Optimizing a Corrugated Horn for Telecommunication and Tracking Missions using a new flexible Horn Design Software

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***Abstract*— A new design approach and an associated software tool for conical corrugated horn antennas has been developed in a joint TICRA-Thales Alenia Space-ESA project. The software is developed such that it supports the user in designing an optimized horn antenna in a natural way with stepwise refinements both in geometry, in optimization parameters selection and in design requirements definition. The techniques presented have been validated on a case where a highly optimized horn has been designed, manufactured and measured.**

I. Introduction

Corrugated conical horns play a key role in telecommunications systems, whether on the spacecraft as part of the dedicated telecom payload and the telemetry system, or in a ground terminal as primary source of single or dual reflector optics. In addition to the pure telecommunications service, these horns are often also required to carry a tracking function, usually by providing access to the so-called tracking modes at the throat of the horn.

Tracking capabilities are thoroughly implemented in ground terminals. With the new broadband telecommunications services, the satellites will generate very narrow, multiple spot beams, with stringent requirements imposed on the pointing accuracy. Therefore it is necessary also to provide tracking capabilities on the telecom antenna itself, which creates a need for efficient telecommunications horns with integrated tracking capabilities. This in turn requires availability of efficient design tools for these kinds of feed systems. Several analysis tools have been developed which allow the analysis of the corrugated conical horn with single mode excitation (fundamental or tracking). Because these are analysis tools they require the user to provide the geometry of the horn beforehand.

Over the years, the analysis tools have been used as design tools either by multiple runs where the user manually changes the geometry in each iteration, or by spawning the analysis tool from a synthesis tool. For many reasons such optimization schemes are rather limited with few or no possibility of handling complex optimization scenarios e.g. only allowing the horn to be optimized with respect to the telecommunication properties, finding sub-optimal solutions etc... Therefore, in order to be able to meet the stringent requirements of next generation multi-mode horns, there has been a need for a new optimization approach that allows a highly flexible formulation and management of the optimization scenario including simultaneous optimization of the antenna performances for both the fundamental mode and higher order mode excitation.

A new design approach for conical corrugated horn antennas has been developed in a recent joint TICRA-Thales Alenia Space-ESA project [1]. The new approach [2] offers high flexibility through all the steps of the design procedure. The new approach utilizes a newly developed software tool obtained through a complete redevelopment of the existing CHAMP software (see [2]). A comprehensive validation scheme was chosen for the new procedure both in terms of the accuracy of the electromagnetic models and in terms of the adequacy of the overall procedure for circular symmetric horn antenna design. A new horn was thus designed and produced by Thales Alenia Space. The predicted optimized horn performance has been verified through measurements.

Other approaches for somewhat similar problems associated with horn antennas synthesis have been presented, e.g. [3-6], with the horn profile modeled in terms of a wavelet expansion, piecewise second-order polynomials over sub-sections, or splines.

The present paper outlines the new design approach and the associated software tool. The application of the procedure for designing the new horn antenna will be explained in detail. Finally, a section covers the validation procedure including production and measurements of the new horn.

II. Modeling and Analysis

The flexibility for designing the horn is obtained with a leveled and modular approach in the overall horn modeling together with a similar modular formulation of optimization scenario. It enables an easy-to-manage stepwise performance driven design procedure where more and more refined designs are produced in a sequence of optimizations leading to antenna horns which are highly optimized.

A. Modeling with sections

In many corrugated horn analysis tools, the horn interior geometry is described corrugation by corrugation leading to a horn-geometry model in terms of several hundred geometrical parameters. This detailed piecewise modeling is required in the mode matching analysis. However, this modeling of the geometry is not well-suited for synthesis due to the high number of parameters.

