ALMA Band 9 cartridge

A.M. Baryshev[1,2], F.P. Mena[1,2], J. Adema[1,2], R. Hesper[1,2], B. Jackson[1], G. Gerlofsma[2], M. Bekema[2], K. Keizer[1], H. Schaeffer[1], J. Barkhof [1,2], C.F.J. Lodewijk[3], D. Ludkov[3], T. Zijlstra[3], E. van Zeijl[3], T.M. Klapwijk[3], W. Wild[1,2]

[1] *SRON Netherlands Institute for Space Research, Groningen, the Netherlands*

[2] *University of Groningen, Kapteyn Astronomical Institute, Groningen, the Netherlands*

[3] *Kavli Institute of Nanoscience, Faculty of Applied Sciences, Delft University of Technology Lorentzweg 1, 2628 CJ Delft, The Netherlands*

* Contact: A.M.Baryshev@sron.nl, phone +31-50-3638287

***Abstract*— The Atacama Large Millimeter Array (ALMA) is a collaboration between Europe, North America, and Japan to build an aperture synthesis telescope with more than 50 12-m antennas at 5000 m altitude in Chile. In its full configuration, ALMA will observe in 10 bands between 30 and 950 GHz, and will provide astronomers with unprecedented sensitivity and spatial resolution at millimetre and sub-millimetre wavelengths.**

Band 9, covering 602-720 GHz, is the highest frequency band in the baseline ALMA project, and will thus offer the telescope's highest spatial resolutions.

This paper describes the design of the Band 9 receiver cartridges for the Atacama Large Millimeter Array (ALMA). These are field-replaceable heterodyne front-ends offering high sensitivity, 602-720 GHz frequency coverage, 4-12 GHz IF bandwidth, and high quasioptical efficiencies. Because the project will ultimately require up to 64 cartridges to fully populate the ALMA array, two key aspects of the design of the Band 9 cartridge have been to take advantage of commercial manufacturing capabilities and to simplify the assembly of the cartridge.

I. INTRODUCTION

The Atacama Large Millimeter Array (ALMA) is a collaboration between Europe, North America, and Japan to build an aperture synthesis telescope with 64 12-m antennas at 5000 m altitude in Chile [1]. In its full configuration, ALMA will observe in 10 bands between 30 and 950 GHz, and will provide astronomers with unprecedented sensitivity and spatial resolution at millimetre and sub-millimetre wavelengths.

Band 9, covering 602-720 GHz, is the highest frequency band in the baseline ALMA project, and will thus offer the telescope's highest spatial resolutions. Furthermore, sub-mm observations with Band 9 of ALMA will provide complementary information to observations with the observatory's lower frequency bands, due to the fact that submillimeter line observations typically probe warmer, denser material than mm-wavelength observations, while continuum observations over a broad range of frequencies will better constrain dust temperatures.

The ALMA Band 9 cartridge is a field-replaceable unit containing the core of a 600-720 GHz heterodyne front-end. 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.

Primary requirements of the Band 9 cartridges include:

- double side-band (DSB) operation with $T_{N,rec}$ = 173 K over 80% of the 614-708 GHz LO frequency range;
- an intermediate frequency (IF) bandwidth of 4-12 GHz with low power variation across the band (6 dB peak-to peak and 4 dB within any 2 GHz) and a total output power level of -37 to -24 dBm;
- detection of two orthogonal linear polarizations with cross-polarization levels of -20 dB;
- 80% coupling of the cartridge's optical beam to the telescope secondary;
- long lifetime and high reliability; and
- the design must be consistent with the need for series production of 64 cartridges.

A series of first eight band 9 receivers (see Fig. 2) has been finished and fully tested. This paper will report and summarize the measured performance and discuss possible steps for further improvement.

