Electromagnetic Analyses and Characterization of the ALMA Band 6 Receiver Optics

R. Lehmensiek(1), A. Navarrini(1), and J. Effland(1)
(1) Central Development Laboratory, NRAO, Charlottesville, VA, 22903, http://public.nrao.edu

Abstract

We performed a thorough electromagnetic (EM) analysis of the ALMA Band 6 receiver cartridge optics. The current Band 6 receiver's far-field pattern has a large sidelobe at some frequencies. We identified the origin of this sidelobe to be caused by reflections from the dielectric layers of the cryostat's IR (InfraRed) filters and the vacuum window. This reflected energy hits the outside flange of the horn and radiates back toward the ALMA Cassegrain reflector. The addition of a layer of radiation-absorbent material (RAM) on the feed horn flange prevents the sidelobe. Details of the EM analysis strategy and the measured radiation results are presented.

1. Introduction

The Atacama Large Millimeter Array (ALMA) Band 6 (211-275 GHz) cryogenic receiver [1], shown in Figure 1, has three cold stages with operating temperatures of 4 K, 15 K, and 110 K. The ALMA Band 6 front-end optics are housed on the 4 K stage and consist of two offset ellipsoidal focusing mirrors, a corrugated feed horn, and an orthogonal mode transducer that separates the dual linear polarized signal entering through the horn from the 12-meter (and 7-meter) Cassegrain reflector systems. Hereafter, the signal is down-converted to the Intermediate Frequency (IF) band by two independent sideband separating Superconductor-Insulator-Superconductor (SIS) mixers and then amplified. A quartz vacuum window (at room temperature) and two multi-layered dielectric IR filters, located on the ALMA cryostat's 110 K and 15 K stages (Figure 2), are in the optical path between the reflector system and the two cryogenic ellipsoidal mirrors. The ALMA receiver optics design is described in [2]. In the original Band 6 cartridges, a sidelobe caused by the reflections from the dielectric layers reflecting off the electrically large flat rim of the feed horn [3] was reduced from -15 dB to -25 dB by chamfering the rim of the horn (Figure 3). The chamfer reduces the reflection off the horn's rim as the energy is scattered in other directions than back towards the optical mirror, i.e. the optical path. Figure 4 shows the measured sidelobe before chamfering the horn. The feedhorns in all Band 6 cartridges were replaced by the chamfered version. However, even with this modification, an excess sidelobe was still present: The chamfered rim helped reduce the sidelobe, but it was not sufficient to eliminate it.

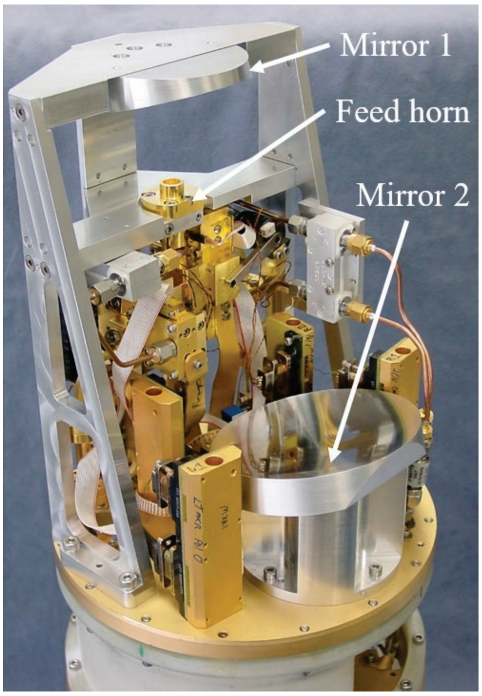

Figure 1. The ALMA Band 6 cold cartridge assembly showing the components on the 4 K stage.

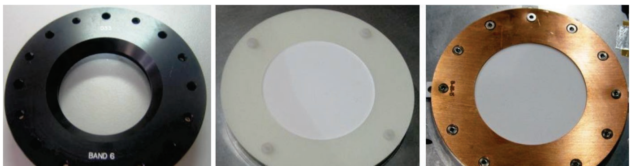

Figure 2. The Band 6 vacuum window (left), 110 K IR filter (middle), and 15 K IR filter (right) assemblies.

