Performance of the Band 3 (84-116 GHz) receiver for ALMA

S. Claude, F. Jiang, P.Niranjanan, P. Dindo, D. Erickson, K. Yeung, D. Derdall, D. Duncan, D. Garcia, D. Henke, B. Leckie, M. Pfleger, G. Rodrigues, K. Szeto, P. Welle, I. Wood and K. Caputa, A. Lichtenberger and S-K. Pan

***Abstract*— Band 3 covering 84 to 116 GHz is one of the ten bands that will form the Front End Receiver for the Atacama Large Millimetre Array. A Band 3 receiver prototype and one unit have been assembled and tested at the Herzberg Institute of Astrophysics. This paper will give an overview of the Band 3 design and also present the performance of the first deliverable unit. The single sideband (SSB) system noise exceeds the specifications (TSSB< 37 K) over the full RF band with a minimum TSSB of 26 K and a maximum of 34 K. In addition to details of the system noise performance other characteristics such as image rejection and cross-polarization are also presented.**

I. Introduction

The Atacama Large Millimetre Array (ALMA), that will be built in the Atacama desert in Chile at 5000 m altitude, consists of an array of 50, 12 m antennas operating in the millimetre and sub-millimetre range. An additional 16 antennae array will form the Atacama Compact Array. The Band 3 receivers, covering the frequency range 84-116 GHz, will operate in spectroscopic and continuum modes on both arrays.

II. Receiver Design

The receiver consists of a cartridge (Fig. 1) that can be inserted in the main ALMA front-end cryostat. The signal collected by the telescope is focussed to the Band 3 cartridge using a set of warm mirrors (one flat and one ellipsoidal) that are fixed to the top surface of the front-end cryostat [1]. Note that the data presented in this paper were taken without the warm mirrors. After the vacuum window (consisting of a moulded high-density polyethylene disk with anti-reflection grooves on both sides), IR filtering is done at 80 K will be a PFA moulded disk and at 15 K with a Mupore membrane [1].

On the 4 K stage the input signal is collected by a corrugated aluminium feedhorn and its PTFE plano-convex lens [1]. The two orthogonal polarizations (0 and 1) are split using an Orthomode Transducer (OMT) [2]. From that point, the two polarization channels are identical in design and therefore only one of the two will be described.

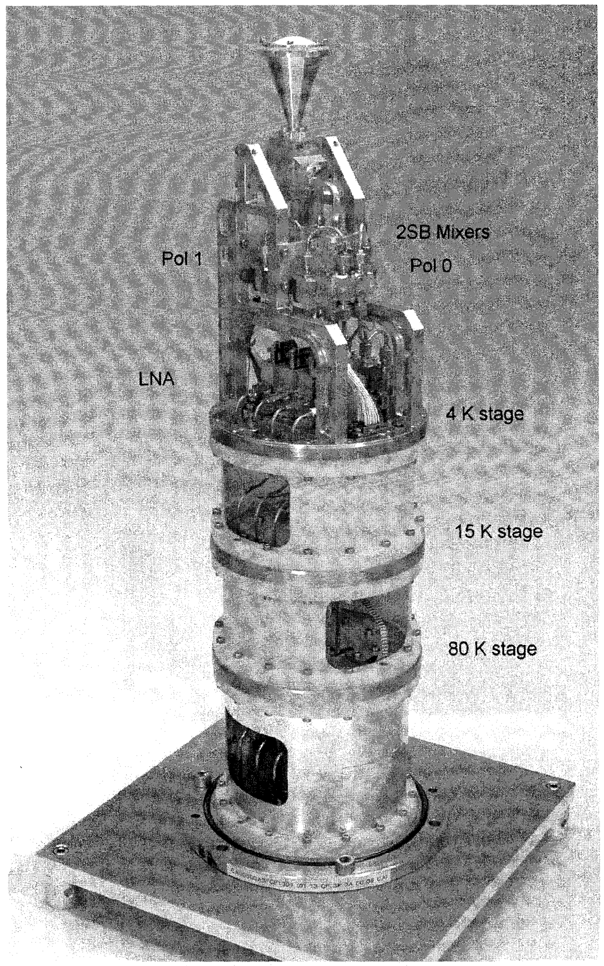

Fig. 1: Photograph of the Band 3 cartridge (height is 508.5 mm)