Consequently, the new procedure is based on new ways of modeling the horn. The horn may be divided in several sections, and in each section three levels of horn geometry models can be used: 1) predefined profile functions, 2) spline functions, and 3) a detailed piecewise modeling. As a major advantage, the user may start with model 1 and during the design process convert to model 2 and subsequently to model 3. If a pre-defined profile function is used, the overall horn geometry is described in terms of a few parameters only. Considerably more parameters are needed when splines are used. Finally, as mentioned above, very many parameters describe the geometry when detailed piecewise modeling are used. Note that the various levels may be mixed. A throat section with a few individual corrugations may be modeled in details with a detailed modeling whereas the other sections may be modeled with splines or predefined functions. The user may thus combine the various models in various sections. Whenever input to a mode matching analysis is required, a detailed piecewise modeling of the complete horn is automatically generated from the current section wise models.

The features discussed above are reflected in the design of the software tool which enables easy management of the various sections and associated models. In the example shown in fig. 1 a horn profile is modeled with four sections. The first interior section is a linear profile function that models the feeding wave guide. Next, a corrugation list section is used to model a mode converter and a spline section models the main horn profile. Finally an exterior section models the most important part of the outer profile.

B. *Analysis*

Whenever needed, the user can easily set-up and perform an analysis of the horn performance usually over a frequency band represented by a number of discrete frequencies. The analysis is in general divided into a horn-interior problem solved by mode matching, and a horn-exterior problem solved by the Method of Moments. The CPU-time required for an analysis depends on the complexity of the geometry. The horn in fig. 1 can be analysed in 1.5 second per frequency on a fairly standard Intel dual core PC. Further discussion of the analysis methods can be found in [2]. This very efficient analysis is highly desirable because it is repeated many times during an optimisation.

III. Optimisation

When the initial modelling of the horn has been completed, the user will typically investigate if an optimisation can lead to improved performance. Here the initial horn will be used as an initial solution or starting point for the optimisation process. If this horn is prepared by a skilled antenna horn designer, it will already be well suited for the application at hand and thus a good starting point.

The modular and flexible approach used in the modelling is carried into the optimisation management and interface. The optimization management includes the selection of optimization variables and the specification of the optimization goals which correspond to the objective function.

A. *Optimisation parameters*

The choice of optimisation parameters – also called variables – is a key task in the optimisation scenario set-up. This choice is usually hard-wired in traditional synthesis software. In the new software tool, however, any real valued input parameter of the profile model in any section – be it geometrical or electrical (e.g. dielectric coefficient) – can be included in the set of optimisation parameters. Usually a few parameters will be used in initial runs. Then more and more and often different parameters are included as the design is refined. The user may even prescribe independent parameters that don't appear in the horn model explicitly. Explicit parameters may thus be set up to depend on independent parameters through functional expressions making the choice of optimisation parameters extremely flexible.

B. *Optimisation goals*

The second key task is the choice and specification of the optimization goals and the associated object function. Once again a modular approach is used. The goals management is thus developed like a tool box where the designer can construct the overall objective function with many different elements each of which inflicts some specific performance measure. The types of goals are divided into three groups: 1) Return loss goals, 2) beam pattern goals and 3) tracking beam goals. All goals are equipped with a

