Performance of the First Three Preproduction 35 – 50 GHz Receiver Front-ends for Atacama Large Millimeter / submillimeter Array

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***Abstract*—The Band-1 receiver front-end cartridges for Atacama Large Millimeter Array, which covered 35 – 50 GHz frequency range, are now in preproduction stage. For the first three preproduction cartridges, the measured receiver noise temperature is less than 16-31K for any combination of the in-band RF and LO frequencies. The measured gain flatness, even with the limitation of the optical window of the cryostat and the broadband matching of the cryogenic amplifiers, is typically lower than 5 dB over any 2GHz window. Extracted aperture beam efficiency is typically higher than 80% over the full frequency range. The crosstalk over the orthogonal channel is lower than -63 dB. For the suppression of the unwanted lower sideband, the imaged band suppression is higher than 20 dB for the worst case and around 30 dB typically.**

***Index Terms*—radio astronomy, heterodyne receiver, cryogenic low-noise amplifiers, gain variation, upper sideband scheme**

I. Introduction

Millimeter-wave (mmw) interferometric array for astronomy was well developed since 1980s. The development of the mmw technology leads to the newer generation telescopes with superior capability such as higher sensitivity, broader instantaneous bandwidth, and excellent linearity. Currently, the world's largest radio telescope, Atacama Large Millimeter Array (ALMA), is equipped with Band-3 to Band-10 receivers covering the frequency range from 84 GHz up to 950 GHz. For longer wavelength, the Band-1 receivers provide frequency coverage over 35 – 50 GHz with 10 to 15 times quantum-limited sensitivity.

Components and subsystems for the ALMA Band-1 receivers were developed since 2008, including the low-noise amplifiers and the mixers [1-3], the optics system and the orthomode transducers [4-7], and the filters [8]. The design of the prototype receiver cartridge and the first system testing resulting was presented in [9] and [10]. Measured results of the first three preproduction receiver cartridges are presented in this paper. The specifications of the receiver key performance items are listed in Table I.

II. Receiver Front-End Cartridges

The cartridge of the ALMA Band-1 receiver front-end is divided into two parts, of the cold cartridge assembly (CCA) and the warm cartridge assembly (WCA). The CCA is operated under 15K temperature to cooled down the InP HEMT cryogenic low-noise amplifiers (CLNAs) to achieve quantum-limit performance. Orthomode transducer and horn antenna in

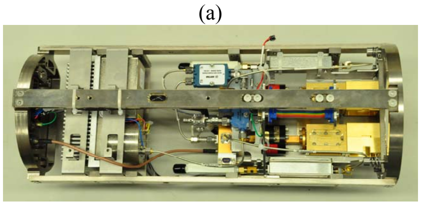
TABLE I.
SPECIFICATIONS OF THE ALMA BAND-1 RECEIVERS

Item	specification
RF Frequency (f_{RF})	35 – 50 GHz
LO Frequency(f_{LO})	31 – 38 GHz
IF Frequency (f_{IF})	4 – 12 GHz
Polarization	Linear, dual polarizations
Sideband Scheme	Upper sideband
Noise Temperature (T_{RX})	<32K fullband, <25K for 80% BW
Gain Compression	< 5% when the load temperature (T_{LOAD}) change from 77K to 373K
Image Band Suppression	> 10 dB over 90% of IF BW, > 7 dB over full IF BW
Total Output Power	-32 to -22 dBm in f_{IF} range (when 10K < T_{LOAD} < 800K)
IF Power Variation	< 6.0 dB for full f_{IF}, < 5.0 dB for any 2 GHz range, < 1.35 dB for any 31 MHz range
Amplitude Stability	<4 x 10^{-7} at 0.05 sec < T < 100 sec; <3.0 x 10^{-6} at T = 300 sec
Signal Path Phase Stability (Long-term delay drift)	< 22 fs for 20 sec < T < 300 sec
IF Phase Variation	< 4.5 degree RMS for any 31 MHz
Optics – Aperture Efficiency	> 80.0 %
Optics – Polarization Efficiency	> 99.5 %
Optics – Focus Efficiency	> 98.0 %
Optics – Illumination Error	< 5.0 mrad (0.287 degree)
Optics – Polarization Alignment	Within + - 2 degree
Cross Talk between the two orthogonal channels	-63 dB

