Design Realisation and Measurements of a High Performance Wideband Corrugated Horn

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Abstract

We report on the design and realization of horn antennas required to have high performances with respect both to the return loss and the cross polarisation level over a wide band.

1. Introduction

Corrugated horns have been studied at large mainly for space applications. The work reported here was intended to design a microwave source with less than –40dB VSWR, less than –50dB cross polarisation and low sidelobes over 20% bandwidth. Additional constraints concern the beamwidth and the volume of the source. The results presented in this paper were obtained using the method of moment (MoM) technique based on the solution of integral equations, which is feasible because the symmetry of revolution allows reducing the problem to 1D integral equations. After reviewing the main theoretical issues in section 2 we summarize in section 3 the results of a thorough parametric study aimed at optimizing the profile to meet the requirements. Section 4 presents the realization of horns and Section 5 displays the results of the measurements with comparison with the numerical investigation.

2. Theory and state of the art

The importance of a symmetric radiation pattern for spatial antennas was stressed by Jeuken [1] and he investigated the conditions necessary to obtain a far field diagram independent of frequency, rotationally symmetric and with circular polarization, showing that they could be met by conical corrugated horns. Since then the theory of corrugated horns has been extensively studied in the seventies and since then by many authors, particularly Clarricoats [2], T. Bird [3], Mac A. Thomas [4, 5], Jansen and Jeuken [6], and their respective coworkers. The book by Olver and Clarricoats [7] contains an extended analysis varying independently the most important parameters and giving information on the return loss and the cross polarisation. The additional problem of the synthesis of wide band corrugated horns was first addressed by Dragone [8] and more recently by Zhang [9].

A. Integral Equations and Corrugated Horns

On a general Huygens surface let *J* and *K* be the electric and magnetic equivalent currents, each one has a longitudinal (in the meridian plane) and a transverse (azimuthal) component indexed by *L* and *T* respectively. Similarly the far fields (electric and magnetic, longitudinal and transverse) are given, besides the azimuthal dependence, by functions of the bearing angle b which may be expressed as integrals of the currents on the meridian of the surface. From these formulas it is seen that, in order to achieve a rotation-symmetrical diagram or equivalently zero cross-polarization, the following relations should hold between currents : $J_L = -K_L$ and $J_T = -K_T$

The corrugated horn achieves this by making the magnetic field and the electric field similar at the surface of the underlying cone, and this in turn is obtained by designing the corrugations so that the transverse magnetic field essentially vanishes at the entrance of the grooves, which is achieved when their depth is such that the admittance (ratio of the azimuthal magnetic field to the radial electric field) vanishes ; then both fields have vanishing azimuthal components. Now the theory shows that inside the smooth cone the fields may be expanded in so-called hybrid modes (mixtures of TE and TM spherical modes) of two types, HE_{1n} for which $J_L = K_L = 0$ $J_T = -K_T$ (no x-polar) and EH_{1n} for which $J_L = K_L = 0$ $J_T = K_T$ (maximum x-polar). The challenge of the design of the meridian is, assuming that higher modes do not propagate, to obtain the generation of a forward travelling mode HE_{11} with the

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smallest possible reflection without exciting the HE_{1n} mode. Once the solution by integral equations is obtained it is easy to study the modal content of the field at different positions in the horn to gain insight into the causes of the appearance of VSWR and/or cross-polarization.

B. Numerical issues

Given the azimuth dependence of the fields, by the rotational invariance the Electric Field Integral Equation (EFIE) reduces to a 2x2 matrix of one-dimensional equations, which are much easier to handle than 2D's and have proven very precise for the determination of the currents on corrugated structures including the VSWR [10]. They are especially valuable in that case, since the meshing of a 2D corrugated surface is extremely costly whereas that of the meridian involves only a few points per corrugation and keeps feasible even for very long horns.

The EFIE relates the unknown currents on the horn surface to an incident field, expressing that the total tangential electric field vanishes on the conducting surface. This surface is generated by the meridian of the feeding wave-guide and the horn downstream from a fixed section on the guide at abscissa $z = 0$; the incident field is the field radiated by the equivalent currents generated on that section. Thus if, at $z = 0$, all modes but TE11 are evanescent, the excitation is a superposition of a forward travelling and a backward wave, and depends, up to an overall constant, from one complex number, on the reflection coefficient R. After solving the EFIE with 2 different right hand sides corresponding, say, to $R=0$ and $R= -1$, the correct linear combination of the two solutions is obtained from the continuity of the electric field at $z = 0$, which implies 2 equations for each point of the section ; both of them should yield the same result, which furthermore should be independent of the radial coordinate of the point (see [10] for details).