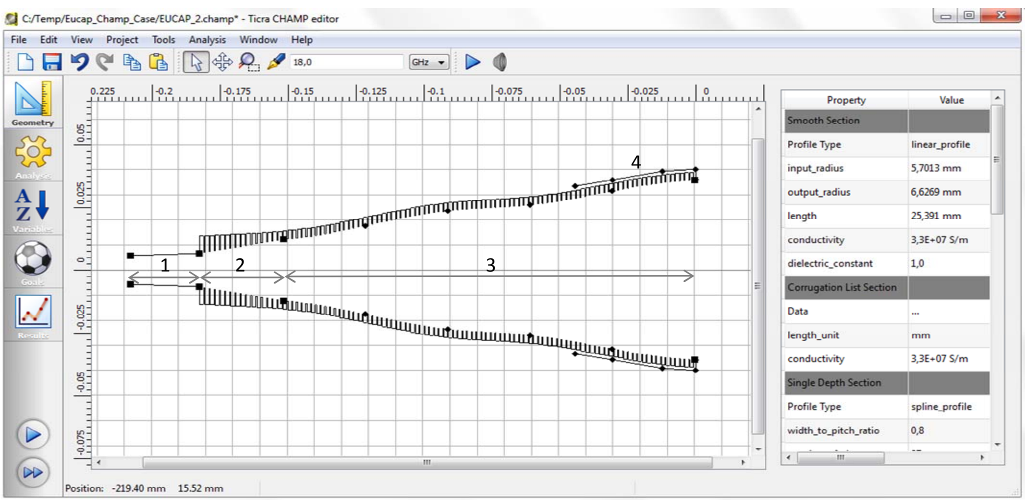

Fig 1. Modeling in sections.

frequency-dependent weight factors which enable control of the mutual influence of the goals during an optimisation. Usually a simple combination of goals is used in the initial runs to optimise the most important performance measures. The solution is then refined in subsequent runs by adding goals that improve problematic performance measures.

C. *Optimisation methods*

When the optimisation parameters and goals have been specified, the optimisation can be initiated. The horn performance must be calculated through an analysis of a horn with a geometry that corresponds to the current iteration point. The software assumes excitation by a single mode in the feeding waveguide. The mode is either the fundamental TE11-mode or one of the modes TM01, TE21, or TE01, used for tracking purposes. The analysis of the horn-exterior is only available for a horn excited with the fundamental TE11-mode. The software offers four optimisation methods: 1) The Hald and Madsen method, [7], for non-linear minmax optimisation, 2) the Hanson and Krogh method, [8], for non-linear least squares optimisation, 3) the Nelder-Mead Simplex algorithm and 4) a Genetic Algorithm (GA). Minmax is the default. This method always concentrates on the worst case goals at any point during the iteration. The least squares as commonly known will tend to spread emphasis over all goals. The GA is included for global search of a large region.

IV. Designing a new horn antenna

The starting point of the optimization process was an existing wideband telecom and tracking Ka band horn ([17.7-20.2 ; 28-30] GHz) developed for a previous mission. This horn offered satisfying RF performances (nearly -30 dB VSWR and cross polarization) but its efficiency was too low for actual needs (around 65/70%).

The aim of the optimization was to improve the efficiency all over the bands (specifications over 70/75%) and especially in the Tx and Rx user bands ([19.7-20.2 ; 29.5-30] GHz) where the efficiency needed to be maximized as much as possible. Moreover, this had to be obtained without any deterioration of the other parameters. Further, it was required that the new horn should have a length and an aperture similar to the initial one. In order to obtain an optimum design and to reduce design time, a strategy had to be defined. The strategy which led to the new improved horn is presented in the following.

First of all, the initial geometry must be carefully chosen because it drastically influences design time and optimization results. The existing horn design was thus chosen and simplified in order to get a manageable flexible initial geometry with few optimisation variables (only one spline section with ten nodes).

The next step focused on the optimisation of the efficiency. The aim was to maximize it while at the same time avoiding deteriorating VSWR and cross polarization performances. The horn performance in terms of efficiency was thus improved in a sequence of optimization runs where the efficiency goals were increased from run to run. This procedure was stopped when it appeared that the efficiency could not be further improved without too large degradations of the others RF characteristics. These optimizations were made with only 3 frequencies per band (lower, central and upper frequencies) in order to converge quickly on the initial design.

Apparently, the potential of the set of degrees of freedom associated with the initially selected geometry had been exhausted in the first sequence of optimisations since no more improvement could be obtained. Therefore, the geometry was made more complex (one spline section with twenty nodes). Thanks to these additional degrees of freedom, further improvements of the efficiency were obtained. Moreover, as the design began to be more complex and the optimised performance got closer to the efficiency specifications, the number of frequencies was increased to 6 Tx frequencies and 5 Rx frequencies per band in order to cover all the frequency plan properly. Once again, the sequence of optimisation was stopped when no more improvements could be obtained.