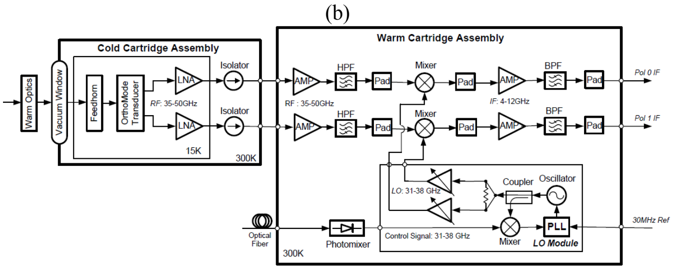
front of the input ports of the InP HEMT CLNAs are also cooled to 15K to minimize the input noise contribution to the system. The output of the CLNA is connected to the long stainless steel waveguide section for temperature gradient and thermal isolation, and then the signal passes through the isolator and vacuum feedthru to the WCA.

The RF chains in WCA are composed of 2nd stage RF amplifiers with high linearity, high-pass filters, diode mixers, IF amplifiers and IF bandpass filters. The CLNAs provide more than 35 dB gain, thus the noise contributed by the warm RF and IF chain is negligible. The local oscillator (LO) is generated by a Ka-band phase-locked YIG oscillator and then divided into two channel, and passing through variable gain amplifier to pump the mixers. Fig. 1 shows the cold cartridge assembly, warm cartridge assembly, and the block diagram.

(a)



(b)



(c)

Fig. 1. ALMA Band-1 receiver cartridges: (a) Cold cartridge assembly #01 and #02, (b) warm cartridge assembly #01, (c) receiver front-end block diagram, which is slightly different to the prototype shown in [10].

III. Measured Performance

For the specifications listed in Table I, the most critical ones are the receiver noise temperature, gain compression, IF power variation, and the stability. For these items, the measured results are discussed below. The optical performance is also briefly addressed.

A. Receiver Noise Tmperature

Since the Band-1 receiver is with the longest wavelength, HDPE lens in room temperature is used for focusing. Along with the two R blocking filters at 115K and 15K radiations shields, it is estimated that optics loss contribution to the receiver noise temperature is around 12.7 K at 35 GHz and reduced to 11.1 K at 50 GHz. The insertion loss of the OMT is around 0.4 dB, thus the noise contribution is around 1.5 K under 15 K environment. The cryogenic low-noise amplifier is with the 10–13 K mid-band and 13–18 K edge-band noise temperature, 35–37dB insertion gain, the estimated receiver noise temperature should be lower than 32 K at the higher frequency band edge and lower than 25 K over 80% of the receiver band.

Actually, additional noise ripple will be introduced by the impedance mismatch at the output of the CLNA. Due to the limitation of the hybrid microwave integrated circuit process, to fulfill the requirements of high gain, ultra-low noise and broadband requirement, the input and output reflection coefficient of the CLNA is sacrificed. The CLNAs are typically with reflection coefficients around -2 dB at the input ports and -4 dB at the output ports. With multiple reflections in RF path, one can observe that there is about ±2.5 K receiver noise temperature ripple over 0.5 GHz, as shown in Fig. 2(a). At any given RF frequency points, the measured results are lower than 31K at 49–50 GHz, and below 25K for 35–45 GHz. For any given LO frequencies, the receiver noise temperature in average over the whole IF band is lower than 26 K, as shown in Fig. 2(b).