The RF signal (84-116 GHz) is down converted to 4-8 GHz using a side-band separating (2SB) mixer unit which is described in detail in [3]. The outputs of the 2SB unit are the upper sideband (USB) and the lower sideband (LSB) centred at 6 GHz. The signals are then amplified with cryogenic low noise amplifiers [4] fixed to the 4K stage. Since these amplifiers are optimized for low noise, bandwidth, and gain (rather than the input RF impedance match) the use of 4-8 GHz isolators (from Pamtech)

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A. Lichtenberger is with the University of Virginia, Charlottesville, USA

S-K. Pan is with the National Radio Astronomy Observatory, Charlottesville, USA

prevents signal reflections between the mixer unit and the amplifier.

The IF signals are then brought out to the cartridge vacuum flange using UT85 BeCu-SS coaxial cables. In order to satisfy the ALMA IF power level requirements, 30 dB room temperature IF amplifiers (one per IF channel) are added at the output of the cartridge.

To facilitate troubleshooting during operation, temperature sensors are placed at each stage of the cartridge and on each mixer assembly. Bias voltages for the mixers and the amplifiers are fed through two MDM-51 connectors on the vacuum flange. Inside the vacuum and room temperature, a mixer and LNA bias protection circuit card, consisting of clamp diodes, is connected to the MDM-51 feedthrough. The card also generates an electronic serial number for the cartridge and polarisation number. A standard twisted pair wiring harness (36 AWG phosphor-bronze, 450mm long), with MDM-25 connectors on each end, feeds the bias from the 300 K to the 4 K plate. Each amplifier has an integrated bias circuit for the SIS mixers.

The local oscillator (LO), of which a full description can be found in [5], is generated by a YIG oscillator (15-18 GHz). The LO signal is amplified and frequency multiplied by 6 before it is fed through the WR-10 vacuum feedthrough. A Mylar membrane is used to provide the vacuum seal for all feedthrough waveguides. The LO is brought to the mixer unit using an SS WR-10 waveguide (one per polarization) with bends to allow for thermal contractions between the different cryogenic stages. To attenuate the LO thermal noise, a 10 dB absorber is inserted at the 4 K end of the waveguide.

III. Receiver performance

A. *Receiver noise temperature*

The Band 3 receiver is tested at HIA using a three stage cryostat, provided by the National Astronomy Observatory of Japan (NAOJ). The Band 3 cartridge noise temperature is measured using a liquid nitrogen load (bucket with absorber liner) and a room temperature load. A chopper wheel switches the input signal from the hot to the cold load. The output IF of the receiver is filtered using a fixed bandpass 4 GHz filter for the wideband measurement or a 100 MHz YIG filter for narrow band measurements. The signal is then amplified before it is detected by an Agilent 4418B power meter and an Agilent 4412A CW power sensor. The receiver noise temperature of the Band 3 receiver is using the standard equation:

$$T_{rec} = \frac{Th - Tc \times Y}{Y - 1} \text{ where}$$

$$Y = \frac{PHin}{PCin}$$

Th and *Tc* are the calibrated hot and cold load temperatures. Since the liquid nitrogen bucket is seen by the feedhorn after a couple of mirror reflections, the true temperature of the cold load is not the same as the temperature of the boiling point of liquid nitrogen which is 77.35 K. The cold load is calibrated by placing a cone made of the AN72 Eccosorb absorbing material directly over the cryostat window. *Tc* is calculated to be 83.3K

PHin and *PCin* are power meter readings when the hot and the cold loads are presented to the input of the band 3 receiver. Therefore, *Trec* is the measured single side band noise temperature, un-corrected for imperfect image rejection. The corrected single side band noise temperature is calculated as follows;

$$T_{SSB} = Trec\left(1 + \frac{1}{R}\right)$$

where
R is the image rejection.

