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

Yuh-Jing Hwang\textsuperscript{a}, Chau-Ching Chiong\textsuperscript{a}, Yau-De (Ted) Huang\textsuperscript{b}, Chi-Den Huang\textsuperscript{b}, Ching-Tang Liu\textsuperscript{b}, Fang-Chia Hsieh\textsuperscript{b}, Yen-Hsiang Tseng\textsuperscript{b}, Po-Han Chiang\textsuperscript{b}, Chih-Cheng Chang\textsuperscript{b}, Chin-Ting Ho\textsuperscript{b}, Shou-Ting Jian\textsuperscript{b}, Chien-Feng Lee\textsuperscript{a}, Yi-Wei Lee\textsuperscript{a}, Alvaro Gonzalez\textsuperscript{c}, John Effland\textsuperscript{d}, Kamaljeet Saini\textsuperscript{d}, Marian Pospieszalski\textsuperscript{d}, Ricardo Finge\textsuperscript{e}, Valeria Tapia\textsuperscript{e}, Nicolas Reyes\textsuperscript{e}

\textsuperscript{a} Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), Taipei, Taiwan, ROC.
\textsuperscript{b} Aeronautical System Research Division, National Chung-Shang Institute of Science and Technology, Taichung, Taiwan, ROC.
\textsuperscript{c} National Astronomical Observatory of Japan (NAOJ), Tokyo, Japan
\textsuperscript{d} National Radio Astronomy Observatory (NRAO), Charlottesville, VA, USA
\textsuperscript{e} Universidad de Chile, Santiago, Chile

\texttt{yjhwang@asiaa.sinica.edu.tw}

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 inband 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
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. Receiver Noise Temperature
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 $3 \times 10^{-7}$ 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.

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 ($\eta_t$), spillover efficiency ($\eta_s$), polarization efficiency ($\eta_p$), and focus efficiency ($\eta_f$), are measured and all extracted from the vector beam pattern scan. Then the aperture efficiency is calculated from these factors as

$$\eta_{ap} = \eta_t \cdot \eta_s \cdot \eta_p \cdot \eta_f$$

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.
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.

**Table II. Measured Cross Talk of the ALMA Band-1 Preproduction Receivers**

<table>
<thead>
<tr>
<th>LO</th>
<th>RF</th>
<th>Pol</th>
<th>SN 01</th>
<th>SN 02</th>
<th>SN 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>39</td>
<td>0</td>
<td>-78.02</td>
<td>-92.97</td>
<td>-77.94</td>
</tr>
<tr>
<td>31</td>
<td>39</td>
<td>1</td>
<td>-75.29</td>
<td>-93.99</td>
<td>-78.91</td>
</tr>
<tr>
<td>35</td>
<td>43</td>
<td>0</td>
<td>-79.41</td>
<td>-93.21</td>
<td>-82.75</td>
</tr>
<tr>
<td>35</td>
<td>43</td>
<td>1</td>
<td>-67.27</td>
<td>-92.22</td>
<td>-65.36</td>
</tr>
<tr>
<td>38</td>
<td>46</td>
<td>0</td>
<td>-72.19</td>
<td>-91.32</td>
<td>-74.77</td>
</tr>
<tr>
<td>38</td>
<td>46</td>
<td>1</td>
<td>-71.70</td>
<td>-95.21</td>
<td>-85.02</td>
</tr>
</tbody>
</table>

**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 interferometric 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.

**References**


