Optimization of corrugated horns radiation patterns via a spline-profile

Christophe Granet
CSIRO Telecommunications & Industrial Physics
PO Box 76, Epping 1710, NSW, Australia

1. Introduction

Corrugated horns are widely used as feeds for reflector antennas [1] or as direct radiators, as in global earth illumination from a satellite [2] [3] or source antenna in an anechoic chamber. Shaping the radiation pattern of a corrugated horn is mainly done by shaping the profile [4-6], and to a lesser extent, for wide-band applications, by using a mode-converter [7-9] tuned to the design frequency.

In the literature, the profile of corrugated horns is optimised either by using known information on the effect of conventional profiles [4] or by combining some of these profiles [5,6]. Some authors report successful optimisation [10,11] using as parameters the profile and/or slot-depths of each corrugation.

In this paper, we define the profile of a corrugated horn as a spline and optimise the radiation pattern by shaping the profile. A computer program has been written to optimise the profile to meet a specified radiation pattern. The horn synthesis is based on minimization of a penalty function representing a measure of the extent to which the pattern constraints are violated. The approach is similar to that which has been applied to the synthesis of array feeds for reflectors with gain pattern constraints [12], the only difference in this case being that profile-parameters rather than feed-parameters are the variables to be optimised. The penalty function is of the least p^{th} index form with p set equal to 2. The minimization is done via a quasi-Newton method in which the derivatives are approximated by finite difference. The envelope is supplied by the user as a list of angular points where an upper-bound and a lower-bound for the co-polarised pattern is specified as well as an upper-bound for the cross-polarised pattern (see Fig. 1).

2. Geometry of the horn

Our approach is based loosely on the work described in [13], where a smooth-walled horn was optimised to provide the desired radiation pattern by allowing each section to have its radius and length optimised. A cubic spline was then fitted to these points to provide a so-called “serpentine-profile”.

Our approach is slightly different. First of all, we want to optimise a corrugated horn. Secondly, only a few points (or nodes) are used along the length of the horn to generate the spline, namely 2 extreme nodes and 5 inner nodes.

We have designed an optimisation program that uses the following parameters (see Fig. 2):

- a_i : input radius, the first extreme node (fixed value)
- a_o : output radius, the second extreme node
- d_o : the allowed displacement of the output radius (usually set as ±20% of a_o as the required beamwidth of the radiation pattern is known and a_o can be estimated [1])
- a_1, a_2, a_3, a_4, a_5 : radii of the 5 inner nodes
- d_1, d_2, d_3, d_4, d_5 : the allowed displacements of each of the inner nodes (making a_1, a_2, a_3, a_4, a_5 constrained variables)
- L_1, L_2, L_3, L_4, L_5 : the positions of each of the inner-nodes as percentages of the horn’s length (not used as variables in the first release of the program)
- number and pitch of the corrugations, pitch-to-width ratio and number of slots in the mode-converter

The user enters the above parameters and, a_1 to a_5 and a_o are optimised to try to provide the desired radiation pattern by minimizing the penalty function. The constraints d_1 to d_5 and d_o are applied to these values to force the optimiser to create shapes which are physically possible to manufacture, which have sections bound by a certain height to allow the use of off-the-shelf aluminium billets for manufacture or which are desirable for integration inside a known physical environment.

In the first release of the program, a conventional mode converter is used [7], but other mode-converters will be added soon [8,9]. The depth of the slots is calculated via the following formulae each time the profile is optimised, i.e., at each iteration of the optimiser, to keep the wall impedance optimal:

- for $1 \le j \le N_{MC} + 1$ (where N_{MC} is the number of slots in the mode-converter):

$$slot-depth_j = \left[0.4 - \frac{j-1}{N_{MC}} \left(0.4 - \frac{1}{4} \exp\left(\frac{1}{2.114 (k_i\, a_j)^{1.134}} \right) \right) \right] \lambda_i$$