If the measured receiver noise is 37 K, the added noise can be 3.7 K for a 10 dB image rejection or 0.37 K for a 20 dB image rejection. Typically, for the band 3 receiver, a 15 dB image rejection (see section B below) is obtained so the added noise is 1.1 K. Noise temperatures presented in this paper are corrected for the imperfect image rejection of the 2SB mixers.

In the ALMA cryostat, the Band 3 mixers will be operated at a temperature of 4 K +/-0.25 K. Furthermore, a separate tuning table will be used for each of the mixers. Therefore, it is important to generate the tuning table (mixer bias and LO power as function of LO frequency) for optimum noise performance at the prescribed operating temperature. Table 1 was generated by tuning the mixer of a prototype cartridge at 3.75 K and then the receiver noise was measured when the mixer was operated at 4.00 K and then 4.25 K. The same procedure was then followed at 4 K and then at 4.25 K. Tuning the mixer at 4.00 K provides the optimum noise performance for a mixer that will be operated between 3.75 and 4.25 K. When the mixers are cooled the I-V curves are changed so that the energy gap is increasing. As a result, the optimum bias is varying with operating temperature. It should be noted that for consistency with the ALMA cryostat, all mixer noise data presented in this paper were taken at 4.00 K. An improvement of 1.7 K can be obtained if the cryostat is cooling the mixers at 3.75 K.

Mixer tuning temperature (K)	*Measured Treceiver*		
	@ 3.75K	*@ 4.00K*	*@ 4.25K*
3.75	37.1	39.8	44.5
4.00	36.9	38.6	42.1
4.25	38.1	39.3	41.1

Table 1: Polarization 0 USB mixer temperature – Band 3 prototype

The Band 3 receiver single sideband noise performance is plotted for each of the four IF channels as a function of the RF frequency in Fig 2. Each point corresponds to an average of the noise taken in 4 GHz band centered at 6 GHz. Therefore, the receiver can detect signals within the full RF bandwidth 84-116 GHz simultaneously with two polarizations. The noise temperature specification is such that the noise must be less than 37 K for 80 % of the RF band and less than 62 K for any point within the RF band. This noise includes the input cryostat window at the input end and the warm IF amplifiers at the output end.

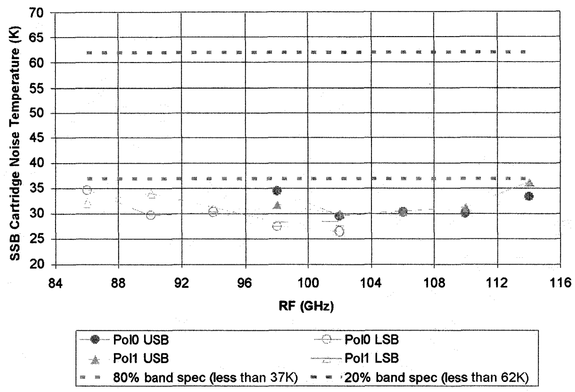

Fig 2. Band 3 Receiver broadband noise temperature

Using a 100 GHz YIG filter, the narrow band noise is also measured for each channel between 4 and 8 GHz. The noise must be less than +/-25% of the average noise. An example is shown in Fig 3.