The horn profiles investigated in this study involve up to hundred corrugations, which means an overall meridian length of about 50 wavelengths; as the required accuracy is achieved with 40 to 80 discretisation points per wavelength, the number of real unknowns (4 per point) does not exceed 16000.

3. Results of a parametric study

More than hundred horns were calculated in the numerical survey. We summarize the results concerning the influence of the principal parameters without referring in detail to the literature, because it contains many contradictory results and because published results were often found difficult to reproduce without knowing the accurate dimensions of the horn, generally not indicated. The results are namely very sensitive to the horn profile.

D. Bandwidth consideration

Zhang [9] studied large bandwidth corrugated horns both in terms of return loss and cross polarisation, and indicated how to choose the dimensions in order to have a wide band horn. This sets a geometrical domain such that the dimensions allow HE11 to exist and EH11 to vanish. So the teeth to groove width has to be modified in order to meet requirements on both a low cross polarisation level and a large bandwidth. According to [9], the slots width has to be very thin at the beginning of the corrugated section (t / g = 7) (with t the tooth width and g the groove width) and becomes larger at the end of the corrugated section (t / g = ½). This way to modify the groove to tooth width ratio seems to be the only way to increase the bandwidth and maintain the cross polarisation level to a low value.
Two series of results were obtained : results for the return loss versus frequency show a bandwidth close to 10 % at – 45 dB and 17 % at – 40 dB, using an input taper. Varying both depth and width of the slots inside the waveguide section and without input taper, there is a clear benefit with 35% of bandwidth at – 40 dB for the x-polar and 22% at – 45 dB.

E. VSWR versus cross-polarization

There does not exist a single general model for characterising horns having low VSWR and low x-polar level over a wide frequency band. In terms of local equivalent surface impedances it may be stated that the VSWR depends on the smoothness of the impedance variation while the x-polar depends on the overall balance. Therefore the VSWR does not change significantly in general when the length is increased by addition of equal corrugations ; on the other hand the x-polar may change if the additional corrugations are not exactly adapted. But x-polar may also be generated by abrupt changes in the profile and is finally sensitive to all details of the geometry. This may be understood intuitively by considering the requirements of the balanced hybrid conditions, which cannot be met in the transition region between guide and horn ; so the imbalance appearing in that region must be compensated by the subsequent corrugated region and it takes more or less length until one can consider that each new corrugation should meet the balanced condition. It is verified that this is more and more true when the flare angle increases. The x-polar tends to increase with the flare angle, to decrease as a function of the frequency, and to have a negative slope wrt frequency at the operating frequency.

For a high performance design at a single frequency both in VSWR and cross polarisation level, the widths of slots and teeth should not to be modified along the horn. Then a VSWR below – 50 dB may be obtained but without a large bandwidth. To obtain a large bandwidth horn (with respect to both the VSWR and the cross polarisation), one of the best solutions consists in varying the teeth widths along the profile and not including an input taper. As a disadvantage the VSWR is higher than previously but it can be maintained to a constant level (only a few dB variations) on a very large bandwidth. Moreover the solution is very stable. In particular increasing the number of corrugations does not affect the VSWR. It is difficult to decrease the cross polarisation level to the same value. Using both a smooth input taper and modifying the teeth widths along the profile leads to a high value of the cross polarisation (-26 dB). The cross-polarisation comes from the EH11 hybrid mode. This mode is evanescent in the profile we have synthesised and the horn length plays an essential role to decrease the cross-polarisation level. A value of - 45 dB seems to be the best reachable level on a significant bandwidth. This low value has been obtained choosing an operating point regarding the different modes such that HE11 propagates and EH11 is attenuated. This operating point is defined in terms of teeth / grooves dimensions from which equivalent electrical properties may be deduced.

4. summary of the various manufactured horns

The horn can be divided into two different parts. The first one is the rotationally symmetric part (radiating part) and the second one is the rectangular to circular junction necessary to be able to test the horn with standard equipment.