- for $N_{MC} + 2 \le j \le N$ (where N is the total number of slots):

$$slot-depth_j = \frac{\lambda_i}{4} \exp\left(\frac{1}{2.114 (k_i\, a_j)^{1.134}} \right) - \left(\frac{j - N_{MC} - 1}{N - N_{MC} - 1} \right)$$

$$\left[\frac{\lambda_i}{4} \exp\left(\frac{1}{2.114 (k_i\, a_o)^{1.134}} \right) - \frac{\lambda_o}{4} \exp\left(\frac{1}{2.114 (k_o\, a_o)^{1.134}} \right) \right]$$

where λ_i is the wavelength of the frequency f_i at which the mode converter is optimised, λ_o is the wavelength of the frequency f_o for which the last slot of the horn (at the aperture) will be optimised, $k_i = \frac{2\pi}{\lambda_i}$ and $k_o = \frac{2\pi}{\lambda_o}$.

3. Example

As an example, a corrugated horn with spline-profile was optimised to be used as a feed for a multibeam antenna [14] where a high-performance, low sidelobe horn was required to work over the 10.70 to 12.75 GHz band. The original horn [14] is 680 mm long and was used as a starting point. The length of the horn was gradually shortened after several optimisations to finally end up with a horn 500 mm long (>25% reduction in length) comprising 125 corrugations (compared to 165 in the original design). Figure 3 shows the geometry of the horn after optimisation while Figs 4 to 6 show the radiation pattern at 10.70, 11.70 and 12.75 GHz, respectively. The gain of the horn is 25.3 dBi at 11.70 GHz and the return loss over the required bandwidth is better than 25 dB. The phase-centre is relatively constant and is located 100 mm inside the horn when measured from the aperture. The mode-converter was designed for $f_i = 11.70\,GHz$ and $f_o = 12.48\,GHz$.

Interestingly enough, the optimised profile looks very similar to the one designed by trial and error [14]. At the input, the profile is close to a “bowl-shaped” profile [3,4], confirming that low sidelobes are achieved by using such profiles, while at the output, it is close to a Gaussian profile that is known to maintain good radiation properties over the required bandwidth [5].

4. Conclusions and future work

A computer program has been written to optimise the radiation pattern of a corrugated horn by optimising the profile via the coefficients of a cubic-spline. The procedure was applied to a practical example and good performance was achieved.

The next step is to include more options for the design of the mode-converter and allow more parameters to be optimised, such as the length of the horn, the slot-depths (for narrow-band applications) and even the slot geometry. Some work on other optimisation algorithm should also be carried out, like for example, the genetic algorithm. Another approach would be to include as many parameters as possible in the optimisation and let the optimiser loose. There is scope for a lot of research and many odd-looking corrugated horns will probably adorn reflector antennas in the future.

5. References

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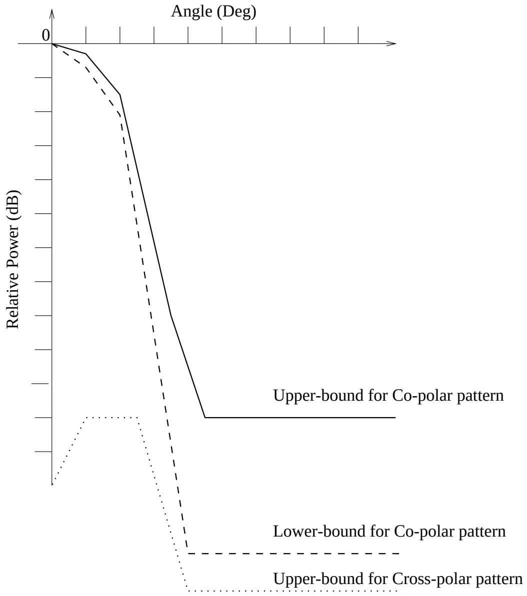

Figure 1: Envelope-pattern used for the optimisation.

