution at millimeter and submillimeter wavelengths. Band 9, covering 600-720 GHz, is the highest frequency band in the baseline ALMA project, and will thus offer the telescope's highest spatial resolution.

The ALMA Band 9 cartridge is a compact unit containing the core of a 600-720 GHz heterodyne receiver front-end that can be easily inserted into and removed from the ALMA cryostat present in every antenna. The core technologies of every cartridge include low-noise, broadband SIS mixers; an electronically tunable solid-state local oscillator; and low-noise cryogenic IF amplifiers. These components are built into a rigid opto-mechanical structure that includes a compact optical assembly mounted on the cartridge's 4K stage that combines the astronomical and local oscillator signals and focuses them into two SIS mixers as shown in Fig. 1.

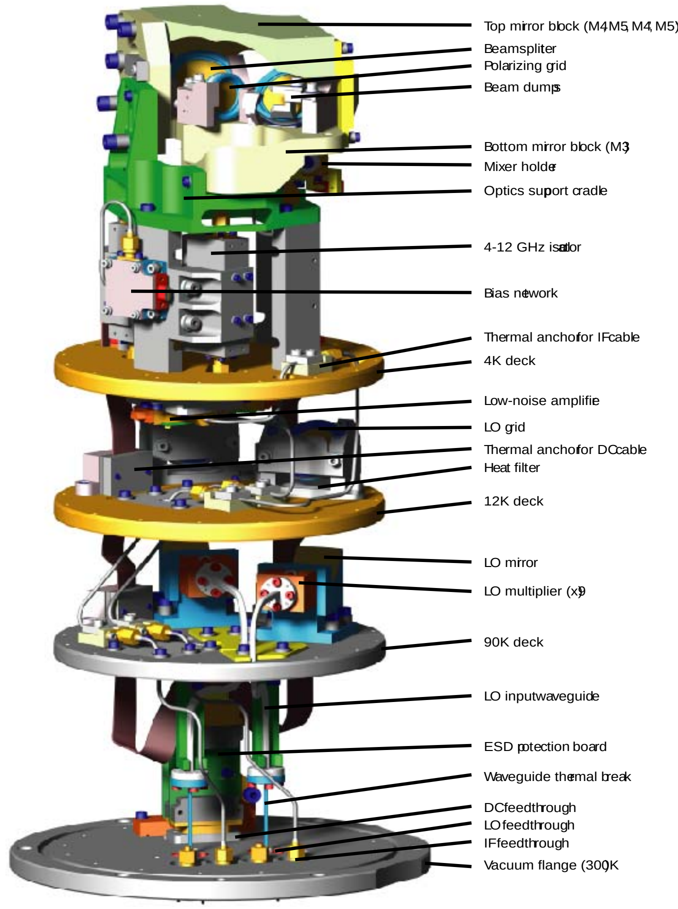

Fig. 1. Layout of the ALMA band 9 receiver..

In this article we present the noise measurements of the first eight receiver units with an emphasis on the extremely large IF bandwidth (4-12 GHz). The IF gain slope, receiver linearity and saturation, receiver beam pattern and cross polarization level measurements are also presented.

II. Receiver Layout

A. Overall layout

The ALMA band 9 receiver layout [1] is shown in Fig. 1. The receiver elements occupy four temperature levels. The temperature levels (4, 12, 90, and 300 K) are provided to the cartridge body from the main ALMA cooler and the cryostat cooling distribution system. The receiver insert (cartridge) can be placed into the main ALMA cryostat without disassembling the cartridge or the cryostat. The heat contact is