Then, as the design had nearly reached the efficiency goals, the geometry was made even more complex in order to recover minor degradations on return loss and cross polarization specifications. The new geometry consisted in two spline sections with ten nodes. The first section was approximately one third of the total length and the second one two thirds. Such a subdivision should ensure a higher sensitivity to parameters with influence near the throat. Once again, goals were made stricter from one optimisation to the next until specifications were met or until achievable optimum performance was reached. Furthermore, at this point, goals were added to control the return loss and the roll-off of the tracking mode. At this stage, optimizations were made with 11 Tx frequencies and 9 Rx frequencies. Due to these adjustments and to another succession of optimization runs, specifications concerning fundamental and tracking VSWR, cross polarization and efficiency were met.

The next step consisted in focusing on the efficiency in the user bands. To push it to its limit, the design was made more complex with 20 nodes per section. Therefore, during the optimization process, it appeared that while user efficiency increased, XPD decreased, and XPD goals were thus added to keep an XPD similar to that of the initial horn. After another series of iterations where goal values and weights were accurately adjusted, an optimum design was finally obtained. This optimum design met all the specifications including user band efficiency goals and the overall horn performances were greatly improved. This could only be achieved within reasonable time limits due to the limited number of optimisation parameters. The new horn design was deemed much fit for actual industrial needs and a prototype was thus manufactured.

Subsequently, the spline profiles were transformed into detailed step designs and further optimisations were made. This led to an even better solution but also to a much more complex design and much longer optimisation time.

V. VALIDATION SCENARIO

The horn was manufactured as a according to flight standards. After a 3D control that showed that the horn was correctly produced (maximum deviation of 43 µm from the CHAMP design), a measurement campaign was carried through. For the telecom mode, the horn was measured alone. A return loss measurement was settled using a vector network analyzer and exploiting a TRL calibration. Radiation performance of the horn was verified in an anechoic chamber. The same procedure was used for the tracking mode except that a feed element was added to the horn to extract the tracking mode. An excellent agreement was found between predictions and measurements (fig. 7, 8, 9 & 10).

VI. OPTIMIZED HORN PERFORMANCE

In order to pinpoint the effect of the optimization strategy, we will focus on the efficiency performances. As it can be seen on figs. 3 & 4, we have increased the Tx gateway efficiency ([17.7-18.2] GHz) by more than 6% (even more for lower frequencies which will allow a decrease in spill-over losses, when using the horn in a reflector) and around 4% for Rx gateway band ([28-28.5]GHz). Therefore, the main results are the great improvement of the user efficiency performances. The Tx and Rx user efficiencies are increased by more than 8% (even up to 16% for the upper Tx frequencies). The gain is extremely significant and it has not reduced the other RF performances (fig. 5 & 6).