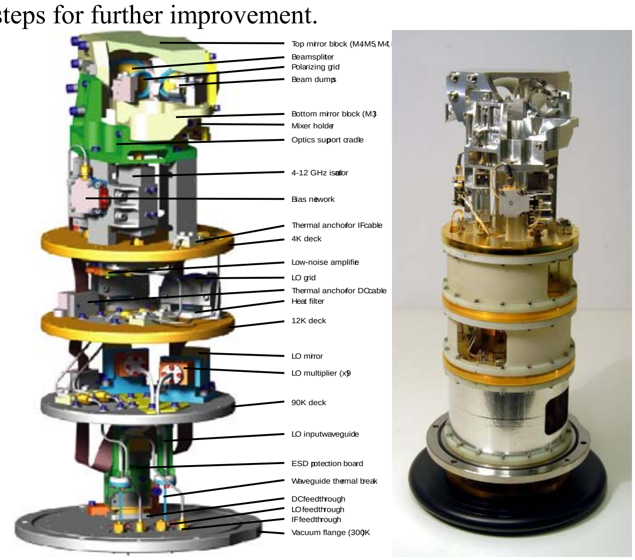

Fig 1 Layout (left) and photograph of ALMA band 9 receiver cartridge.

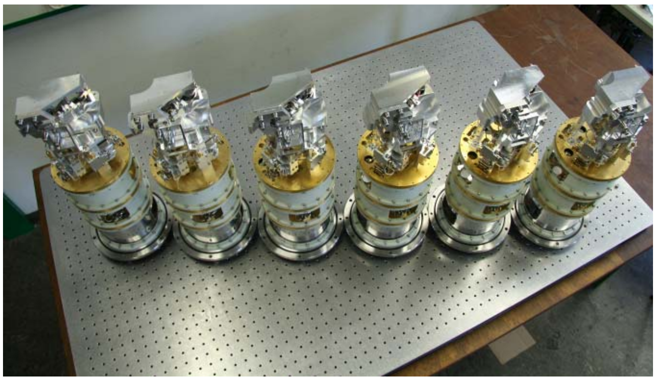

Fig 2, Photograph of six ALMA band 9 cartridges of a series of eight pre-prototypes, two cartridges have already been delivered to the ALMA project.

The detailed receiver design has been reported earlier and can be found in [2, 3, 4].

II. ACHIEVED RECEIVER PERFOMANCE

In this section we summarise the performance that was achieved for the first series of eight band 9 receiver cartridges as measured in a small cartridge cryostat that contains only one cartridge. The 2.7 K temperature at the 4K-stage at the test cryostat was actually heated up by a system of resistive heaters and kept at 4 K to represent the expected ALMA front end cryostat temperature level. All measurements reported in the following sections were performed at 4 K mixer temperature unless stated otherwise.

A RF Band coverage

The receiver RF coverage was measured by means of a Fourier Transform Spectrometer (FTS) for each of the SIS mixers. A summary of measurement results is shown in Fig 3. Good repeatability for many SIS mixer units has been achieved. Note that the data was obtained in air with long beam paths (~1 m) and the response is modified by a water vapour absorption lines at around 557 GHz and 753 GHz. The sensitivity curve is peaked at the higher end of ALMA band 9 because of the better atmospheric transmission at the ALMA site at these frequencies. The total receiver bandwidth is limited due to the maximum achievable current density of the AlO_x SIS junction technology (9 kA/cm^2). Making the design bandwidth wider for this current density value can only be done by reducing the peak coupling and thus degrading the receiver noise performance [5]. A different type of SIS junction barrier based on AlN [6] allows to achieve wider band coverage as discussed in [5] and also in the following sections.

The receiver noise temperature was measured by a standard Y-factor technique using 300K and 80K black body radiators presented in front of the receiver. The IF coverage has been analysed by using a tunable 4-12 GHz YIG filter with a bandwidth of approximately 40 MHz. The receiver noise temperature, integrated over the 4-12 GHz IF band is presented in Fig. 4 as a function of LO frequency. All receivers have been measured with the same experimental set-up following the same LO frequency plan allowing easy comparison. Noise temperature values are not corrected for LO insertion optics that is internal to the receiver. Fig. 4 data directly represents sensitivity values that one would expect to obtain at the ALMA telescopes.

The best achieved noise temperature is about 80 K for a 4 K mixer physical temperature. This number improves to ~ 63 K when the mixer is cooled to 2.7 K – the lowest temperature the closed cycle cooler can reach in the test set-up.