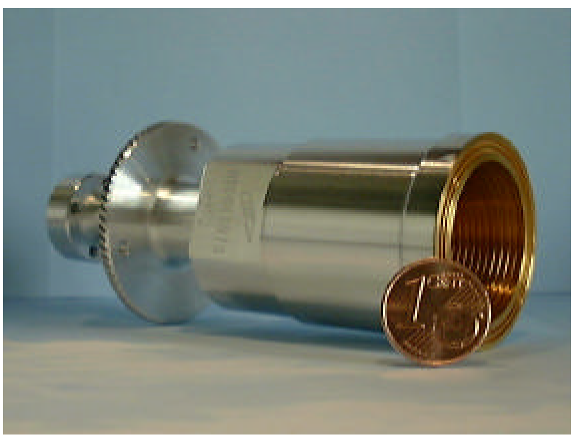
During the study, several horns have been designed and manufactured. They are detailed in the following sections. Their characteristics are summarized in Table 1.

Designation	Manufacturing method	Junction design	W/G I/F
HORN 1	Classical milling (grooves) and spark erosion (junction) – two pieces	"Classical"	WR 10
HORN 2	Electroforming – one piece	"Smooth"	WR 8
HORN 3	Electroforming – one piece	"Classical"	WR 8

Table 1: The various horns

HORN 1

The junction design is performed by intersection of a rectangular waveguide and a conical circular section and is named as "classical" junction design in the following. The junction termination is in WR10. The manufacturing process is spark erosion. The radiating part is performed by "classical milling", i.e. direct machining of the grooves inside the horn. The main difficulty for the "classical milling" was the first grooves machining in the throat region. This is the reason why the horn has been made in two pieces. The first one was composed of the junction and the 10 first grooves. The junction has been performed by spark erosion on one side. On the other side the first grooves were machined by "classical milling". The second piece, including the rest of the radiating part of the horn was also realized by "classical milling". Then the two pieces were assembled by screws. The horn is made entirely with the same aluminium alloy. Figure 1 shows the realization hereafter referenced as HORN 1.



a) b)

Figure 1 : HORN 1 a) performed by "classical milling" for the grooves and spark erosion for the rectangular to circular junction and HORN 2 performed by electroforming process b)

HORN 2

The results obtained for HORN 1 in cross-polarisation were bad (abnormal lobes on the horn axis and E/H planes). It was consequently decided to change the junction design as well as the circular input diameter (limitation of higher order modes). The rectangular section was changed to WR8 in order to be compatible with the circular input diameter. The junction design has been replaced by a "smoother" one without any angles from the circular input to the rectangular output. Due to technical difficulties for this new junction design, the manufacturing process has been changed to electroforming in order to be able to realize the new junction. HORN 2 corresponds exactly to this new design. The advantages of the electroforming process are an easier control by checking the mandrel before gold deposition and the possibility to fabricate the horn in one piece, avoiding misalignment and assembling accuracy difficulties. This HORN 2 performed by electroforming process is presented on Figure 2.

HORN 3

In parallel to the HORN 2, a set of two identical horns has been manufactured with the same geometry than horn 2 except the junction that is still the "classical" one instead of the new "smooth" design. Figure 3 shows this HORN 3 performed by electroforming process.

