A New Multiband Receiver for the ALMA Prototype 12 m Telescope of the Arizona Radio Observatory

E. F. Lauria, G. P. Reiland, A. W. Lichtenberger, A. R. Kerr, and L. M. Ziurys

Abstract – A new receiver has been designed, constructed, and tested and is in full scientific use at the 12 m telescope operated by the Arizona Radio Observatory (ARO). The receiver package consists of four separate dual polarization frequency bands in a modular cryostat with rapid band selection capability through a simple mirror assembly. The four bands cover the astronomically important atmospheric windows at 1.2 mm, 2 mm, 3 mm, and 4 mm wavelengths. In the 3 mm and 1.2 mm wavelength regions, the receiver employs Atacama Large Millimeter Array (ALMA) Band 3 (84–116 GHz) and ALMA Band 6 (211–275 GHz) sideband-separating (SBS) SIS mixers, while at 4 mm (67–90 GHz), cryogenic HFET amplifiers are used. Sideband separation for the 4 mm band is achieved through a room-temperature E-band down-converter developed at ARO. The 2 mm band (125–180 GHz) consists of SBS mixers developed from the device level by ARO in collaboration with the Central Development Laboratory at the National Radio Astronomy Observatory and the University of Virginia Innovations in Fabrication Laboratory. The 2 mm window is accessible by a single broadband mixer that covers all of ALMA Band 4 (125–157 GHz) and 40% of ALMA Band 5 (157–211 GHz). The mixer chip has a series array of four SIS junctions, similar to ALMA Bands 3 and 6. The new 2 mm mixers have noise temperatures $<$45 K across the majority of the RF range with image rejection $>$15 dB at most frequencies. The 2 mm mixers have proven to be exceptionally robust, with system temperatures $\sim$100 K on the sky at moderate elevations and good weather conditions and with excellent baseline stability. Scientific observations are currently under way in all four frequency regions.

1. Introduction

In 2013, the Arizona Radio Observatory (ARO) of the University of Arizona formally acquired the Atacama Large Millimeter Array (ALMA) 12 m prototype antenna, which at the time was located at the Very Large Array site of the National Radio Astronomy Observatory (NRAO) in New Mexico. This antenna replaced the aging 12 m antenna at Kitt Peak, formerly operated by NRAO but now an ARO facility. In the spring of 2013, the ARO staff began to disassemble the ALMA antenna, removing all ancillary equipment, electrical wiring, external mechanical structures, magnet motor drives, and other components, leaving only the reflector and its pedestal. In the fall of 2013, the reflector was removed from the pedestal, and both were transported separately to Kitt Peak via truck by Precision Heavy Haul, with help from Marco Crane. In the meantime, the old 12 m structure was removed from the dome on Kitt Peak and a new foundation prepared. The pedestal was installed in the dome in November 2013 and the reflector in December 2013. The antenna was then completely reassembled and the control system brought into working condition. The antenna was moving and tracking by July 2014, at which time the 3 mm receiver of the previous 12 m telescope was installed for operation. First light was in September 2014 at 115 GHz, and scientific observations began in December of that year. The new 12 m telescope was opened for full 3 mm operation in the spring of 2015.

The old 12 m telescope operated in three frequency bands: 68–90 GHz (4 mm), 90–116 GHz (3 mm), and 130–170 GHz (2 mm). The 3 mm band had been upgraded with ALMA Band 3 sideband-separating (SBS) mixers, but the other two bands utilized the previous generation of NRAO SIS mixers. These mixers employed adjustable backshorts for image suppression and had narrow IF bandwidths of only 600 MHz centered at 1.5 GHz. Therefore, when the new antenna was commissioned in 2014, the only viable receiver was the 3 mm band. To employ the full potential of the new 12 m telescope at the Kitt Peak site, a proposal was submitted by the fifth author to the Major Research Instrumentation Program at the National Science Foundation to construct a new receiver for the 12 m antenna with current-generation devices and state-of-the-art performance and was subsequently funded.

