J. of Electromagn. Waves and Appl., Vol. 18, No. 3, 387–396, 2004

DESIGN OF AN IMPROVED PROFILED CORRUGATED CIRCULAR HORN AT 320 GHZ

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Abstract—A high performance horn for radio astronomy applications in the 350 GHz band is presented. Perspective application will be in the Atacama Large Millimeter Array radio telescope. The horn is a dual profiled corrugated circular horn designed for constant beam waist position very high return loss and very low cross-polar level.

1. INTRODUCTION

Dual profile corrugated circular waveguide horns (DPCCH) are very interesting structures for high performance feed systems. A DPCCH is realized with a squared sine section followed by an exponential section shaping the inner corrugations profile. This complex curvature may be optimized for additional requirements, basically giving the horn design more degrees of freedom with respect to classical horn structures [1]. The effects of profiling the horns by adding an exponential taper are accurately described in [2]. An exhaustive description of different methods for profiling the horn corrugations are given in [3], where very interesting effects over the performances are outlined.

In particular, DPCCH have some distinctive features. For example, DPCCH have shown to meet electrical requirements typical of radio astronomy applications with reduced size and weight [4]. Moreover the effects of tuning the phase center position by shaping the exponential profile, without changing in practice other features like beam size, side lobe levels, return loss and cross- polarization, has been recently investigated [5].

In this paper the problem of exciting the Gaussian beam fundamental mode is addressed. By using the available degrees of freedom the goal is to make the waist position as stable as possible against frequency in a larger than 30% band centered at 320 GHz while keeping very high performances in terms of return loss and cross-polarization.

The high frequency leads to a very small structure involving a very critical fabrication process. To stay far away from a hard to fabricate horn, some constraints have to be put as regard the allowed values for the corrugations geometry, especially in the throat region. With respect to recent works ([4, 5]) a new design method has been developed, including a stochastic algorithm in the optimization procedure, to efficiently speed up the search of the optimum in the presence of a more complicated cost function involving a high number of parameters both geometrical and electrical.

2. DESIGN

The horn requirements adopted in the design are those relative to the Atacama Large Millimeter Array (ALMA) radio telescope [6] which is in advanced design process, with some prototypes already built and which is scheduled to be completed in 2010. The ALMA radiotelescope will be located in northern Chile and is committed by the European Southern Observatory (ESO), with European, United

States and Japanese sponsorships. The 320 GHz horn specifications are summarized in Table 1.

Table 1. Horn requirements.

Specification	Value
Frequency	320 GHz
Bandwidth	30%
Beam waist (w_0)	1.85 mm
Return loss	> 30 dB
Cross-polar level	< -30 dB

Working frequency is very high and bandwidth quite broad, as compared to standard horn applications. This makes manufacturing critical. The gain, which is implicitly given by the beam waist requirement [7], correspond to about 25 dB which is a typical value for secondary focus feeds. The very good input matching (high return loss) and the very low level for the cross-polarization maximum are related to the high sensitivity required in detecting the signals coming from the sky with very low cross-talk between the two orthogonal polarizations.

The horn design is carried out by using a very powerful and well tested analysis software tool based on a hybrid technique exploiting both the Mode Matching (MM) and the Method of Moment (MoM) [8].

The MM is able to accurately model the wave propagation in the horn interior by expanding the field into circular waveguide eigenfunctions. The eigenmodes of the various elementary circular waveguide sections forming the horn couple each other because of the scattering at every step discontinuities of the internal corrugations. Hence each elementary section is characterized through its Generalized Scattering Matrix (GSM). The connection of all elementary GSM leads to a single GSM characterizing the whole horn interior. The GSM approach gives to the simulation code great accuracy and high stability.

The MoM allows to correctly take into account the effects of the horn external part. Flange effects may have non-negligible impact over feed performances like beam pattern and cross-polarization. For axially symmetrical structures, as in this case, a very efficient MoM formulation for Bodies of Revolution (BORs) exists and it is here implemented, speeding up calculation time.

The Horn design is sought by exploiting the above mentioned code within an automatic optimization procedure based both on the Quasi Newton Method (QNM) [9] and Genetic Algorithms (GA) [10].

Because of its relative speed, related to other methods, QNM is best suited in searching the optimum when the iteration starting point is already within the basin of attraction of the optimum point itself, otherwise, as it is well known, it gets struck in the nearest local minima. On the other hand GA, even if more CPU demanding and generally slower, like other stochastic methods performs a global search and do not get trapped in local minima.