The performance of ALMA as an interferometer and the integration time is determined by the most insensitive receiver unit of the interferometer, thus additional attention was given to uniformity. Excellent repeatability of the receiver noise performance has been achieved for the first eight receivers in the 640 – 700 GHz range.

The noise temperature degradation towards the lower part of the ALMA band 9 fully corresponds to a reduced mixer coupling that was measured by the FTS (see Fig. 3). This is due to bandwidth limitations of the AlO_x junction technology and is expected to be improved by the application of AlN tunnel barriers.

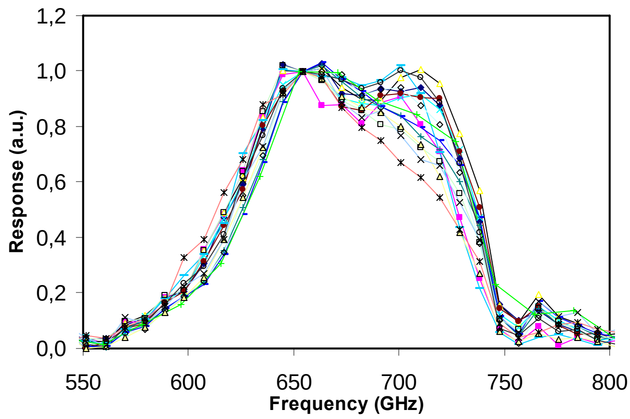

Fig. 3, RF band coverage of eight pre-production band 9 receivers measured with a Fourier Transform Spectrometer using the SIS mixers photo response.

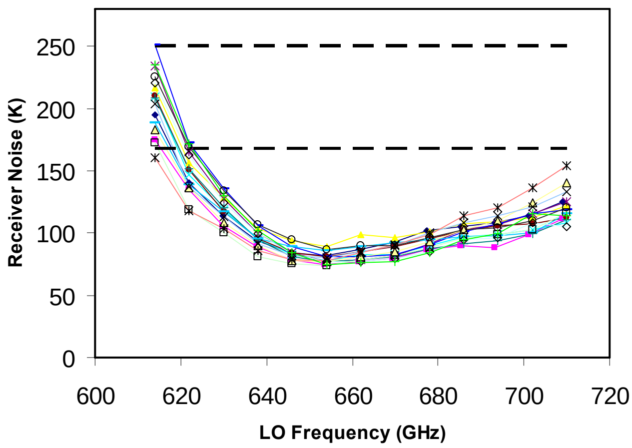

Fig. 4, ALMA Band 9 receiver noise temperatures, integrated over the 4-12 GHz IF vs. LO frequency measured in front of the receivers. There are 16 curves corresponding to 8 receivers with two polarisations each. Dashed lines are ALMA specifications for sensitivities across 20% (upper line) and 80% (lower line) of the frequency band, respectively.

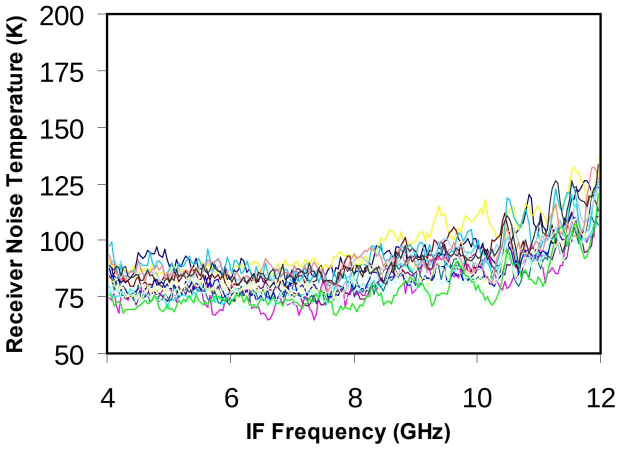

Fig. 5, Measured receiver noise temperature as a function of IF for eight cartridges, for two polarization channels each, at 670 GHz LO frequency.