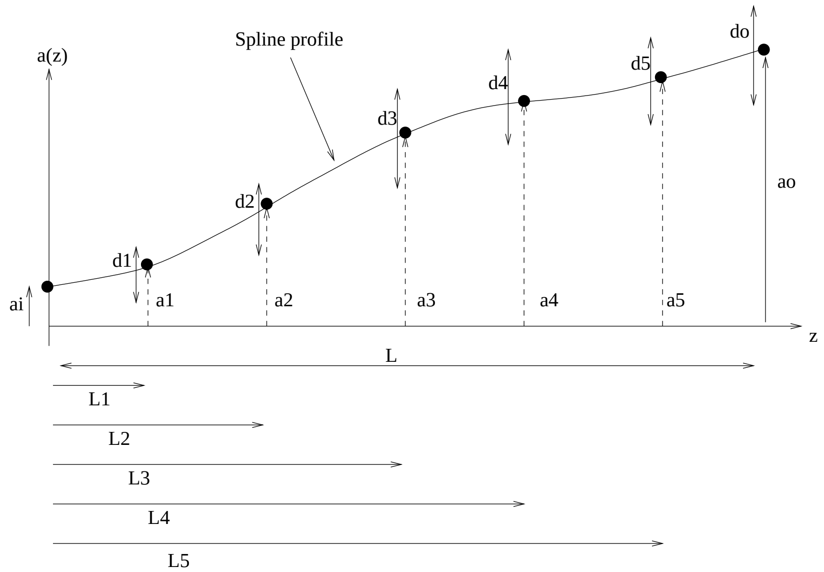

Figure 2: Spline-profile horn geometry.

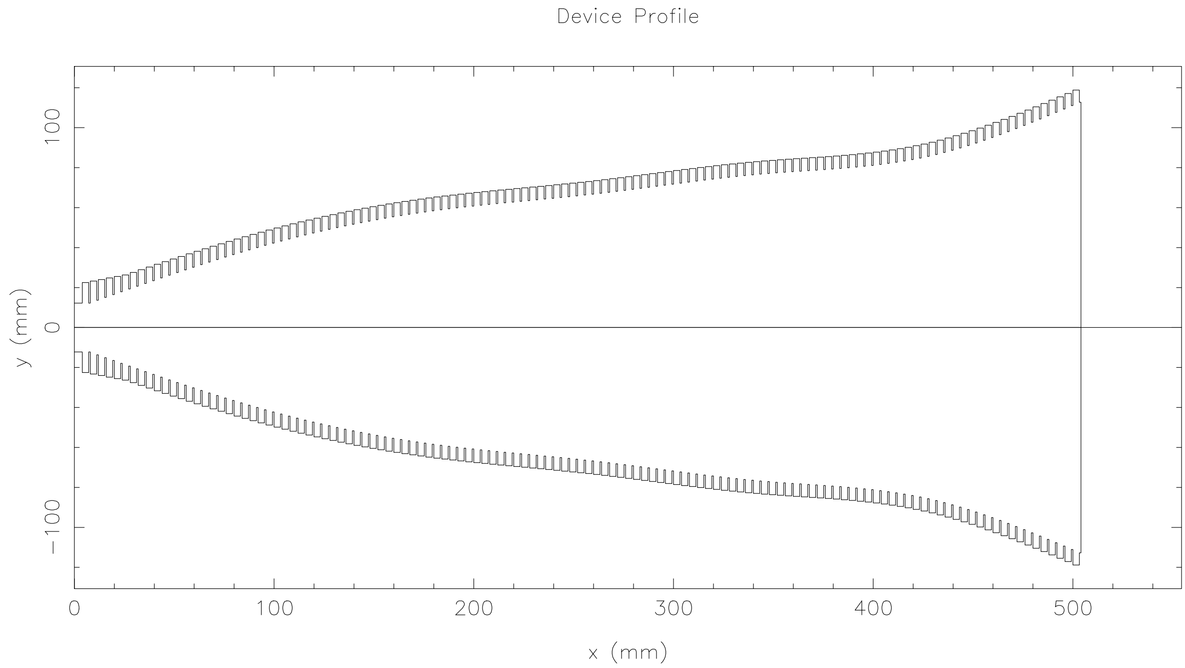

Figure 3: Geometry of the spline-profile corrugated horn.