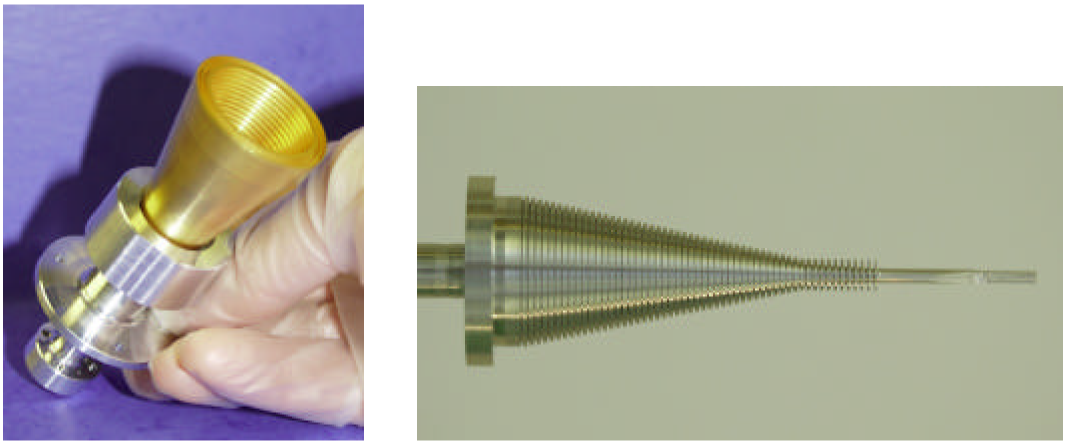
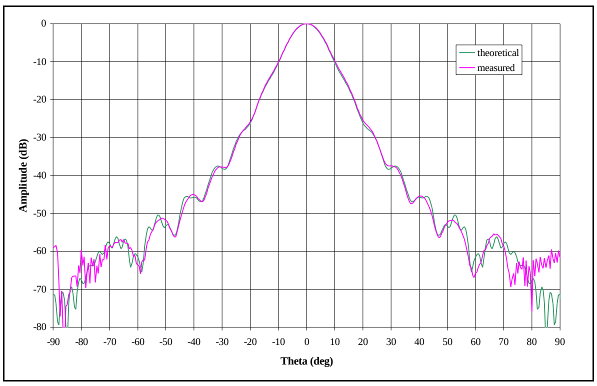


Figure 2 : HORN 3 performed by electroforming process (right figure: the mandrel).

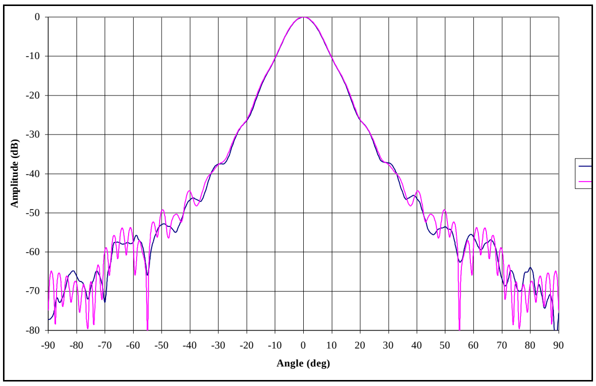
5. Measurements

A. Far field patterns

Comparisons were made for different frequencies for the E_plane, the H_plane and the cross polarization. Only the H planes results are presented. Identical results have been obtained in the E planes. The copular patterns were all approximately the same for the 3 horns. The differences were obtained in the x-polarisation pattern.



a)



b)

Figure 3: Computed versus measured pattern in H plane at the centre frequency using two different machining techniques : classical milling a) – electroforming b)

The agreement between theory and measurement is very good down to - 60 dB. For angles greater than 70°, the pattern accuracy is degraded because, starting from this angular value, the RAM (RF Absorptive Material) around the horn becomes more an obstacle than an absorber.

C. Cross-polarization

The results presented hereafter apply to the cross polarization. The agreement is quite satisfactory considering the very low level predicted. It is much better at the bandwidth extremity for higher values of the cross polarization.

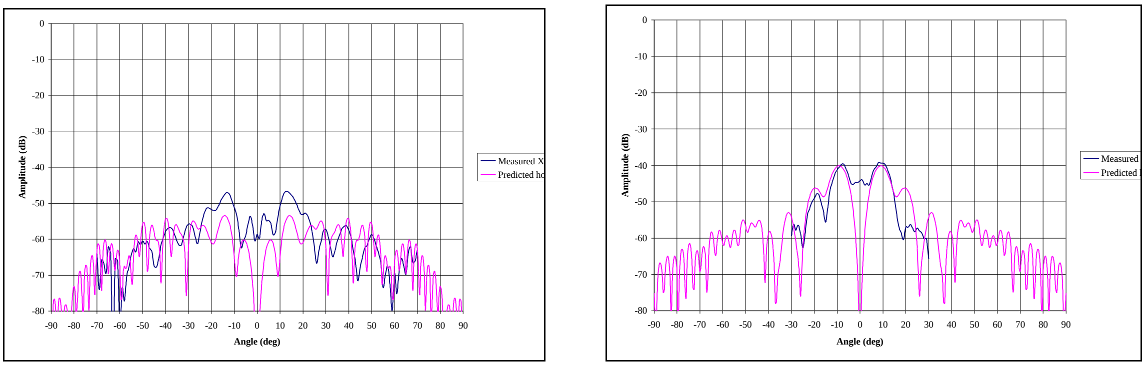


Figure 4: HORN 2 cross-polarisation : Computed versus measured pattern in the 45° plane a) and in the 135° plane b)

In order to verify the wideband characteristics of the horn, RF pattern have been measured from 76.56 to 109.10 GHz for the HORN 2 RAL 1 corresponding to 35 % of relative bandwidth.