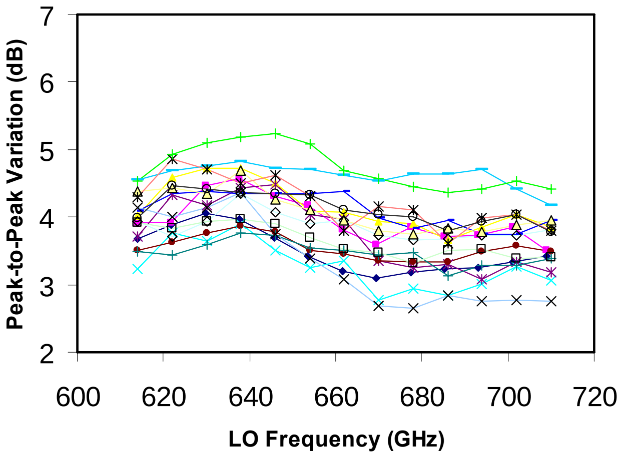

Fig. 6, Estimated maximum peak to peak output IF power variation in a 2 GHz window vs. LO frequency.

C. IF band coverage

The typical receiver IF response is shown in Fig. 5. The noise temperature was measured by means of the Y-factor technique for each IF frequency, which was set by an electronically tuneable YIG filter. The filter bandwidth is approximately 40 MHz. Excellent IF coverage is achieved for IF frequencies below 11 GHz with a minimum noise temperature of about 75 K. The response above 11 GHz is degraded because of several reasons:

- The single junction tuning circuit used in the mixer chip design has a relatively large stray capacitance that shortens out the SIS junction at large IF frequencies. This effect starts to be visible already above 8 GHz IF.
- All IF components used in the cartridge IF chain such as IF isolator, cryogenic IF amplifier, and room temperature IF amplifier have their performance simultaneously degraded at frequencies above 11 GHz. This explains the sharp increase of noise temperature above 11 GHz.

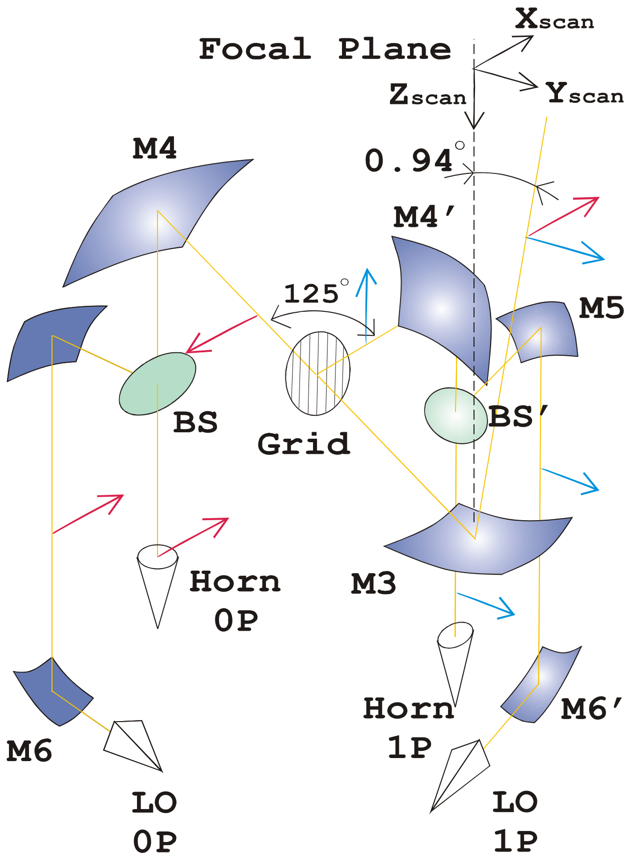

Fig. 7, Optics layout of the band 9 system.

Typical maximum receiver IF output power variations within any 2 GHz wide window of IF band is shown in Fig. 6 for all eight cartridges with two polarisations each. This is an important receiver parameter, because ALMA uses two bit digitization in its correlator leading to a limited dynamic range of the backend. A typical value of peak-to-peak variation was about 4 dB.