A hybrid method using a GA with a low number of generations as a rough searcher to get in the optimum basin of attraction, followed by a QNM refinement for the localization of the optimum gives in most cases better performances than any of the two methods taken individually.

Beyond the electromagnetic specifications, further constraints are added in the optimizer to force critical geometrical details to be as large as possible in order to ensure easy machining.

As result a very high performance horn has been obtained with relaxed critical geometry. In particular critical features to manufacture are the corrugations in the throat regions. The obtained design has a slot depth equal to 0.45mm and a slot length equal to 0.09 mm. This leads to a configuration which can be manufactured. The optimized structure is shown in Fig. 1, where the profile of the proposed horn (upper part) is compared with a standard linear profiled horn (lower part) having the same dimensions in terms of overall length and aperture diameter. With reference to the profile formula given in [11] the sine squared region end radius is $R_s = 2.81$ mm, its length is $L_s = 25.79$ mm and the tapering coefficient is $A = 0.7$.

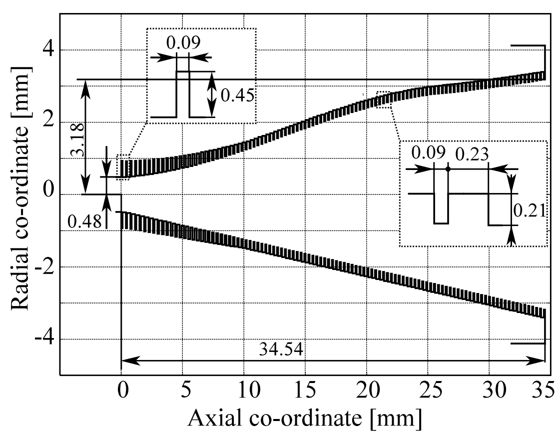

Figure 1. Horn profile of corrugation: linear vs. dual profiled.

Profiling the corrugations has sensible effects only on the waist position and on the main beam shape. Gaussian beams cross-section presents in this case, lines at equal amplitude which are circles centered on the beam axis. The waist is the smallest circle where the amplitude is $1/e$ with respect to the maximum. The waist radius for the profiled horn ranges from 1.8 mm to 1.9 mm in the operative band and its position is at maximum 0.9 mm from the aperture, inside the horn. On the other hand the waist position in the linear horn has 2 mm variation (that is more than two wavelengths), from 1.5 mm to 3.5 mm from the aperture (Fig. 2).

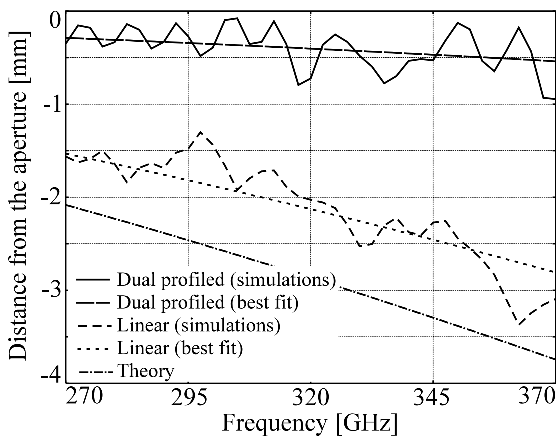

Figure 2. Waist variation comparison at $\phi = 45°$.

In Fig. 2 it is also reported, for the linear horn, the theoretical value of the waist position, given by [12]

$$z = -\frac{R_a}{1 + [R_a/(\pi \cdot w_a^2)]^2 (c/f)^2} \tag{1}$$

where R_a is the radius of curvature of the phase front at the aperture, w_a is the waist at the aperture, c the light speed and f the frequency. The small differences between theory and simulations are due essentially to flange effects, which slightly modify the phase front curvature of the outgoing wave.

Table 2 reports the theoretical values for R_a and w_a for the linear horn, and the respective quantities computed using (1) in a best fit algorithm over the simulated data for both the linear and profiled horn. The waist position is very important in the design of the optical coupling between feeds and reflector antennas. The stability of the waist is crucial in many applications and the possibility of enhancing

Table 2. Parameters.