B. Gain Compression

Gain compression of the receiver is actually determined by the output signal linearity of the RF/ IF components, especially the amplifiers and mixers. For the CLNA which received the signal, even with the 800 K hot load provided by the calibration system of the ALMA, with 37 dB nominal gain, the power level at the CLNA output should be around –30.7 to –28.5 dBm, which is far below the 5% compression point of the output transistor stage. But for the 2nd stage RF amplifiers with 25 dB gain, the output power is around – 5 to – 3 dBm, thus the linearity is a critical issue. For ALMA Band-1 receivers, from the experience gained from measurements, we estimated that the output 1-dB compression point of the 2nd stage RF amplifiers should be higher than +10 dBm, and the receiver IF output 1-dB compression point should be higher than +5.3 dBm to ensure the total system gain compression smaller than 5% when input load temperature is 373 K. After carefully adjusting the warm receiver chain configuration in WCA, the gain compression can be well fit to the specifications, as the measured results shown in Fig 3.

C. IF Power Variation

For broad instantaneous IF bandwidth heterodyne receiver of the radio telescope, the flatness of the in-band response is a key issue.The IF power variation are actually accumulation of the multiple reflection due to impedance mismatch and the variation of the transmission coefficients of the components. The major contribution comes from the cryogenic RF low-noise amplifiers, 2nd stage RF amplifiers, mixers and IF amplifiers.

The variation affects the effective bandwidth into the receiver backend: the frequency portion with higher spectral power will be the dominant bandwidth but the frequency portion with lower spectral power cannot be detected and thus the bandwidth is reduced. From the measurement, we found the variation is dominated by the cryogenic LNA. Fig. 4 shows the best IF power variation cases. Newer version of the output waveguide section for the CLNA will provide suitable attenuation to reduce the multiple reflections and thus reduce the output power variation.

D. Stability Test

Stability Test required for the ALMA receivers include the amplitude stability and the signal path phase stability. For the ALMA Band-1 receiver, the amplitude stability is mainly contributed by the shot noise and the cryogenic amplifier is dominant over the warm active contribution. Fig. 5 shows the measured amplitude stability of the three preproduction receivers. All three receivers are with $\sigma^2(T)$ below 3×10^{-7} over 0.03 to 300 seconds integration time, which well meet the specifications. For signal path phase stability, measured results are between 2–10 fs over 10–300 seconds integration time, which is also well fit to the specifications.

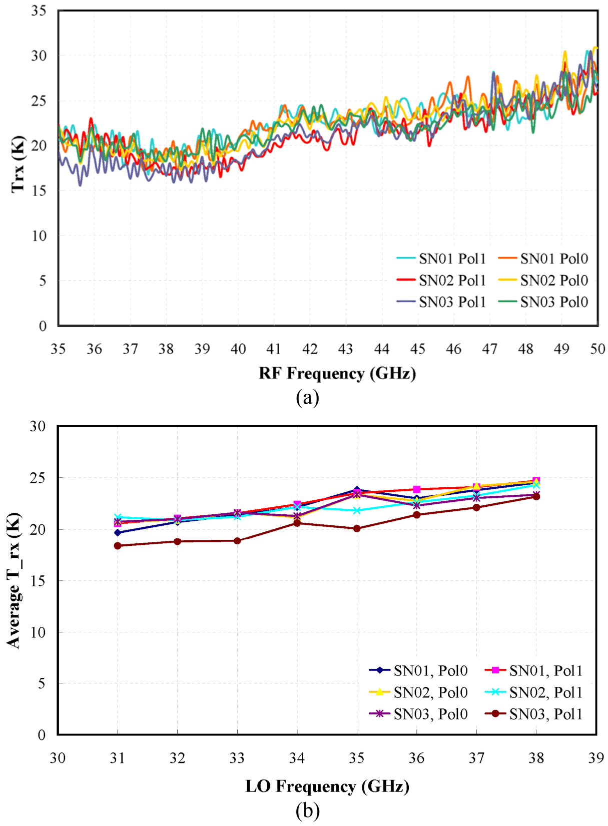


Fig. 2. Measured receiver noise temperature of the first three ALMA band-1 receiver (Serial Number SN01 –SN03), both pol-0 and pol-1 were measured. (a) RF frequency response. For the same RF frequency points with different LO frequencies, average values of the measured noise temperature are shown in the plot. (b) Average noise temperature over full IF band at different LO frequencies.