D. Receiver optics performance

The ALMA band 9 optics layout is shown in Fig. 7. The signal coming from the secondary mirror passes mirror M3 and is then split by a polarising grid into two polarisations codenamed “0P” and “1P”. After the grid the receiver beam is reflected off mirrors M4 and M4’ for each polarisation, correspondingly, and then reaches the mixer corrugated horns. The local oscillator is located at he 90 K cartridge stage and so are mirrors M6 and M6’. The LO signal coming from LO horns passes mirrors M6, M5 and is reflected off a 6 micron thick mylar beam splitter towards the mixer horn for polarisation 0P. Similarly, the LO signal follows the Horn 1P-M6’-M5’-BS’-1P horn path. The excess of LO power that comes through the beamsplitters is terminated in beam dumps (not shown in the picture) located at the 4 K level.

Locating the final stage of the LO multiplier at 90 K and beam dumps allows to minimise the effect of LO insertion to the receiver noise. The added noise from the LO insertion is only about 5..10 K, compared to 15..30 K for a similar arrangement located at the 300 K temperature level.

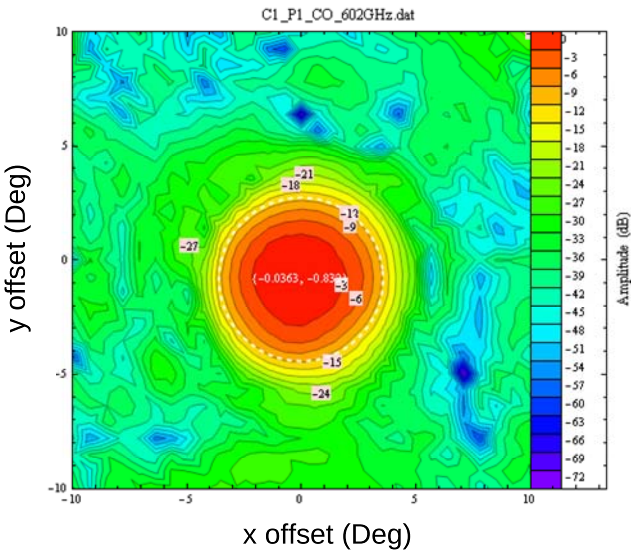

Fig. 8, Far field pattern of the band 9 receiver obtained from measured near field phase and amplitude data. The response is corrected for the source feed horn. The extent of the ALMA telescope secondary mirror is shown as a white dashed line.

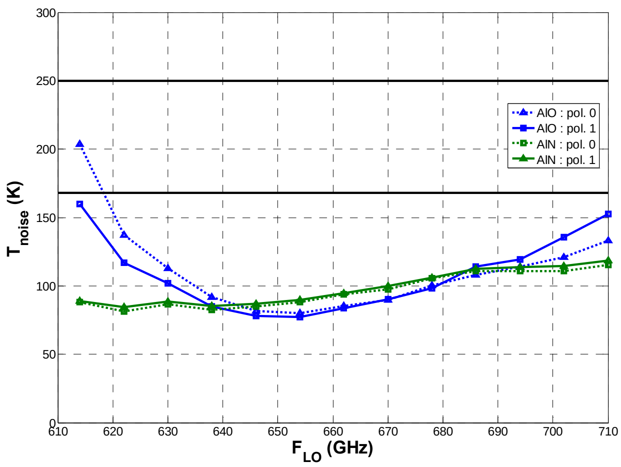

Fig. 9, Measured noise temperatures for AlN and AlOx barrier mixers. The same ALMA band 9 cartridge was used for measurements. The noise temperature is integrated across the 4-12 GHz IF band.

Coupling of the receiver beam to the telescope is one of the key parameters along with noise temperature, determining the overall receiver performance. Therefore careful measurements and analysis have been performed to evaluate the band 9 optics performance [3]. A near field beam pattern measurement system has been developed for this purpose and near field phase and amplitude measurements were carried out for all eight receivers at the band edges and in the middle of the band.

A typical far field beam pattern of a band 9 cartridge is presented in Fig. 8. This pattern was obtained from a near field scan at 602 GHz signal frequency. It demonstrates uniform illumination of the secondary mirror, shown as dashed line contour, with an edge taper of approximately 12.5 dB. This is very close to the design value of 12 dB. The most important parameter here is the aperture efficiency which characterises how much power from a plane wave reaching the telescope is coupled to the receiver. This value can be determined from the measured data and is 82-84% across the ALMA band which is better than the ALMA specification of 80%.