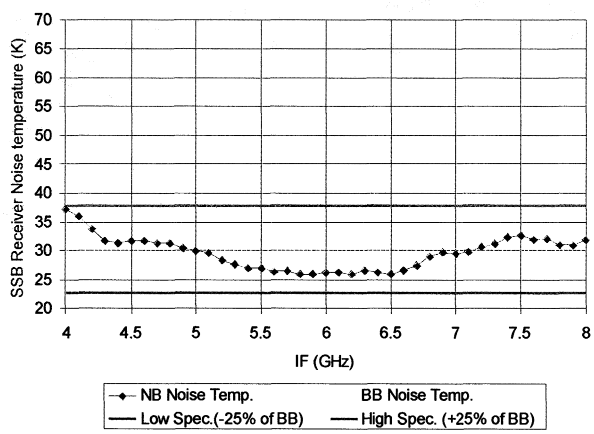

Fig 3: Narrow band noise temperature at LO=100 GHz, Mixer at 4.00K, Pol 0-USB

The noise temperature of the Band 3 cartridge, using a 2SB mixer, can be expressed by the following equation.

$$T_{receiverSSB} = 2(T_{receiverDSB}) + L_{optics}T_{load} - T_{optics}$$

where

T_{load} is 4.2 K, as the image side in the 2SB mixer is terminated by a absorber.

The optics, consist of all the components between the RF vacuum window to the input of the mixer units, T_{optics}=2.5 K, and L_{optic}=0.4 dB

This analysis assumes a perfect image rejection since the noise results in Fig. 2 have already been corrected.

And finally, $T_{receiverDSB}$ is the double side band noise of the mixer including the LO sideband noise which is less than 1 K. Also, the use of a cryogenic attenuator (10 dB) between the LO and the 16 dB coupler reduces the thermal LO noise to a value of 2 K which is included in the $T_{receiverDSB}$.

$T_{receiverDSB}$ excludes the input optics as it is taken at the input of the mixer. The DSB noise consists of the mixer noise and gain in cascade with the cryogenic IF amplifier. The noise contribution of the isolator is 1 to 2 K. As for the mixer [6], its noise is estimated to be 5 to 10 K and conversion loss to be 0.8 to 3 dB. The IF chain noise is dominated by the noise of the cryogenic amplifier since its gain, 35 dB, makes the noise contribution of the subsequent component negligible, i.e. of the order of 0.1 K. The noise of the cryogenic amplifiers is 3.5 K, averaged across the full IF band width. As a result, $T_{receiver\ DSB}$ is equal 13K for best mixer gain and noise, and can be up to 22 K in the worst case.

Taking all the above mentioned noise contributions, the total estimated SSB noise varies from 25 K to 42 K. In practice, the noise varies from 26 K to 36K across the RF band for the four IF channels. It must be noted that the quantum noise at 100 GHz is hv/k=4.8K. Therefore, the best measured noise, 26 K at 102 GHz, is obtained with a mixer operating close to the quantum limit.

B. Image Rejection

In order to measure the image band suppression, a CW signal is injected through the hot load, using a WR-10 waveguide probe and detected in both upper and lower sidebands by the Band 3 receiver. The CW signal is generated by using an Agilent E8257D synthesizer and a X6 Millitech Multiplier. The image rejection of the cartridge is found by using the techniques of Kerr et. al described in [7]. The technique requires the measurement of heat power levels as listed in Table 2.

Input	*OutputPort Detection*
Hot Load	USB
Cold Load	USB
Cold Load	LSB
Hot Load	LSB
Signal source in LSB	LSB
Signal source in LSB	USB
Signal source in USB	USB
Signal source in USB	LSB

Table 2. Configuration of the input and output ports for the measurement of the image rejection.

The image rejection is measured in narrow band mode with a 100 MHz YIG filter across the IF band, for each LO frequency. An example is shown in Fig 4.

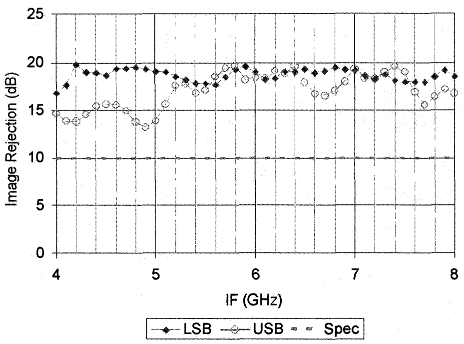

Fig 4: Image Rejection of the Pol 0, LSB and USB, in narrow band mode, at LO=100 GHz.