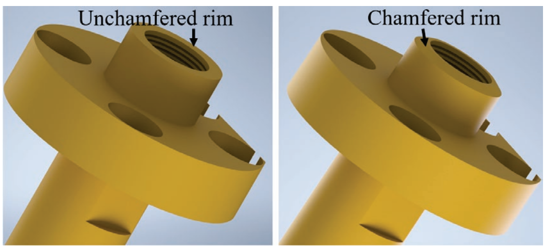

Figure 3. Detail of the Band 6 feed horn with a flat unchamfered rim (left) and with a chamfered rim (right).

The excess sidelobe can affect the fidelity of ALMA images. The primary impact will be on interferometric mosaic images of fields containing strong sources, which

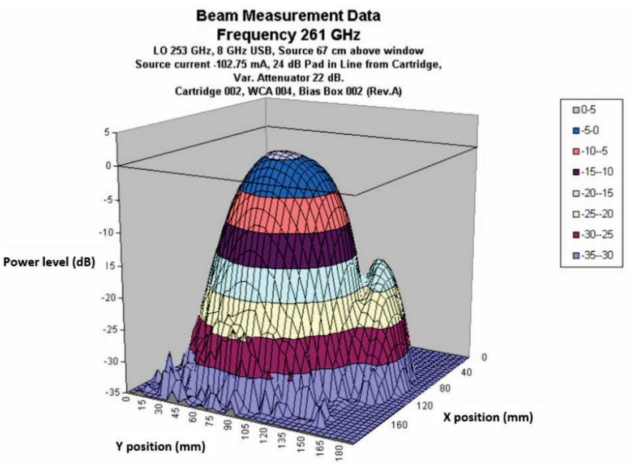

Figure 4. Measured sidelobes caused by reflection from the unchamfered rim on the feed horn.

form a substantial fraction of projects, and all single-dish images of regions with extended emission.

Electromagnetic optics studies of the ALMA antennas and receivers, including Band 6, were described in [4]-[5]. Those studies adopted simplified models of the Band 6 cartridge optics, and they could not explain or identify the origin of the excess sidelobe.

In the framework of the development of the upgraded ALMA Band 6 receiver, called "Band 6v2" [6], we performed a new and detailed analysis of the Band 6 optics to determine if the sidelobe could be reduced further.

2. Band 6 optics electromagnetic analysis

A thorough electromagnetic (EM) analysis of the Band 6 receiver optics is onerous due to the receiver's electrical size and the detail in the geometric model, which also consists of various dielectric materials. An analysis strategy, and to some degree, approximations in the EM modeling, are required. The analysis was performed in TICRA Tools (http://www.ticra.com) using a combination of various EM solvers, namely: Mode Matching, Method-of-Moments (MoM) or the Multilevel Fast Multipole Method (MLFMM), and Physical Optics (PO).

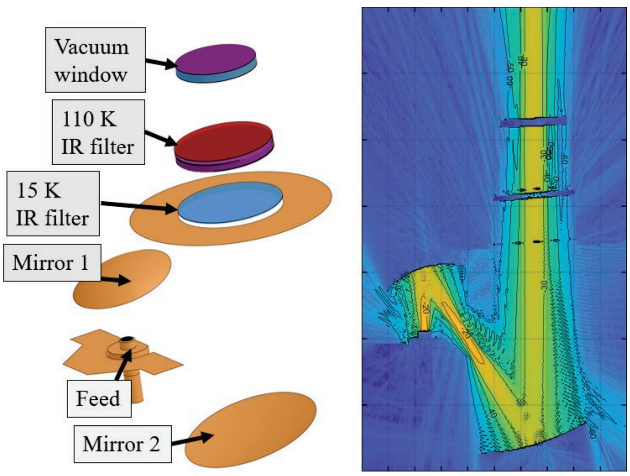

Figure 5. TICRA model of the Band 6 optics showing the cascade of elements (left) and the electromagnetic energy distribution inside the cryostat in the symmetry plane at 245 GHz (right).

The Band 6 optics model is illustrated in Figure 5. The corrugated horn is fed with the fundamental circular waveguide mode and the horn's flange and parts of the support structure are included in the model. The 15 K IR filter is a single layer of Mupor and a circular metal ring represents a part of the top wall of the cartridge housing. The 110 K IR filter consists of a molded PFA cylinder that has triangular grooves on the top and bottom layers and an additional thin Mupor layer. The vacuum window is made from fused quartz and has thin antireflection layers on both sides.