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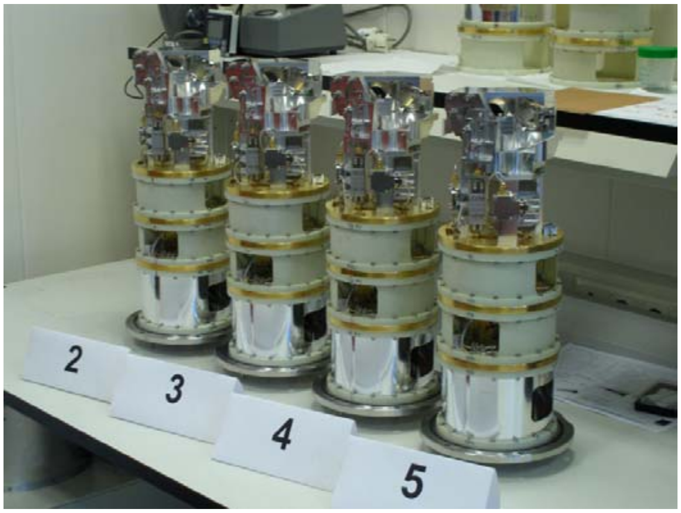

Fig. 2. Photograph of receiver cartridges #2-#5

provided by flexible heat links that only make contact when cryostat is cold and the mechanical support is made at the bottom of the cartridge assembly. The cartridge walls (not shown in figure) are made of fiber glass reinforced epoxy and the construction is rigid enough to maintain the beam orientation within required tolerances for all orientations of the ALMA antenna.

B. Signal optics

The optics forming the main beam is all contained at the 4 K level. The SIS mixer beam is formed by a corrugated horn which is followed by two elliptical mirrors providing a frequency independent coupling between telescope and mixer. A linear wire grid is inserted between the mirrors to split the input beam in to two orthogonal linear polarizations. An additional elliptical focusing mirror and SIS mixer are used to receive the orthogonal polarization. The details and analysis of ALMA band 9 optics has been presented in detail previously [2]. The entire 4 K optics is arranged in a single CNC machined block that also contains part of the LO coupling optics. The relative position of mirrors is ensured by proper manufacturing tolerances of the mirrors themselves and mechanical fastening interfaces.

C. Local oscillator arrangement

A quasi-optical LO insertion scheme was chosen for ALMA band 9 receiver. For each polarization channel an integrated ×3×3 Schottky diode multiplier (made by Virginia Diodes) is mounted on the 90 K stage. Its output beam is formed by a diagonal horn and is coupled by means of two elliptical mirrors: one is mounted on 90 K stage and another is mounted on 4 K stage. The LO beam is inserted into a signal beam just in front of a SIS mixer horn by means of a 6 micrometer thick Mylar® beam splitter (~4% coupling). Most of the LO output power is terminated into the black body absorbers mounted at 4 K level behind the beam splitters.

The ×3×3 multiplier is pumped by a microwave signal in the range of 67.7 to 79.1 GHz which corresponds to an output frequency range of 610 to 712 GHz. This signal is carried from a vacuum WR-12 waveguide flange at the 300 K base plate to a multiplier at the 90 K level by means of a gold plated stainless steel WR-12 waveguide. The pumping level of LO multipliers can be adjusted independently by a room temperature electronics providing optimal pumping level for each SIS mixers. The efficiency of this multiplier improves when it is cooled to 90 K compared to a room temperature and it provides 40 to 100 microwatts of output power across the band.

The room temperature driver for the LO system is made at National Radio Astronomical Observatory (NRAO) in Charlottesville. It is based on a YIG oscillator, its signal is multiplied ×3 and amplified by a power amplifier. Then it is split between two power amplifiers with electronically adjustable gain. These power amplifiers consist of several MMIC chips and use waveguide power combining technology. As a result, the output of these amplifiers is matched to WR-12 waveguide avoiding standing waves in the system. The output power level of this amplifier can be regulated anywhere in the range of 10 to 100 milliwats. Details of similar system can be found in [3].

D. IF system

The band 9 cartridge IF system covers the frequency range from 4 to 12 GHz. The output of every SIS mixer is connected to a three stage InP IF amplifier made by YEBES via a cryogenic 4-12 GHz isolator made by Pamtec. The amplifier noise temperature is in the range of 4 to 6 K, the gain is around 30 dB and the power dissipation at 4 K is about 7 mW. The amplifier output is connected to a vacuum feedthrough interface (situated at the base plate) by a stainless steel cable which is anchored at the 4, 12 and 90 K levels. Finally, at room temperature, a gain-slope-corrected amplifier of 30 dB average gain is used to further boost IF output signal. A 3 dB gain slope across 4-12 GHz band is used to compensate for frequency dependent cable losses and mixer gain variation.