The cross-polarisation performance is summarized in Figure 13.

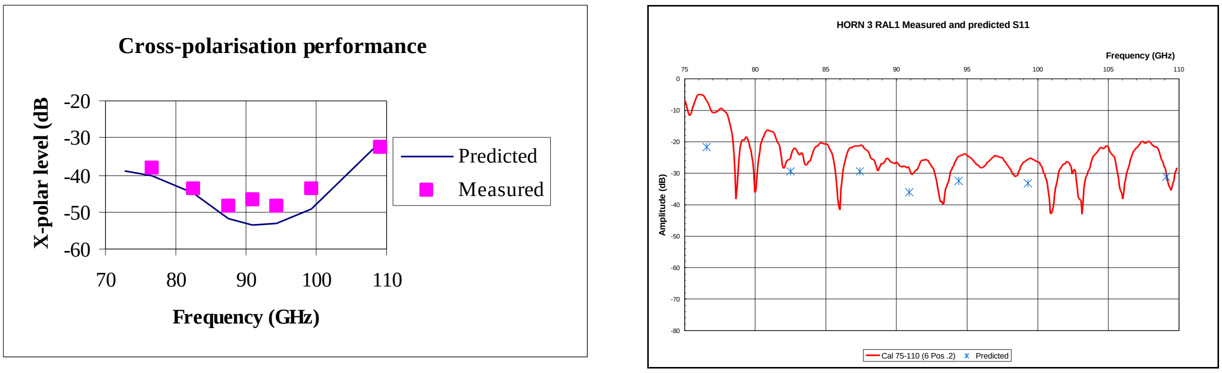


Figure 5: HORN 2 - Computed versus measured crosspolar within 35% of bandwidth

The measured value is the mean value of the maximum levels of crosspolar found in the diagonal planes (45° and 135° cuts).

The VSWR has been measured for the complete bandwidth at the WR8 waveguide interface of the horns with a millimetre vector network analyser (Wiltron 360) equipped with the 75-110 GHz extension. The measurement includes the circular to rectangular junction which is part of the horn. The prediction does not include this junction contribution. This junction terminates with a WR8 rectangular waveguide. The nominal bandwidth for this waveguide is 90-140 GHz and the cut-off frequency is 73.8 GHz. As a consequence the measurements from 75 to 85 GHz are degraded because of the attenuation due to the cut-off proximity.

6. Conclusion

Design procedure

The design procedure has been carried out using a method of moments integral equation code and following Zhang ideas which seem to be the best way to obtain a large bandwidth with respect to both the VSWR and the cross polarisation. Results obtained are 33 % at - 30 dB for the VSWR and 22 % at – 45 dB for the x-polar. Such a result constitutes an improvement as compared to other published studies.

Manufacturing

At such frequencies the manufacturing process is critical. Classical milling is still a good candidate and can be used up to 350 GHz for corrugated horns. For the rectangular to circular junction, spark erosion is a good candidate for direct machining. As a drawback the surface roughness is not as good as classical milling. The electroforming process becomes necessary as the horn dimensions decrease, the mandrel being easier to manufacture and control. The other advantage is that the horn is fabricated in one piece. Both processes has been used in this study and it is not obvious to say which one is the best one. However the horns realised by the Rutherford Appleton Laboratory (UK) (horn 3) using an electroforming process have shown the best results in cross-polarisation.

Measurements

The measurement was another challenge of this study and in particular the cross-polarisation measurement. The results obtained and the excellent agreement with predictions down to very low levels as -50/-60 dB have demonstrated the accuracy of the far field pattern measurements. For VSWR measurements, the comparison predicted/measured is not easy since the junction is not included in the predictions. Nevertheless, the test results are very interesting for such a wideband horn. One interesting point to mention in the VSWR measurements, which have been performed in the time domain, is the fact that we can identify the locations of the structure elements responsible of the VSWR. In this case, the discontinuity in the flare angle at the end of the circular section brings the major contribution to the VSWR.

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