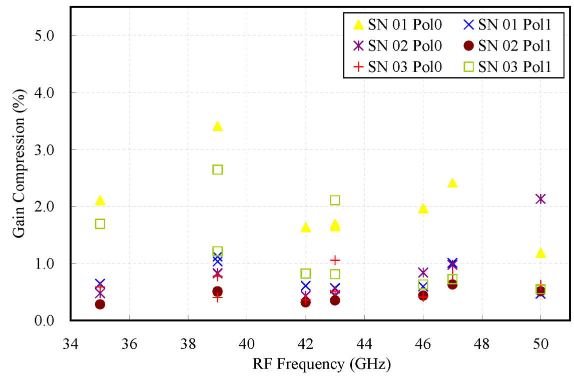


Fig. 3. Measured gain compression of the three preproduction receiver cartridges when input load temperature is 373K. Sampled frequency points are f_{LO} = 31, 35, and 38 GHz, f_{IF} = 4, 8, and 12 GHz. Please note that for the same receiver at the same RF frequency, the gain compression is different under different LO frequency. This is due to the LO-dependent RF power response of the diode mixers.

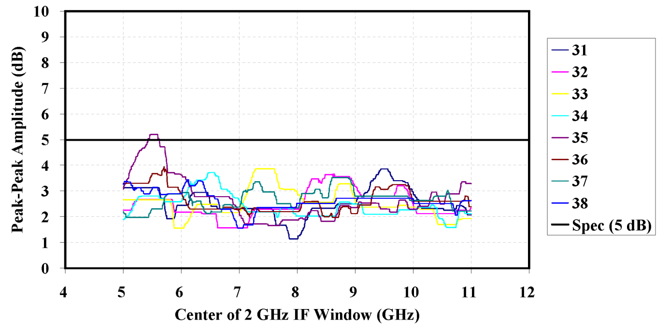


Fig. 4. Example of the measured receiver IF power variation of the ALMA band-1 receiver S/N 01 – 03.

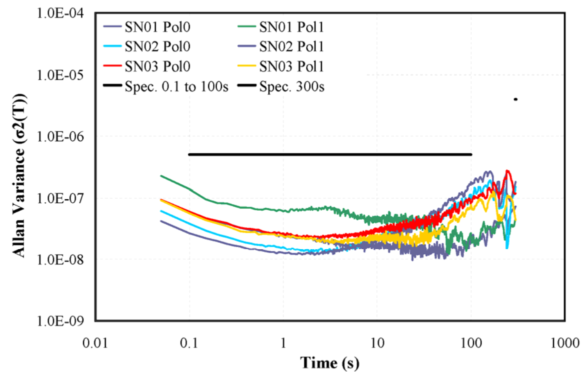


Fig. 5. Measured amplitude stability of the three preproduction receivers. The LO frequency is 35GHz, which corresponds to the RF frequency of 39 – 47 GHz.

E. Measured Optical Performance

The optical performance of the ALMA Band-1 receiver cartridges is measured based on the vector beam pattern scan, including taper efficiency (η_t), spillover efficiency (η_s), polarization efficiency (η_p), and focus efficiency (η_f), are measured and all extracted from the vector beam pattern scan. Then the aperture efficiency is calculated from these factors as

$$\eta_t \cdot \eta_s \cdot \eta_p \cdot \eta_f = \eta_{ap\_FE} \quad (1)$$

The other optical parameters like illumination error, and polarization alignment are also all extracted from the vector beam pattern scan. The results of the aperture efficiency and beam pattern are shown in Fig. 6 and Fig. 7.