The new receiver, now complete, covers four frequency bands in separate modules (4 mm, 3 mm, 2 mm, and 1.2 mm) and is well matched to the Kitt Peak site. The 3 mm band uses ALMA Band 3 mixers, while the 4 mm and 1.2 mm bands employ devices (HFET MIC amplifiers and ALMA Band 6 mixers) developed at the NRAO Central Development Laboratory (CDL). The 2 mm band (125–180 GHz) required the development of a new mixer with a large IF bandwidth (4–8 GHz) and SBS architecture. Motivation for the 1.2 mm band was to allow the 12 m facility to join the Event

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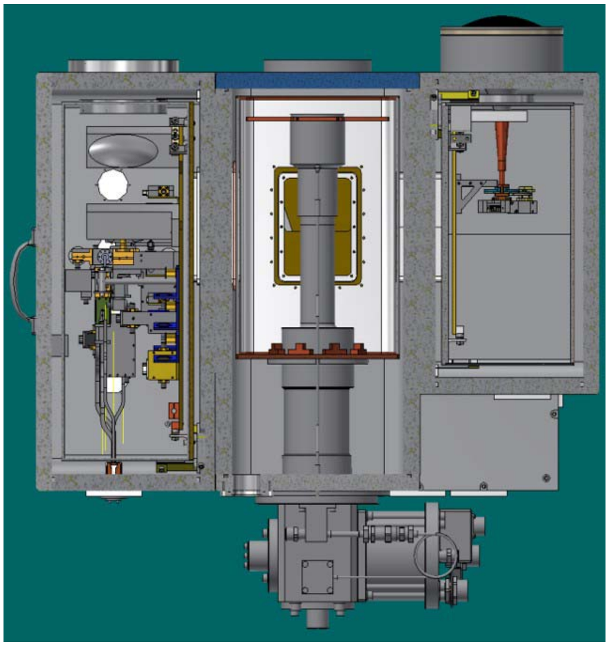

Figure 1. Cross section of the dewar design, showing the centrally located refrigerator cold head and two of the four attached modules. The 4 mm band is on the right, and 2 mm band is on the left. The electronic components are visible, mounted to their individual 4 K plate.

Figure 2. The complete receiver in its mounting frame. The dewar and its four modules are identified by their vacuum windows; the monitor and control electronics (temperature, vacuum, and bias control) are mounted under the dewar.

Horizon Telescope network as well as other spectral line studies.

2. Receiver Design

A main goal in the design of the new receiver was to simplify maintenance and provide easy access to the components inside the dewar. Hence, a modular approach was adopted, as shown in Figure 1. The cryocooler is mounted in a central frame that allows for its removal while the receiver is still attached to the telescope flange. Each band is contained in a rectangular module attached to one of four side walls of the central support frame. Optics, including the vacuum window for each band, are contained within the respective module. A central selection mirror, situated above the dewar, selects a given band for observations. Cryogenic electronic components are mounted on a plate cooled to 4 K within each module. This design enables easy access to these components for a given band as well as streamlined removal of that band if needed with the substitution of a blanking plate. It also allows for band upgrades and improvements without major modification of the dewar system and the central frame. All monitor and control systems, local oscillator, and IF switching electronics are mounted below the dewar package. These electronics control the mixer/cold amplifier bias, temperature monitors, waveguide, and IF signal routing to the back ends.

The complete receiver assembly is shown in Figure 2. The four frequency band modules are visible, each with its vacuum window, facing upward. Beneath the dewar are the control electronics and local oscillator system. The complete assembly, which weighs about 410 kg, is mounted in a frame that is 1.4 m in height (see Figure 2). The frame is bolted to the telescope flange at the secondary focus.

Additional flat mirrors for band selection lie above the dewar in the so-called widget-space. The complete receiver cools down in approximately 16 h.

The 3 mm, 2 mm, and 1.2 mm bands utilize SBS SIS mixers, providing two separate IF signals for upper sideband (USB) and lower sideband (LSB) simultaneously. ALMA Band 3 and ALMA Band 6 mixers are the core of the 3 mm and 1.2 mm bands. These devices were obtained from the Herzberg Institute for Astrophysics and NRAO, respectively. The 4 mm band employs cooled HFET amplifiers from M. Pospieszalski and a feedhorn/lens design by S. Srikanth, both at NRAO. A room-temperature down-converter, developed at ARO, enables sideband separation. All four bands are dual polarization and utilize waveguide orthomode transducers for separating the vertical and horizontal polarized signals (see, e.g., [1–3]). Four simultaneous IF channels (H-Pol/V-Pol, USB/LSB) are available, each with an IF of 4–8 GHz. These signals are coupled into the ARO Wideband Spectrometer (AROWS) back end. This digital Fourier transform spectrometer has a sampling rate of 10 Gs/s and can be configured to produce 2×4 GHz of continuous and usable instantaneous bandwidth. The digitizer/FPGA card was developed by Curtiss-Wright Corporation. Two such cards can be used to generate 16 GHz of instantaneous bandwidth (4×4 GHz), allowing all four IF channels to be processed simultaneously for observations.