E. SIS mixers

Two identical mixers blocks are used in the receiver system. They contain a corrugated horn, an all Nb SIS mixer with single Nb-AlO_x-Nb SIS junction. The mixers are of the

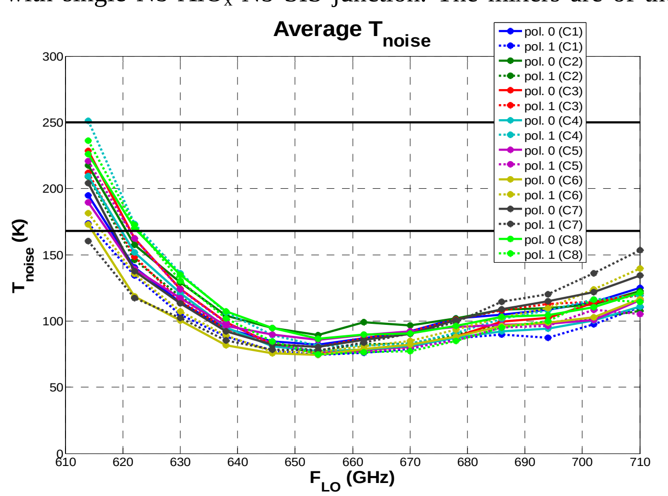

Fig. 4. Measured receiver noise temperature of SIS mixer vs. RF source power for several LO frequencies. Signal frequency was kept at 642 GHz.

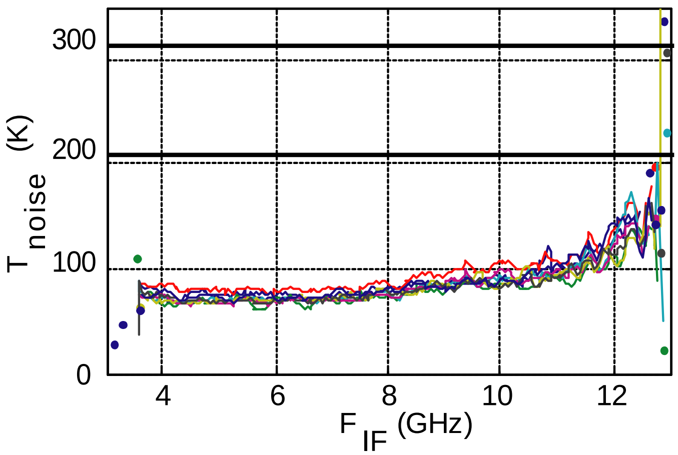

Fig. 5. Measured receiver noise temperature as a function of IF for four cartridges (#1..#4), for two polarization channels each, at 654 GHz LO frequency.

waveguide type and are described in detail in [4]. A superconducting coil is also mounted in the mixer holder to provide suppression of the Josephson effect. A typical operation current of 9 mA is required. A 500 Ohm resistor is built-in close to a SIS junction to be used to heat it up above the critical temperature and so remove any trapped magnetic field flux without dissipating much power. The system can return to operating conditions within 5 seconds.

F. Construction status

A total of eight receiver units have been built and fully characterized to date. Two of them have been delivered to the ALMA integration center for further system test. Fig. 2 shows the photograph of four of the constructed units. A summary of the receiver performance will be presented in the following section.