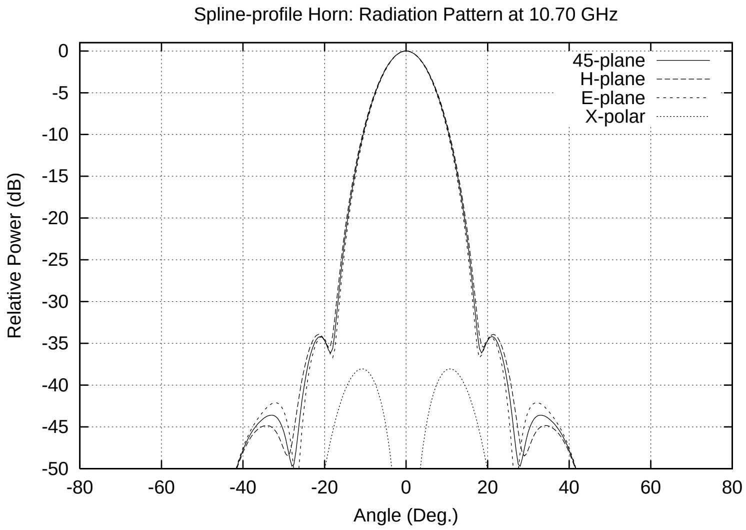

Figure 4: Radiation pattern at 10.70 GHz.

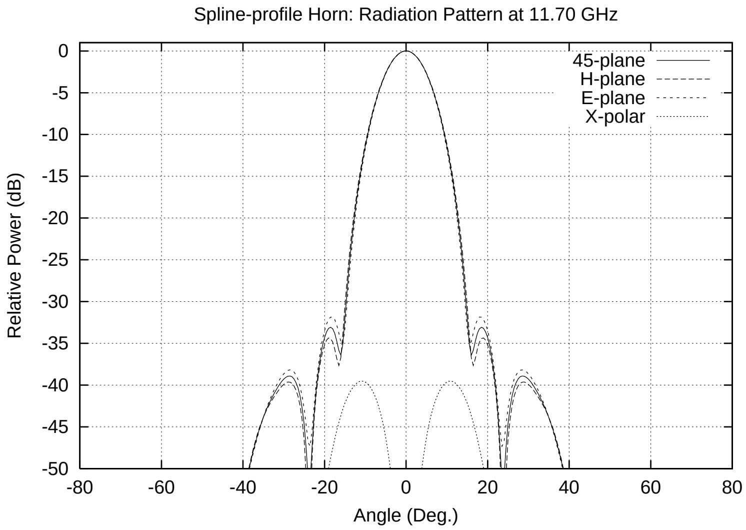

Figure 5: Radiation pattern at 11.70 GHz.

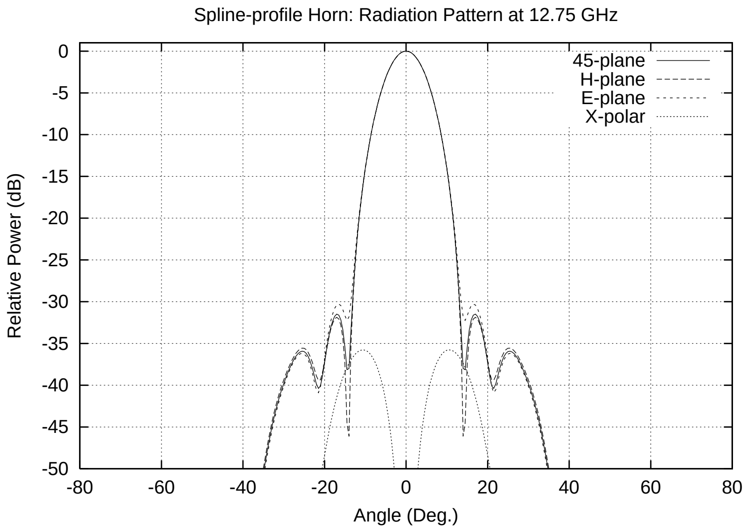

Figure 6: Radiation pattern at 12.75 GHz.