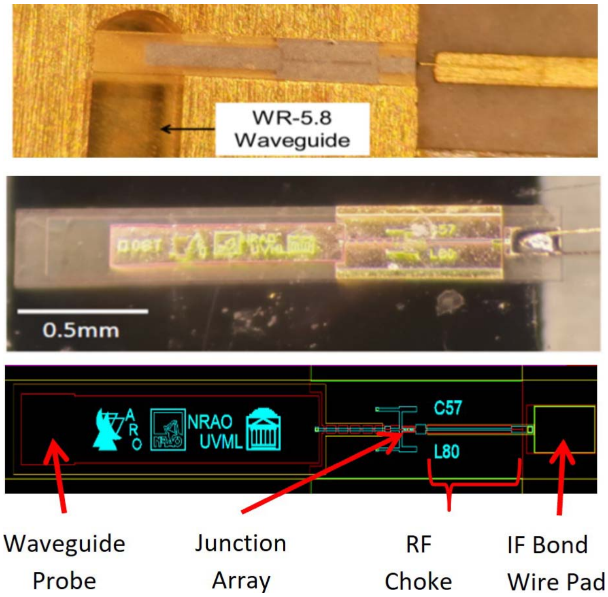

Figure 3. Bottom: The circuitry of the mixer chip. Middle: The 2 mm band mixer chip with IF bond wire soldered on its right edge. Top: The chip as mounted in its mixer block.

3. The 2 mm Band (125–180 GHz) Mixer: Design, Fabrication, and Performance

Development and implementation of the new 2 mm mixer was a key aspect of the receiver, as 2 mm was a legacy band for the former 12 m telescope. The 2 mm mixer was the first one to be developed in-house at ARO. The NRAO CDL assisted in the chip design, and the University of Virginia Innovations in Fabrication Laboratory IFAB fabricated the devices. The design specifications required a mixer that would be SBS, like those at 3 mm and 1.2 mm, and utilized niobium on a quartz substrate. In the SBS configuration, two double sideband mixers are situated between RF and IF quadrature hybrids. Each output of the IF hybrid provides the USB and LSB signals simultaneously with at least 16 dB rejection of the image sideband. The local oscillator is injected into the mixer by a waveguide power splitter and coupler.

The mixer chip was designed with microwave CAD tools, such as Sonnet for the mixer circuit layout, CST Microwave Studio for the 3D structures (e.g., waveguide probe and transmission line transducer), and Microwave Office as the linear simulator for the complete mixer circuit. The mixer substrate is 136 μm thick fused quartz. The mixer current density (J_c) and junction diameter, which determine the mixer junction capacitance, were specified by the IFAB. In this case $J_c = 3200$ kA/cm^2, and the junction diameter is 2.2 μm. A series array of four ($N = 4$) junctions was designed with a normal resistance R_N value of 38 Ω (R_N is the resistance of the array above the gap voltage). The $N = 4$ array results in a larger junction diameter that then reduces the leakage current (the current below the gap voltage). This arrangement reduces the noise and increases the dynamic range of the mixer. For example, when measuring a Y-factor using a room-temperature load, a single-junction mixer will reach saturation, whereas a multijunction series array will still be linear in its response.

