A Multi-Octave Band Feed Horn Antenna for Next-Generation Radio Telescopes

Nasrin Tasouji*, Sara Salem Hesari*†, Alisa Baniadam‡, Adam Densmore†, and Jens Bornemann*
*Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada
†NRC Herzberg Astronomy and Astrophysics Research Centre, Victoria, BC, Canada V9E 2E7
‡National Organization for Development of Exceptional Talents (Sampad) Educational Institute, Urmia, Iran

***Abstract*—This paper presents a spline profile quad-ridged feed horn antenna operating across a 67-163 GHz bandwidth (2.43:1), offering a viable alternative to traditional narrow-band corrugated horn antennas currently used in Atacama Large Millimeter Array (ALMA). This antenna is designed with the goal of achieving very wide bandwidth performance, extending beyond an octave. An optimization method to enhance the design for wide bandwidth, minimal cross-polarization, low side lobe levels, and high Gaussicity aimed at achieving an optimal beam waist is introduced here. The efficacy of this antenna is validated through the analysis of radiation patterns in the H, E, and D-planes in both co- and cross-polarization configurations. This design successfully meets the ALMA optics requirements.**

***Index Terms*—Feed Horn, spline profile, quad-ridged horn, millimeter/submillimeter wave, cross polarization, side lobe level, phase center, and Gaussicity.**

I. Introduction

One of the most popular alternatives for feeding reflector antennas has long been corrugated horn antennas [1], [2], and [3]. Their outstanding ability to produce a radiation pattern with high symmetry, low side lobe levels, and good polarization is the primary factor in their popularity for radio astronomy applications. These characteristics aid in enhancing the gain and caliber of the signal that the reflector receives. For efficient and accurate operation, this kind of antennas usually minimize interference between modes and offer optimal energy transmission due to their unique architecture. Recent developments have made it possible to fabricate them at microwave frequencies, but this presents a major barrier at millimeter-wave frequencies due to decreasing dimensions of the antenna and increasing fabrication costs. The utilization of multi-mode antenna designs, as shown in [4] and [5] is a very successful technique in feed antenna design. The TM11 and TE11 modes in such designs efficiently merge along the antenna's length due to their step discontinuities, producing an in-phase field distribution at the antenna aperture. Nevertheless, these antennas have a restricted bandwidth [6]. Consequently, a different kind of antenna with a wider bandwidth and the ability to combine modes properly was introduced [7]. One such type of antenna that has a greater bandwidth, superior radiation properties, and a shorter length than other types of antennas is the smooth profile antenna. The multi-beam mode, optimized radiation pattern and easy to fabricate needs of telescopes can be satisfied by these antennas. Ref. [8] represented a study on the design of a smooth-walled spline-profile horn for use in the 80–120 GHz band, offering an alternative to corrugated horns with improved electromagnetic performance across the band. The coefficients of a spline function are used to optimize the profile of the horn in order to achieve a specific radiation pattern to meet requirements of Australia Telescope National Facility, ATNF, radio astronomy antenna. In [9], for the RATAN-600 radio telescope, a smooth-walled horn with excellent efficiency has been designed and manufactured. Nevertheless, with a restricted bandwidth and a downside of the higher side lobe level. Additionally, a spline profile horn was created in [10] for KOSMA at the THz frequencies, where the production of corrugated horn presents significant challenges, illustrating the spline profile horn's potential use at higher frequencies. Ref [11] created two smooth-walled spline profile horns, one conical and the other diagonal, and thoroughly compared the outcomes before moving forward with the diagonal design for manufacturing at THz frequency range. Although these proposed designs perform well, but none of them address the fundamental need for modern radio telescopes, which is a wide bandwidth.

This paper introduces a novel multi-octave band antenna design suitable for radio astronomy applications. This feed horn antenna is designed for multi-octave band applications, specifically tailored to meet the optical requirements of ALMA and extend its bandwidth to comprehensively cover Bands 2, 3, and 4, making it a promising candidate for the ALMA radio telescope. To adapt the horn for such purposes, cross-pol less than -20 dB, side lobe level less than -25 dB, reflection coefficient better than -25 dB, phase center location displacement around 2 mm, symmetric beam and acceptable high Gaussicity are considered as goal targets of this design. A feasible half-power beamwidth of 18 degrees and an edge taper of 12.02 dB were selected to ensure compatibility with ALMA radio telescope optical systems. This design indicates the development of a new horn configuration that is different from existing feed horn antennas developed for radio telescopes such as ngVLA [12], which generally require a wide beamwidth and different radiation pattern characteristics.