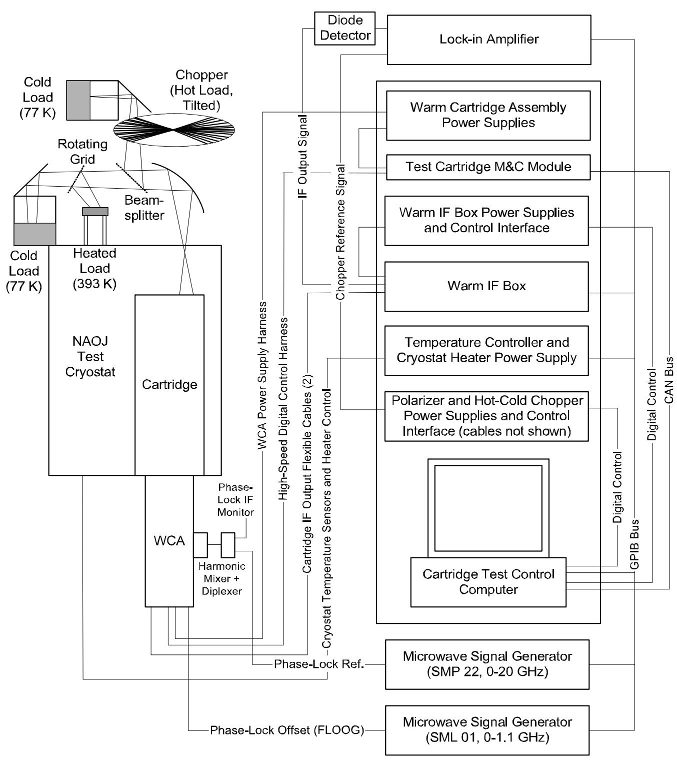

Fig. 7. Experimental layout for measurement of receiver saturation.

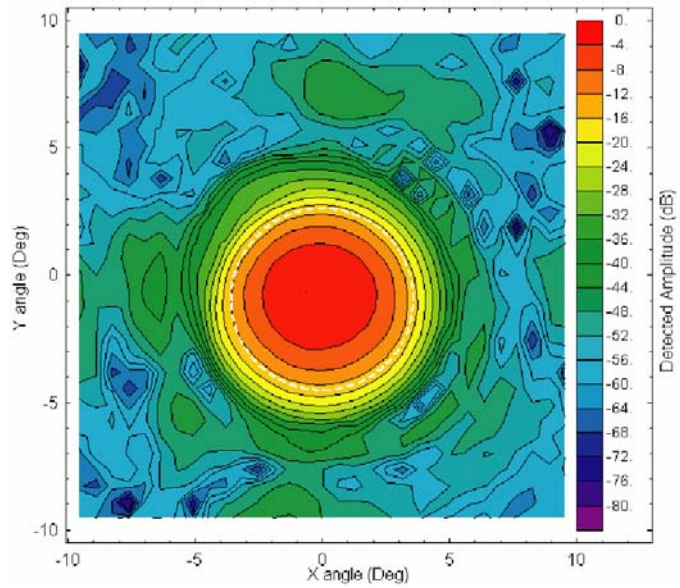

Fig. 6. Receiver beam in far field zone. Dashed line is the edge of the ALMA telescope secondary mirror.

III. Demonstrated Receiver Perfomance and Discussion

In this section a summary of the receiver performance is presented: noise temperatures, IF gain variations, beam pattern, and saturation results. Measurement methods are also outlined.

A. Receiver Noise performance

Noise performance of band 9 cartridge system has been evaluated using a dedicated measurement set-up which includes: a switchable hot/cold load with temperature levels of 80 K (liquid nitrogen) and 300 K (room temperature); a two channel IF system with YIG filters to analyze an IF response; a noise source to calibrate the IF system gain and a control computer with a control software. Most of the measurements can be done in batch mode without any operator's intervention.

During all performance measurements, the receiver was mounted in an ALMA test cryostat which provides the necessary temperature levels. The 4 K stage temperature was maintained by a software PID feed back loop at 4 K during all measurements.

A summary of the measured noise temperature as a function of IF is presented in Fig. 3. The data correspond to the eight built cartridges. The noise temperature is averaged across the IF band and is not corrected for receiver optics. Good repeatability between units has been achieved mainly due to an improved junction production (e-beam lithography) and junction mounting control. A major improvement in sensitivity has been achieved because by mounting the LO source at the 90 K temperature level, thus LO noise contribution is minimal.