	R_a	w_a
Theoretical	40.8 mm	1.83 mm
Best fit, linear	58 mm	1.83 mm
Best fit, profiled	3000 mm	1.85 mm

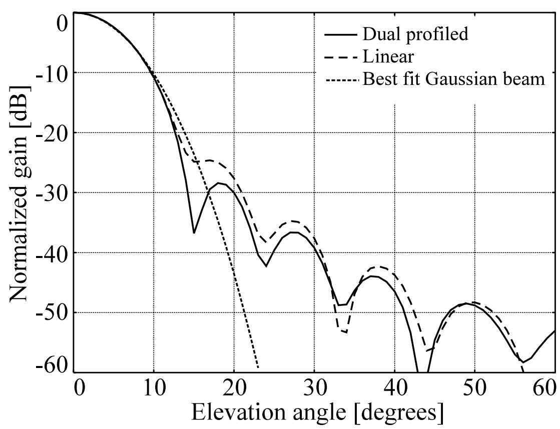

Figure 3. Beam pattern comparison at 320 GHz and $\phi = 45°$.

it by profiling the corrugations is very useful in designing feeds and clusters of feeds.

For what concerns the main beam, the profiling effect may be noticed in Fig. 3. As it can be seen, the main beam shape of the dual profiled horn is preferable because it is steeper for an elevation of about 15°, where the edge of the reflector is located, hence yielding to lower spillover an higher overall antenna efficiency. Moreover it has lower side lobe levels leading to lower antenna temperature. Both patterns have a coupling to the best fit Gaussian beam given approximately by $\epsilon = 97\%$, ϵ being a power efficiency coupling factor defined by:

$$\epsilon = 1 - \frac{\iint_{\Omega} ||E|^2 - |E_G|^2| d\Omega}{\iint_{\Omega} |E_G|^2 d\Omega} \tag{2}$$

with Ω being the main lobe angular region with a power illumination level at the edge greater than -20 dB below the maximum, E and E_G

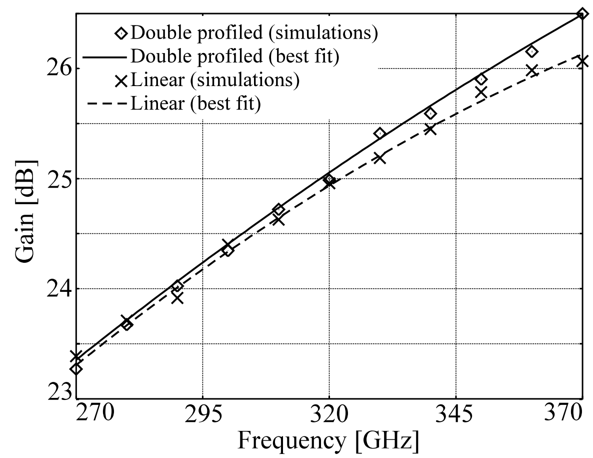

Figure 4. Gain comparison (dotted) and curve fitting (line).

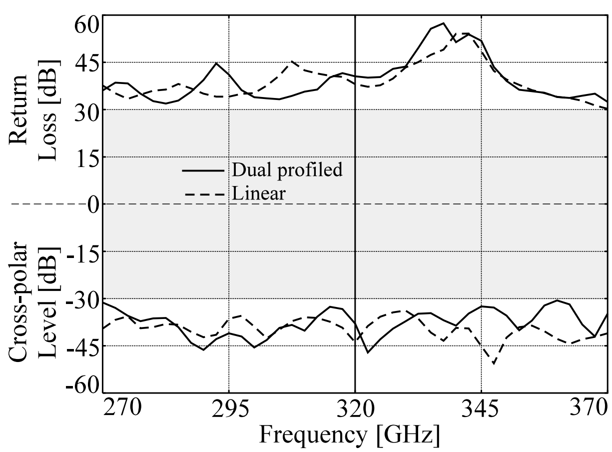

Figure 5. Return loss and cross-polar level comparison.

the pattern of the horn and its best fit Gaussian beam, respectively.

Tha gain plots are given in Fig. 4 and they are very close each other. Best fitting curves using quadratic laws are also drawn to give better evidence of the small differences between the two horns with the gain of the profiled one a bit closer to a linear curve than the other, hence providing higher gain in the upper part of the band.

The designed horn shows very good performances in terms of return loss and cross-polarization as it can be seen in Fig. 5.

Both curves are within the design goal limits, 30 dB for the return loss and −30 dB for the cross-polar level. No noticeable differences turn up by comparing these performances between the dual profiled horn and the linear horn.

3. CONCLUSION

In this paper the problem of designing a high frequency — broad band horn, typical of radio astronomy applications has been addressed. In particular it has been shown the possibility of shaping the main beam and acting on the position of the beam waist with low variations in the bandwidth by using complex profiles of corrugations and to implement a hybrid optimization method based on GA and QNM to efficiently take into account the mechanical limitations related to the throat geometry in the cost function. Some results have been presented and comparison between the proposed horn and a linear profiled - standard type horn, having the same dimensions have been given to highlight the distinctive features of the work done.

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