Figure 6 shows the simulated radiation pattern of the cartridge. The IR filters and vacuum window are neither

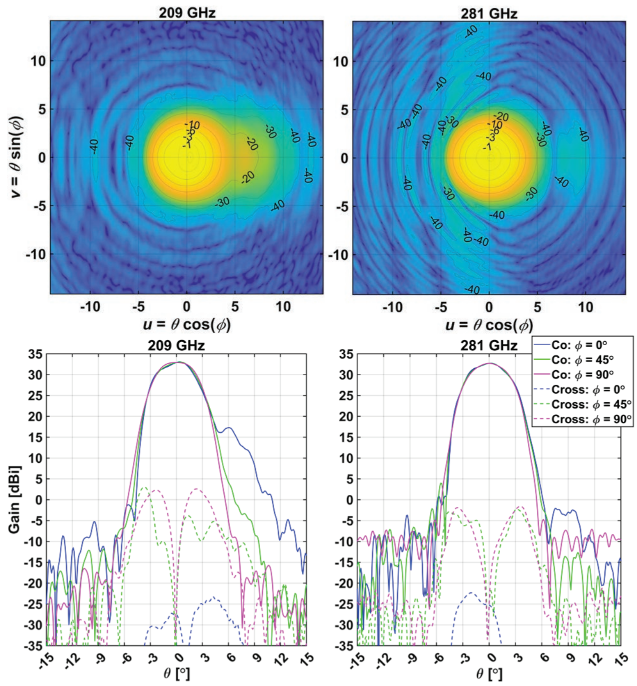

Figure 6. Simulation of the Band 6 cartridge's radiated beam, showing the sidelobe. 2D heat-map of the co-polar pattern (top) and 1D scan (bottom) at 209 GHz (left) and 281 GHz (right).

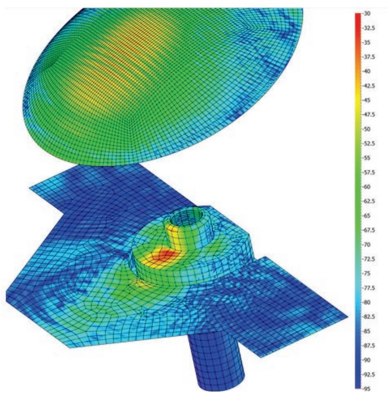

Figure 7. Electromagnetic simulation of the ALMA Band 6 optics showing a high energy density (high electrical currents) on the feed horn alignment flange and bracket near its aperture.

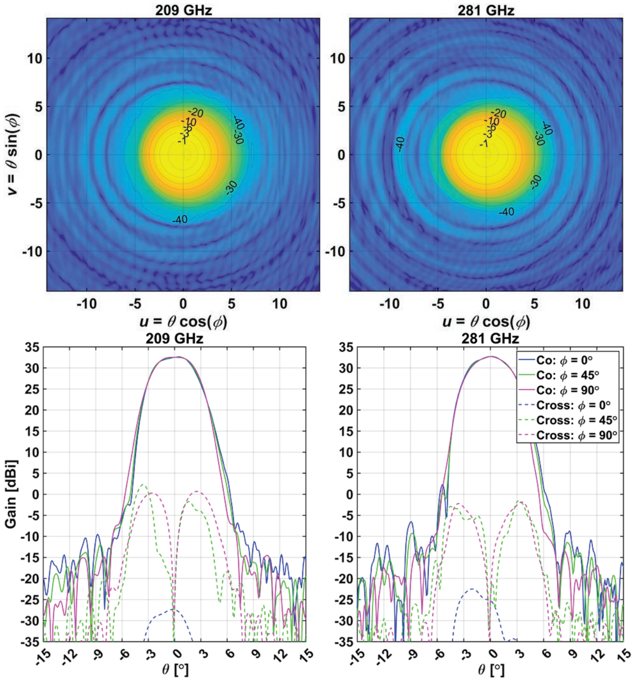

Figure 8. Simulation of the Band 6 cartridge radiated beam, showing the sidelobe. In this simulation an ideal radiation-absorbent material on the horn's flange is assumed. 2D heat-map of the co-polar pattern (top) and 1D scan (bottom) at 209 GHz (left) and 281 GHz (right).