Typical noise temperature dependences on IF are shown in Fig. 5 for four cartridges. Degradation of performance at around 12 GHz is due to a combination of several factors: SIS

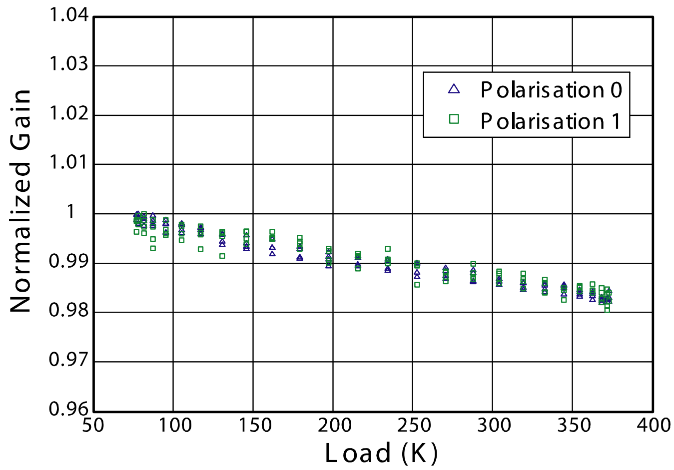

Fig. 8. Receiver small signal gain measured as a function of receiver input signal at 670 GHz LO frequency for two polarization channels.

mixer parasitic capacitance, degradation of 4-12 GHz isolator parameters and increase of noise temperature of cold IF amplifier. Nevertheless, an adequate 4-12 GHz IF band coverage has been achieved.

B. Receiver beam

A typical receiver 2-D beam pattern is shown in Fig. 6. The far field plot has been obtained by a Fourier transform of near field data, which contains both phase and amplitude information. The near field measurement system was based on a method developed earlier [2]. The signal to noise ratio was about 70 dB which is adequate for determining reliably all beam parameters.

The secondary mirror edge illumination taper is found to be in the range of 12 to 14 dB compared to a design value of 12 dB and the beam direction is very close to a nominal 0.94° offset from vertical direction.

The total power of cross polarization signal was found to be about –17 dB relative to a power in the co-polar beam. This is above ALMA specifications but in agreement with physical optics calculations done in GRASP [2].

C. Receiver saturation by a 100° C black body radiation

Special attention was given to measurements of receiver saturation/linearity. Calibration scheme of ALMA assumes that a 100° C black body will be used as one of the calibrators form band 9. It is important to be able to measure accurately a small signal receiver gain as a function of the input signal power.

The measurement layout is shown in Fig. 7. A small signal has been created by using a chopper wheel, covered by 300 K absorber, with an 80 K background liquid nitrogen load. This variable signal was inserted into receiver beam by means of a 14 micrometer thick Mylar beam splitter that has approximately 7 % coupling. A variable temperature load has been made of an additional 80 K liquid nitrogen absorber which is put into transmission arm behind a rotating linear polarizing grid. Signal reflected from the grid was terminated on the hot plate absorber which was kept at 100° C. By changing the angle of the grid one can present an input signal varying from 80 K to 373 K.

Receiver gain has been measured by using a fast Shottky diode power meter which was connected to a lock-in amplifier. The detection IF band of 4-12 GHz was determined by a band pass filter. Using large path length distances (0.8 m) and large IF detection bandwidth allowed us to average out standing waves that always exist in the experimental set-up, thus greatly improving the measurement accuracy compared to a single tone technique [5].

Signal from a lock-in amplifier was measured as a function of grid rotation angle for the range from 0° to 360° which resulted in passing through the same range of input temperatures four times. Input signal strength can be calculated from the grid angle using a Cos^2 law. A typical measurement results are shown in Fig. 8. Receiver compression of less than 2 % has been observed for a 100° C load. Measured gain repeats well when passing the input power range several times which confirms that measurement accuracy is adequate. The measured value of gain does not depend on the level of liquid nitrogen in the load which confirms that this set-up is immune to the presence of moderate standing wave in the system.

IV. Conclusion

In conclusion, we have manufactured and fully characterized eight units of ALMA band 9 receiver covering a 602 to 720 GHz input frequency range. All units demonstrated consistent receiver characteristics with the best measured noise temperature of all being 60 K. An improved measurement set-up has been created for measurements of gain saturation which has low measurement uncertainty due to averaging of receiver standing waves. Receiver gain compression below 2% has been demonstrated for 100° C load.

Acknowledgment

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