II. Feed Horn Design

Since the antenna's initial profile determines its radiation characteristics, selecting the appropriate design is crucial for achieving a circularly-symmetric radiation pattern. It is widely accepted that a sine-to-the-power-p-profile with p less than

1 followed by a Gaussian profile which fits well in these applications as it controls the mode conversion. In fact higher order modes are excited in the correct amplitude and phase which leads to shorter antenna length [13]. The antenna's principal profile is shaped by these two functions. The ridges are introduced to the design to reduce the cutoff frequency and increase the antenna's bandwidth. For this antenna, the most straightforward profile can be obtained using an exponential function. Direct general optimization is time-consuming because of the large number of coefficients for each function. Therefore, an efficient optimization model, which was used in [8], is implemented to achieve the desired results.

Fig. 1. Feed geometry

The high levels of the side lobes in the structure of the horn antenna are generally caused by diffraction at the edge of the horn, as mentioned in [14]. To mitigate this issue, a curved surface was introduced at the antenna's aperture to create a smoother transition between the horn modes and free-space radiation, and it acts as a broadband impedance transformer from the 50-ohm feed to the 377-ohm impedance of the free space. In addition, it was proved that the ridge profile can shape the radiation pattern of antennas. The gradual outward flare of the horn profile, in particular, the bending of the upper ends of the ridges, helps minimize diffraction from the aperture, specially in the lower frequency range and consequently improves the antenna's cross-polarization [15], [16]. Another critical requirement for radio telescopes, to be considered particularly in the H-plane, is beam symmetry. A simple solution is to add corrugations on the curved aperture. The corrugations guide the residual wave at the design frequency to radiate along the conductor-air interface, instead of propagating along the surface, thereby enhancing beam symmetry. Fig. 1 shows the antenna with a flared aperture and a longer ridge with corrugations around its edge.

III. RESULTS

The proposed antenna is designed and simulated using two full wave electromagnetic simulators, Ansys HFSS (high-frequency structure simulator) and CST Microwave Studio (Computer Simulation Technology) to validate its performance. Any discrepancies between the two software's results can be attributed to the differences between the solvers' and mesh settings. Fig. 2 presents the simulated reflection coefficient for the antenna when excited with 9 modes, showing that the reflection coefficient is lower than -25 dB and all higher-order modes are suppressed below -80 dB.

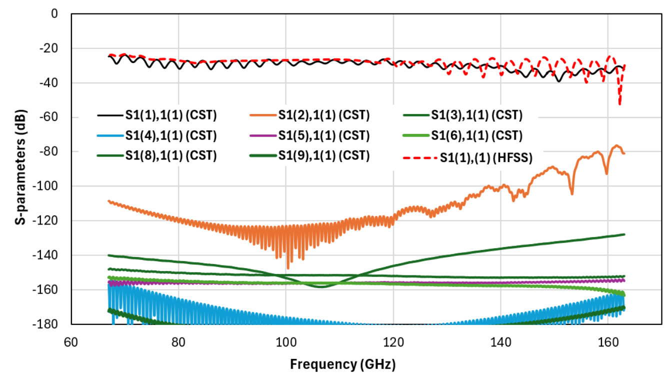

Fig. 2. S-parameters simulated in HFSS and CST.

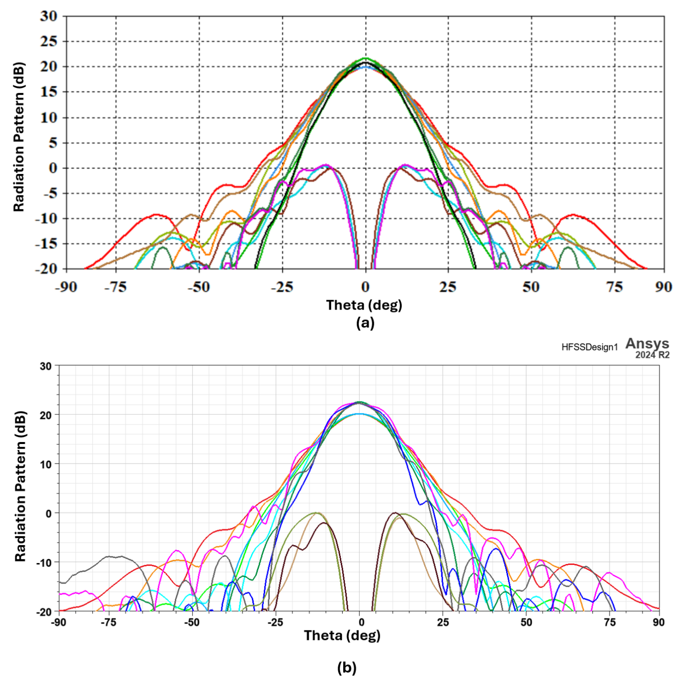

Fig. 3. Radiation pattern of the feed horn in the E, H, and D-planes at 67 GHz, 115 GHz, and 163 GHz simulated in (a) CST, and (b) HFSS.

Simulated radiation patterns in the E-, D- and H-planes, both co-polar and cross-polar components at 67 GHz, 115 GHz and 163 GHz, are shown in Fig. 3. Both the beam symmetry and cross-polarization performance of the antenna indicates its reliability for radio astronomy applications. In the design of this antenna, a 12.02 dB edge taper was selected to align with the optical requirements of ALMA Bands 2, 3, and 4. It is evident that at this edge taper, the half-power beam-width is approximately 18 degrees. Fig. 4 displays the side lobe level (SLL) of the proposed antenna, which remains below -28 dB across the entire frequency range, alongside a graph of gain versus frequency.