electrically transparent nor reflectionless in the frequency band. The analyses revealed that the reflected energy from these dielectric layers propagates back through the ellipsoidal mirrors toward the horn, and due to a slight angle in the dielectric layers, the bulk of this energy hits the outside flange of the horn as shown in Figure 7. The amount of energy arriving on the horn's flange varies over frequency due to constructive and destructive interference of the energy from the various dielectric reflecting surfaces. This energy gets reflected and follows the optics path toward the Cassegrain reflector, causing a sidelobe on one side of the main beam. The addition of a layer of radiation-absorbent material (RAM) on the alignment flange is expected to prevent this sidelobe, as illustrated in Figure 8. For these simulations, we assumed that all reflected energy from the IR filters and vacuum window gets absorbed by the RAM.

3. Beam pattern measurements with and without absorber

To verify the prediction that the sidelobe can be reduced, we performed a characterization of the Band 6 receiver optics beam pattern at a few frequencies across the 211-275 GHz range using the NRAO antenna measurement beam system of the ALMA Band 6 Cartridge Test Set (CTS), shown in Figure 9. The beam scanner emitter is a WR3.4 open waveguide probe fed by a mm-wave source phased-locked with the Band 6 cartridge. For each RF frequency, the near-field probe is scanned on a square grid of points in front of the Band 6 CTS vacuum window, and the measured amplitudes and phases of the Band 6 cartridge optics are recorded for each of the points. The measured data is Fourier-transformed to derive the far-field data. The two following hardware configurations for the Band 6 cartridge were used in the test setup: The nominal configuration, where no absorber is installed near the mounting flange of the feed horn, and the modified configuration, where AN-72 absorber is installed over the feedhorn mounting flange. A picture of the modified configuration, with absorber, is shown in Figure 10 (cartridge serial number CCA6-054 was used for this experiment).

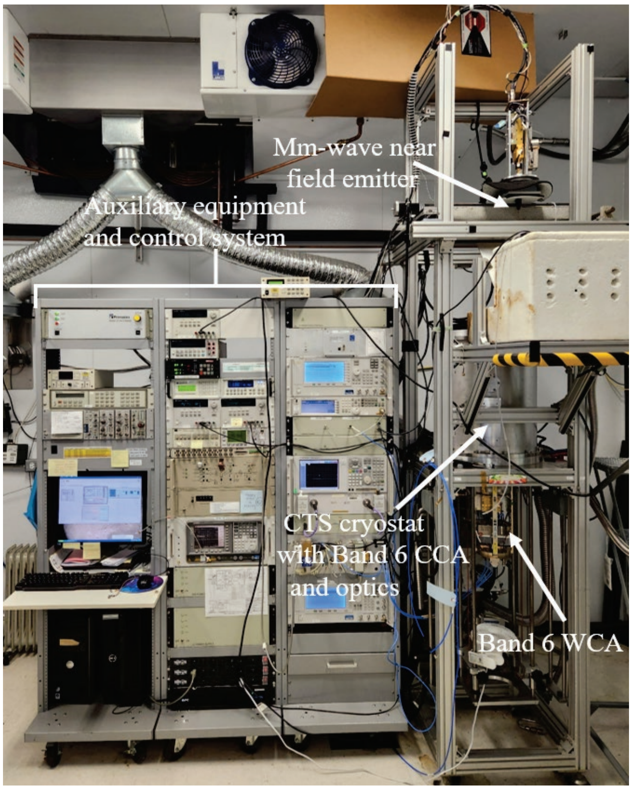

Figure 9. ALMA Band 6 Cartridge Test Set (CTS) at NRAO showing the mm-wave emitter and the cryostat.

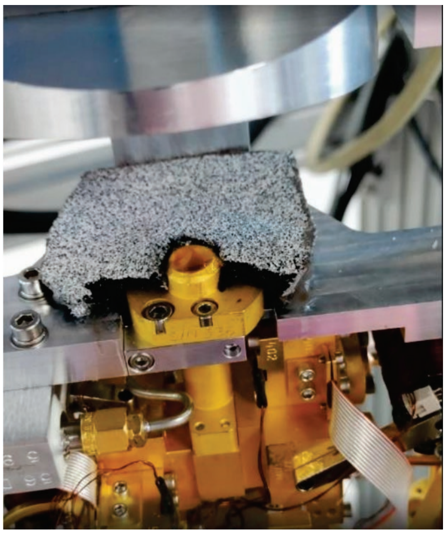

Figure 10. Band 6 feed horn with chamfered rim showing absorber installed near the aperture and on the mounting bracket.