III. AlN Barrier Technology

Recently, a new batch of SIS junctions utilizing an AlN barrier was manufactured and mixer chips suitable for putting into the ALMA band 9 receiver system were delivered. The achieved current density is about 30…50 kA/cm^2.

Using one of the band 9 cartridges as a test bed, performance of the AlO_x and AlN junctions was compared in strictly the same environment and by using the same standard measurement procedures which were developed to characterise ALMA band 9 cartridges [7]. The noise temperature comparison between the two technologies is presented in Fig. 9. It is clear that the RF band coverage is improved without degrading the receiver overall performance. The impact is especially visible at the band edges. For details see [8].

Conclusions

A first series of eight ALMA band 9 receiver cartridges has been completed and fully characterised. All receivers show excellent sensitivity (min T_n=75 K) and IF band coverage (4-12 FGz). An aperture efficiency of 82..82% has been reached for all receivers at all frequencies. New AlN barrier technology has been used for the first time in the ALMA band 9 system leading to significant improvements of the RF band coverage without degradation of noise temperature. This gives an opportunity for further improvements of ALMA band 9 receiver performance.

Acknowledgment

This work has been partially funded by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), under ESO contract numbers 73072/MAP/03/8632/GWI and 16173/ESO/07/14997/YWE. This work was also supported by the Netherlands Research School for Astronomy (NOVA) within a NOVA-II grant. This work has also benefited from research funding from the European Community's Sixth Framework Programme under RadioNet R113CT 2003 5058187.

References

[1] www.alma.cl, www.alma.nrao.edu, www.eso.org/alma .

[2] Hesper, R., Jackson, B.D., Baryshev, A., Adema, J., Wielienga, K., Kroug, M., Zijlstra, T., Gerlofsma, G., Bekema, M., Keizer, K., Schaeffer, H., Barkhof, J., Mena, F.P., Rivas, R., Klapwijk, T.M., Wild, W., "Design and Development of a 600-720 GHz Receiver Cartridge for ALMA Band 9", *16th Int. Symp. on Space Terahertz Technology*, 2005

[3] M. Candotti, A.M. Baryshev, N.A. Trappe, R. Hesper, J.A. Murphy, J. Barkhof, "Quasi-optical Verification of the Band 9 ALMA Front-End", Proc. Of 16th Int symp on Space Terahertz Technology, pp. 79-84, 2005

[4] C. F. J. Lodewijk, M. Kroug, and T. M. Klapwijk, "Improved design for low noise Nb SIS devices for band 9 of ALMA (600–720 GHz)," *Proc. 16th Int. Space Terahertz Technol. Symp., Göteborg, Sweden*, 2005, paper S03-05.

[5] Jacob W. Kooi, Attila Kovács, Matthew. C. Sumner, Goutam Chattopadhyay, Riley Ceria, Dave Miller, Bruce Bumble, Henry G. LeDuc, Jeffrey A. Stern, and Tom G. Phillips, "A 275–425-GHz Tunerless Waveguide Receiver Based on AlN-Barrier SIS Technology", *IEEE trans. On Microwave Theory and Techniques*, vol. 55, NO. 10, Oct 2007

[6] T. Zijlstra, C. F. J. Lodewijk, N. Vercruyssen, F. D. Tichelaar, D. N. Loudkov, and T. M. Klapwijk, "Epitaxial aluminum nitride tunnel barriers grown by nitridation with a plasma source", *Appl. Phys. Lett.*, 91, 233102 (2007)

[7] A.M. Baryshev, R. Hesper, F.P. Mena, B.D. Jackson, J. Adema, J. Barkhof, W. Wild, M. Candotti, M. Whale, C. Lodewijk, D. Loudkov, T. Zijlstra, T.M. Klapwijk, "Performance of ALMA band 9 receiver series", Proc. Of 18th Int symp on Space Terahertz Technology, Pasadena, Californis, USA, 2007

[8] C. F. J. Lodewijk, E. Van Zeijl, T. Zijlstra, D. N. Loudkov, and T. M. Klapwijk, "Bandwidth of Nb/AlN/Nb SIS mixers suitable for frequencies around 700 GHz", these proceedings, 2008.