For each LO frequency, an average was calculated and plotted against the receiver RF bandwidth, in Fig. 5, for the four channels.

The only element in the cartridge that contributes to the image rejection quantity is the 2SB mixer described in [3]. The variation across the IF can be controlled by phase matching the IF cables connecting the DSB mixers and the IF quadrature coupler. The phase and amplitude imbalance of this later component is important as well.

On the RF side, the Phase and amplitude imbalance must be controlled by maintaining a high machining tolerance (5 microns) on the RF waveguide coupler. Also, the gain match of the DSB mixer must be controlled by RF pre-screening prior to the forming the 2SB assembly.

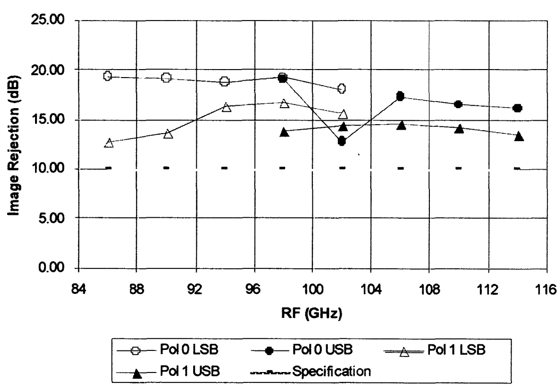

Fig. 5: Image rejection of the four channels

C. Cross-Polarization

Radiating a CW signal using a WR-10 waveguide in front of the receiver window allows to measure the cross polarisation of the Band 3 receiver. The optics of the receiver including the vacuum window, IR filters and corrugated horn plus lens, are not the dominant contributor to the cross polarisation, as opposed to the OMT, described in [2], which is the principal component generating the small amount of cross-polarisation shown in Fig. 6.

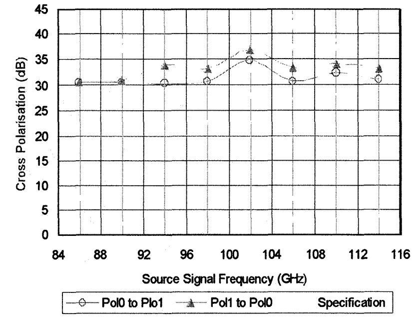

Fig 6. On-axis cross-polarisation

REFERENCES

[1] M. Carter et al. "ALMA Front-end Optics", SPIE Conference, Glasgow, U.K. June 21-25, 2004 pp 1074-1084 Vol. 5489

[2] Edward J. et al. "The Bøifot Orthomode Junction", ALMA MEMO #425, 2002/05/22

[3] P. Dindo et al. "Design and Characterization of Two Sideband SIS Mixer RF Hybrids for the Band 3 Receiver (84-116 GHz)", 30th Int. Conf. Infrared and Millimeter Waves, Williamsburg, USA, September 19-23, 2005.

[4] N. Jiang et al. "Low-noise InP HEMT amplifier", Proceedings of the SPIE, Volume 5489, pp. 848-857 (2004).

[5] E. Bryerton et al. "Development of Electronically Tuned Local Oscillators for ALMA", 30th Int. Conf. Infrared and Millimeter Waves, Williamsburg, USA, September 19-23, 2005

[6] S.-K. Pan et al "A Fixed-Tuned SIS Mixer with Ultra-Wide-Band IF and Quantum-Limited Sensitivity for ALMA Band3 (84-116 GHz) Receivers", 15th International Symposium on Space Terahertz Technology, April 2004.

[7] A.Kerr et al. "Sideband Calibration of Millimeter-Wave Receivers", ALMA Memo #357, March 27, 2001.