The measurement results of the Band 6 cartridge co-polar far-field patterns at 211 GHz and 243 GHz are illustrated in Figure 11. The patterns on the left panels, referring to the nominal Band 6 cartridge optics configuration with no absorber, show a pronounced sidelobe at a level ≈-25 dB below the beam peak. In contrast, the patterns on the right panels, referring to the configuration with absorber, show no sidelobe and match the prediction obtained by electromagnetic simulations illustrated in Figure 8.

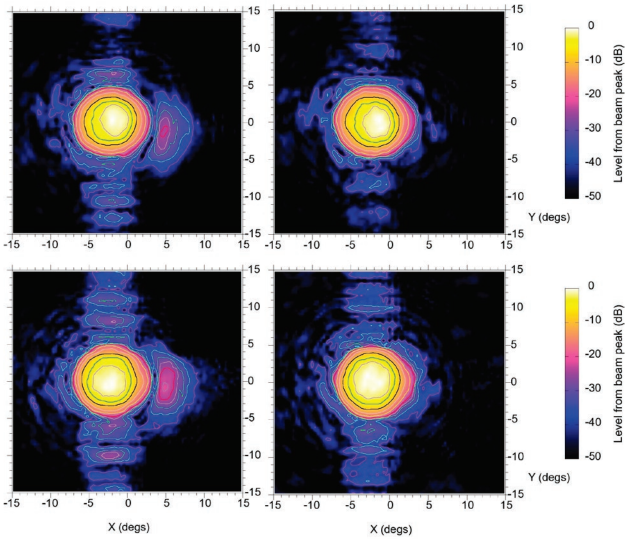

Figure 11. Comparison of the measured ALMA Band 6 cartridge sidelobes without absorber (left) and with absorber (right) installed near the feed horn at 211 GHz (top) and 243 GHz (bottom).

4. Conclusion

We performed a thorough EM analysis of the Band 6 receiver optics and predicted the origin of the excessive sidelobe to be caused by the energy reflected from the IR filters and vacuum window dielectric layer toward the feed-horn, bounced back, and re-radiated in the direction of the cartridge main beam. The addition of a layer of AN-72 radiation-absorbent material on the flange prevents this sidelobe, and this has been verified through measurements performed with the beam scanner of the Band 6 Cartridge Test Set.
For the second-generation Band 6 receiver currently under development, Band 6v2, we plan to permanently incorporate a suitable radiation-absorbing layer near the feed-horn aperture and its mounting bracket.

6. Acknowledgements

We thank J. Jackson and M. McLeod from NRAO for their contribution to the Band 6 optics test and to the cartridge monitor and control software, respectively.

References

[1] J. Effland, A.R. Kerr, M. Morgan, G. Ediss, R. Groves, "Band 6 Cartridge Design Report," *ALMA Front End Report FEND-40.02.06.00-060-I-DSN,* 18 May, 2017.

[2] J. W. Lamb et al. "ALMA Receiver Optics Design," *ALMA Memo 362*, Apr. 11, 2001.

[3] B. Lazareff, "A Tentative Mechanism for the Origin of Sidelobes in the Band 6 Beam Pattern," ALMA document FEND-40.02.06.01-036-A-REP, March 2005.

[4] C.Y. Tham and S. Withington, "The ALMA Receiver Optics Design - Electromagnetic Analysis," *ALMA document Report,* Jul. 2003.

[5] K. Pontoppidan, "Electromagnetic properties and optical analysis of the ALMA antennas and Front-Ends," *ALMA document ALMA-80.04.00.00-026-A-REP,* Jan. 2008.

[6] A. Navarrini et al., "ALMA Band 6v2 receiver development status," *2023 XXXVth Gen. Assem. Sci. Symp. Int. Union Radio Sci. (URSI GASS)*, vol. 00, pp. 1–4, 2023.