F. Cross Talk

The cause of the cross talk of ALMA Band-1 receiver is mainly due to the limited isolation of the distribution network of the local oscillator and the reflection coefficient of the output ports of the 2nd stage RF amplifiers. Limited isolation between two orthogonal ports is also another contribution, but this factor should be negligible if considering 47–55 dB isolation between two orthogonal ports of the OMT. The measured cross talk of the three cartridges is shown in Table II. All the sampled frequency points are compliant to the specification, which should be –63 dB or lower.

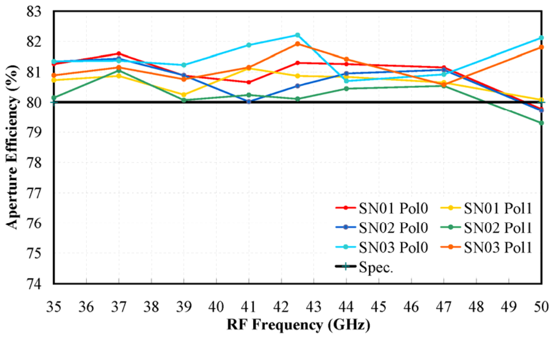


Fig. 6. Aperture efficiency over RF frequency for the SN01-03

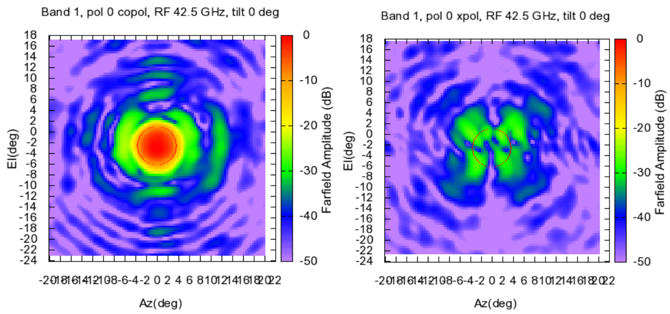


Fig. 7. Sampled beam pattern of the receiver optics: RF frequency = 42.5 GHz, SN 02 receiver, pol-0 co-polarization and cross-polarization.

TABLE II.
MEASURED CROSS TALK OF THE ALMA BAND-1 PREPRODUCTION RECEIVERS

LO	RF	Pol	SN 01	SN 02	SN 03
31	39	0	-78.02	-92.97	-77.04
31	39	1	-75.29	-93.99	-78.91
35	43	0	-79.41	-93.21	-82.75
35	43	1	-67.27	-92.22	-65.36
38	46	0	-72.19	-91.32	-74.77
38	46	1	-71.70	-95.21	-85.02

TABLE III.
COMPARISON OF THE Q-BAND RECEIVES FOR MILLIMETER-WAVE ASTRONOMY

Telescope	Frequency (GHz)	T_{RX} (K)	Ref.
Australia Telescope Compact Array (ATCA)	30–50 GHz RF, IF BW = 8 GHz/pol	27–50 K	[11]
Jansky Very Large Array (JVLA)	40–50 GHz RF IF BW = 8GHz/pol	23–39 K	[12]
Korea VLBI Network (KVN)	42.11–44.11 GHz IF BW = 2 GHz/pol	40–50 K (Ulsan), 70–80 K (other)	[13]
ALMA Band-1 (pre-production)	35–50 GHz RF, IF BW = 8 GHz/pol	17–31 K	(This work)

IV. COMPARISON AND SUMMARY

The existing radio telescopes with Q-band receivers are mostly built in 1980s, but in the past 10 years, based on the latest technology, most of them are all with receivers upgraded. In Table III, the measured performance of the Q-band receivers for inteferometric telescope array of radio astronomy are listed. With limitation set by the optics position among the group of the 10 receiver bands, ALMA Band-1 receiver front-end is with higher optical noise contribution but the receiver noise temperature is still the lowest one if compare to the other telescopes. With higher and drier site, the Band-1 receiver will provide states-of-the-arts system temperature and observation with highest mapping speed in Q-band.

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