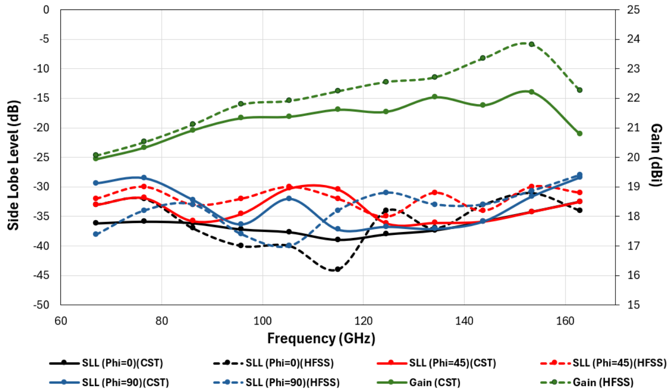

Fig. 4. Simulated gain and side lobe suppression in CST and HFSS.

To reduce the spill-over, the phase center of the feed in radio telescopes is usually placed at the focal point of the reflector. Thus, keeping the phase center variation low is crucial to guarantee accurate alignment between the radiation pattern of the antenna and the focal plane of the telescope [6]. Fig. 5 illustrates the phase center variation which remains less than 2 mm and aperture efficiency across the frequency range from 67 to 163 GHz.

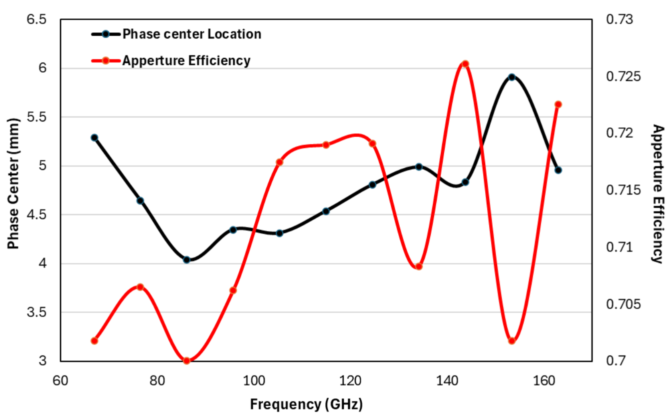

Fig. 5. Simulated phase centre location relative to horn aperture and aperture efficiency.

The cross-pol level of an antenna is another important consideration when assessing its use as a feed horn in radio telescopes, since it can increase the overall noise level of the system. Cross-pol, which causes power leakage between the two orthogonal polarizations, is often characterized as undesirable [17]. The low cross-polarization level for this antenna, as indicated in Fig. 6, demonstrates the reliability of this antenna for radio astronomy applications. When an antenna's radiated pattern travels via several lenses, grids and reflectors, the concept of Guassicity becomes extremely important as an indication of the antennas performance. Gaussicity refers to the highest possible power coupling to the fundamental free space mode. Achieving high Gaussicity involves ensuring that the initial fundamental modes in the horn antenna's aperture are excited with the proper phase and amplitude [18]. To calculate the Gaussicity of this antenna, simulated far field patterns and equations mentioned in [19] are considered. The results are presented in TABLE I. The Gaussicity peaked around the center frequencies but decreased at higher frequencies due to changes in the beam waist.

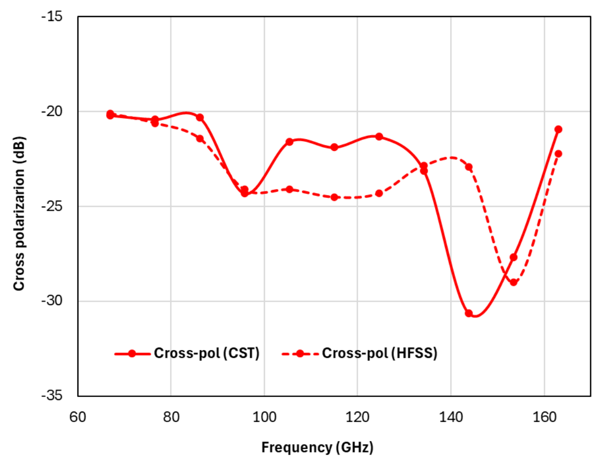

Fig. 6. Simulated cross polarization across the frequency range in CST and HFSS.

TABLE I
CALCULATED η_g FOR DIFFERENT FREQUENCIES OF THE SMOOTH-WALLED SPLINE-PROFILE.

Frequency	67 GHz	90 GHz	110 GHz	130 GHz	150 GHz	163 GHz
η_g	95.4%	97.99%	97.1%	97.07%	97.97%	91.22%

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