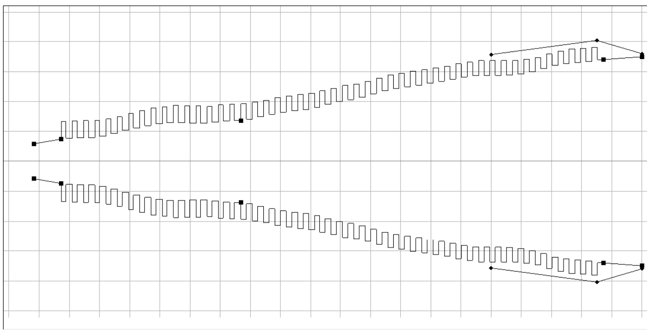

Fig.2: Optimized horn geometry

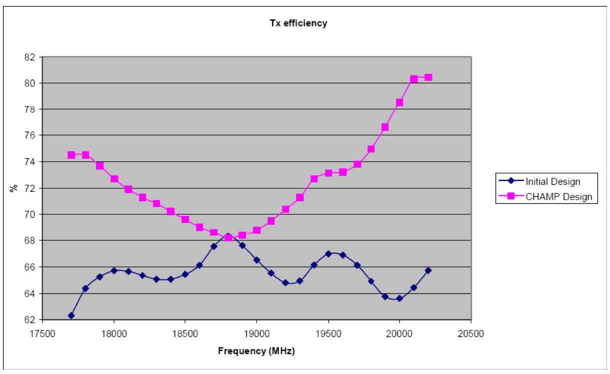

Fig.3: Initial vs. optimized Tx efficiency

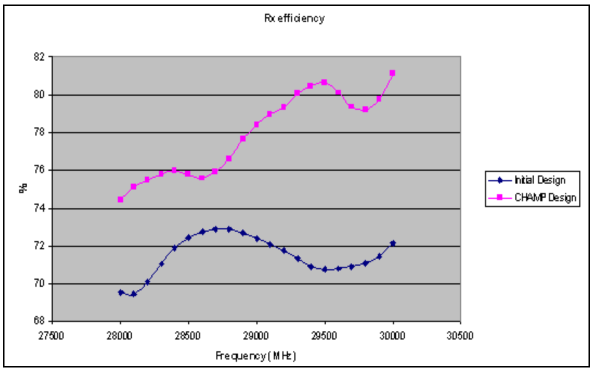

Fig. 4: Initial vs. optimized Rx efficiency

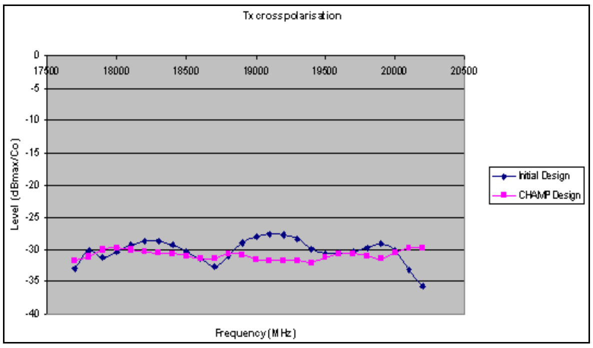

Figure 5: Initial vs. optimized Tx cross polarization max

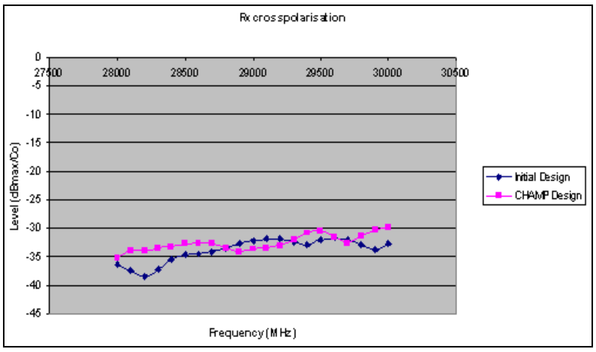

Figure 6: Initial vs. optimized Rx cross polarization max

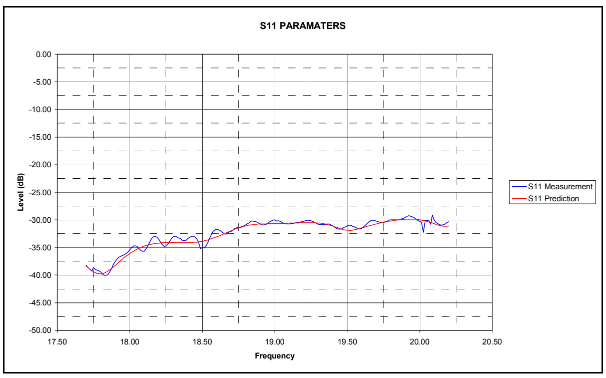

Fig. 7 :Measurements vs. predictions Tx VSWR

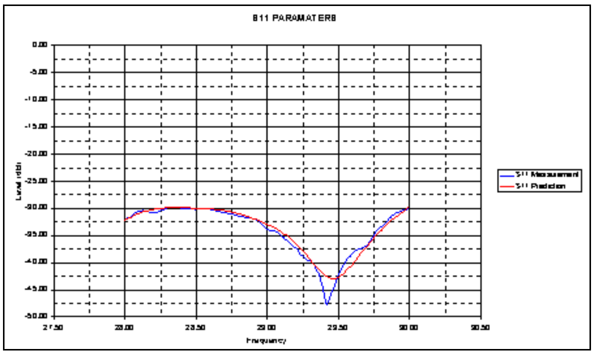

Fig. 8 : Measurements vs. predictions Rx VSWR

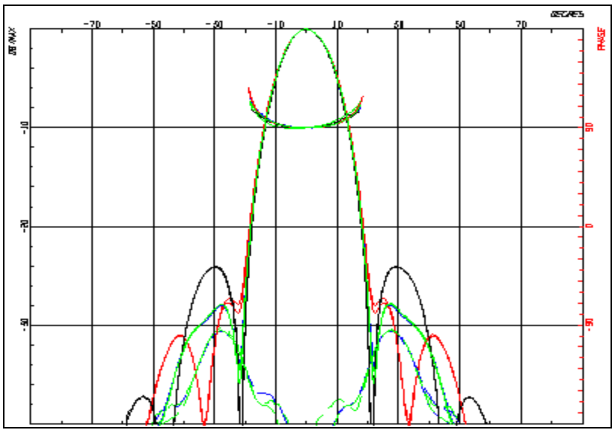

Fig. 9: Measurements vs. predictions pattern at 17.7GHz for cuts 0, 45, 90 and 135°

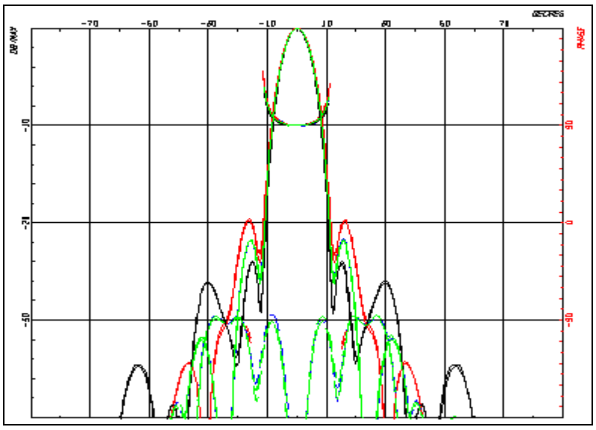

Fig. 10: Measurements vs. predictions pattern at 30GHz for cuts 0, 45, 90 and 135°

VII. CONCLUSIONS

The objective of the present project was to develop a new procedure and software for designing rotational symmetric corrugated horn antennas. The new tool has then been used to design an optimized horn which was manufactured and tested to validate the software calculations.

The SW-developments focused on evolving the legacy CHAMP analysis tool into a synthesis tool. The CHAMP tool now allows the user to simultaneously optimize the horn performances for both the fundamental mode and tracking mode excitation.

The new tool was used to redesign and optimize an existing horn. The RF-performance was greatly improved. It was possible to increase the directivity in all parts of the frequency bands considered, leading to an enhancement of the aperture efficiency from ~65% to ~70% (and even 80% in some part of the bands). The optimized horn was manufactured and RF-measurements performed. The comparisons of the measured and calculated performance show excellent agreement.

During the horn design phase, several points have been demonstrated concerning the new software. First, the time to optimize a design is significantly reduced due to very fast calculations. Second, the CHAMP software facilitates the definition and easy application of an optimization procedure, that allow the user to manage in real-time the optimization project, goals and variables, and to interact deeply with the process. Also, it is our experience that no design software for complex corrugated horns can find a complete optimal solution in a single run. Rather, in practical use the best solutions are found as a result of a development process. Initially a relatively simple system and simple goals are considered followed by a stepwise refinement where more and more details and optimisation parameters are introduced together with more and more stringent goals.

Finally, this study has shown that a fast and accurate tool which allows the user to easily define and apply his own optimization strategy is necessary for horn designers to obtain superior horn designs.

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