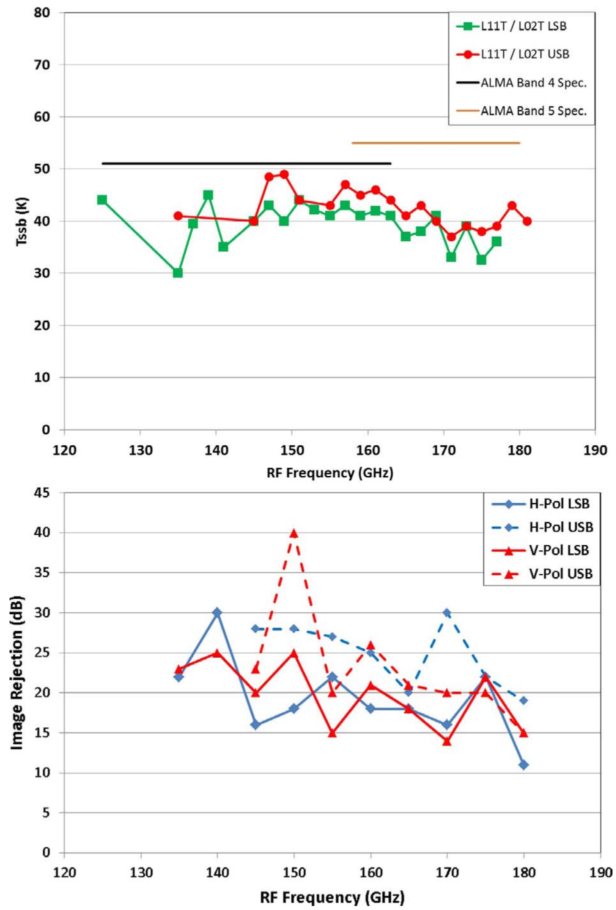

Figure 4. Equivalent receiver noise temperature (top) and image rejection (bottom) of a typical 2 mm band mixer. The ALMA specification for maximum equivalent noise temperature for 80% of the band is shown for Band 4 (black) and Band 5 (orange).

The fabricated chip is 2.4 mm in length and 0.4 mm in width. The IF bond wire is soldered onto the mixer chip by using a gap welding station with a soldering tip attachment. To mount the chip in its mixer block, it is turned over and placed in the device channel. The connection to ground is achieved by using 18 μm diameter pure gold wires placed on a 50 μm wide shelf in the channel that are slightly crushed when the top section of the split-block mixer is attached. Images of the SIS chip and its placement in the waveguide of the mixer block are shown in Figure 3.

Yield of the mixer chips was excellent (~90%). Also, the measured value of R_N agrees with its design goal of 38 Ω, indicating that the desired values for J_c and junction area were achieved in the fabrication process.

Figure 4 shows the noise temperature and image rejection of the ARO 2 mm mixer. As a reference point

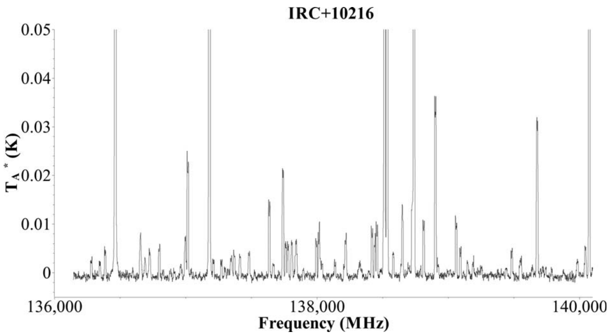

Figure 5. Spectrum of IRC+10216, observed with the new 2 mm receiver near 138 GHz. The sensitivity is <2 mK, peak to peak, after 53 h of integration time. Spectral resolution is 2 MHz.

for the current state of the art, the ALMA specifications for Bands 4 and 5 are shown in black and orange on the same graph. Note that ALMA covers the 2 mm atmospheric window in two separate bands; in contrast, ARO chose their RF bandwidth based on the old 12 m, 2 mm receiver, which covered ~125–180 GHz. As shown in the figure, the measured SSB equivalent noise temperatures are at least as good as the ALMA specifications. Furthermore, the ALMA specification for image rejection is a modest –10 dB, as the main concern is the reduction of atmospheric noise. However, this value is not adequate for weak-line single-dish observations, where the highest level of image rejection is sought. As displayed in Figure 4, most image rejection values are 15 dB or better.

For scientific observations, the 2 mm band proved to be exceptional. Typical total system temperatures on the sky were <150 K, SSB, in good weather and sometimes as low as ~100 K. Therefore, high sensitivity levels could be achieved in relatively short integration times, with the theoretical rms noise levels. Furthermore, receiver stability was outstanding. For example, in position-switching mode, with the "Off" position a degree away from the source, extremely flat baselines were found over 1 GHz of spectrometer bandwidth, even after 8 h of integration. A high-sensitivity spectrum measured with the 2 mm receiver is presented in Figure 5. The spectrum was measured toward IRC+10216 near 138 GHz with AROWS configured with 4 GHz bandwidth and represents 53 h of integration time. These data were taken in beam-switching mode. The baseline is almost a continuous band of spectral lines.

The new receiver with all four bands in full operation was delivered to the 12 m telescope in December 2020. First-light observations occurred in February 2019 with the 1.2 mm and 3 mm bands. Scientific measurements commenced in the spring of 2019, when the 4 mm band was added. The 2 mm band was commissioned during the end of 2020.

4. References

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