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Combined mode matching-integral equation technique for feeders optimization

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Abstract

The realization of high performances feeders is of fundamental importance for satellite telecommunication antennas. A powerful numerical technique for the analysis of circular corrugated horn is briefly presented and exploited, jointly with an optimization algorithm, to obtain optimized feeders. The code has been successfully used to develop horns currently mounted on telecommunication satellites. A sample of the most significant projects developed with this CAD environment will be also shown.

1 Introduction

Satellite telecommunication systems require high performances in term of extremely low cross polarization, low return loss, high power level, and low level of passive intermodulation over a range of above 30% of the frequency bandwidth.

An accurate design of primary feeders is essential to meet such requirements. Among the available feeders, circular corrugated horns have long been the most popular as they feature very low cross polarization and low return loss over a broad frequency range. Other kind of circular feeders have to be mentioned that, if properly designed, provide performances of comparable quality.

It is worth mentioning also that design schedules are shortening and costs reducing. In this scenery, CAD procedures employing increasingly accurate models must be used to keep competitiveness in the marketplace.

The aim of this paper is to present both a procedure developed for the optimum design of circular primary feeders and some manufactured models designed with such procedure. The feeders presented are currently mounted on

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some of the most important telecommunication satellites and represent, for their high performances, the state of the art in this field.

2 Design and Optimization Procedure

The approach employed for the analysis of circular corrugated feeders is based on a hybrid technique which combines the use of the generalized scattering matrix (GSM) for modeling the interior of the horn, with the combined electric and magnetic field integral equation (CFIE) to account for the surface electric current on the exterior perfectly conducting wall of the feeder. In particular, the radial discontinuities of the interior cross section of the horn are modeled via the full-wave mode-matching (MM) technique, while the exterior shape of the feeder is rigorously accounted for by the CFIE. Details on the this technique, that allows analyzing feeders with axial symmetry, are given in [1].

The advantages provided by the approach fully developed in [1] can be summarized as:

- the GSM technique allows introducing a high number of different corrugations inside the horn without resulting in a too heavy computational cost;
- the interior region, where the GSM technique is conveniently employed, and the exterior one, where only CFIE technique is applicable, may be coupled through an aperture not necessarily coincident with the geometrical one;
- the design can be improved by introducing optimization techniques based on the evaluation of sensitivity.

The above mentioned accurate and flexible analysis method has been used to develop an optimum design procedure which consists of the following steps:

1) the desired kind of feeder (Potter, Dual-Mode, Conic, Corrugated, Profiled, etc.) is chosen according to its application;
2) a first design of the feeder's geometry is obtained by using simple approximated analytical formulas [2]. In this step the surface separating the interior and exterior problems, treated via the full-wave mode matching and the CFIE, respectively, is defined;
3) an optimization of the feeder's geometry considering a limited number of parameters as, for instance, total length, flare angle, and corrugation's width to depth ratio is possibly performed;
4) if the previous optimization performed on a small set of parameters does not lead to a horn with desired requirements, an optimization on all the geometric parameters of the feeders relevant to its interior, that is to the part modeled via the GSM, is accomplished. The whole interior of the horn, a limited section comprising a few teeth, or a particular corrugations' parameter (for instance the depth) can be optimized;
5) the external shape of the feeder, that is the geometrical parameters pertinent to the part of the horn analyzed by means of the CFIE, can be optimized;

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6) the sensitivity and the worst case performances of the designed circular horn, are computed, in order to check the effects of mechanical tolerances and thermal dilatation.

The optimization procedure of steps 3) to 5) is based on the minimization of an error function U which is defined as

$$\mathrm{U}^{(n)}(\mathbf{a}^{(n)}) = \sum_{i} \sum_{k} | w_k(\mathrm{f}_i)(\mathrm{F}_k^{(n)}(\mathbf{a}^{(n)}, \mathrm{f}_i) - \mathrm{S}_k(\mathrm{f}_i)) | . \qquad (1)$$

In the above equation $\mathrm{U}^{(n)}$ is the error function at the n–th step of the optimization procedure, relative to the feeders characterized by the set of parameters $\mathbf{a}^{(n)}$. U is defined as the weighted sum of the differences between the desired k–th performance at the frequency f_i, $\mathrm{S}_k(\mathrm{f}_i)$, and its achieved counterpart at the n–th step of the optimization process, $\mathrm{F}_k^{(n)}(\mathbf{a}^{(n)}, \mathrm{f}_i)$. The differences are more or less emphasized at different frequency values by the weighting functions $w_k(\mathrm{f}_i)$. The various features F_k of the feeders, optimized in different ways by properly defining the weighting functions w_k, are: maximum directivity, maximum value of the crosspolar component, return loss, and beamwidth at various radiated power levels.

The error function U is conditioned also by some penalty functions which account for limitations on the values of the set of geometric parameters **a**. This functions are necessary in order to obtain geometrical dimensions of the feeder that are compatible with mechanical manufacturing processes.

The searching of the error function's minimum is accomplished by using the Davidon-Fletcher-Powell method [3], that employs the gradient of the error function and the approximation of the inverse of the Hessian [4]. In order to reduce the computational cost of the numerical partial derivatives with respect to a particular geometric parameter, which involve the computation of the total GSM of the feeder, a procedure able to avoid cascading the generalized scattering matrices of all the discontinuities inside the horn has been conceived. It consists of storing, for each discontinuity i of the interior part of the horn, three generalized scattering matrices: that relative to the i–th discontinuity itself, that pertaining to the block of discontinuities from the first to the $(i-1)$–th, and that characterizing the block of discontinuities from the $(i+1)$–th to the last one (Fig. 1). In this way, the evaluation of the partial derivatives with respect to a geometrical parameter of the i–th discontinuity requires computing the GSM of the discontinuity i and cascading it with the generalized scattering matrices which model the block of discontinuities before and after the i–th one. Apparently, the speed up of the optimization process is traded against the amount of memory required.

The design environment is made up of eight main different computer codes, for a total of about 20,000 lines of instructions, running on a single microprocessor. The environment allows not only the design of horns, but also graphical presentations of results (radiation patterns, and performances versus frequency) and both 2D and 3D geometric models of the feeders.

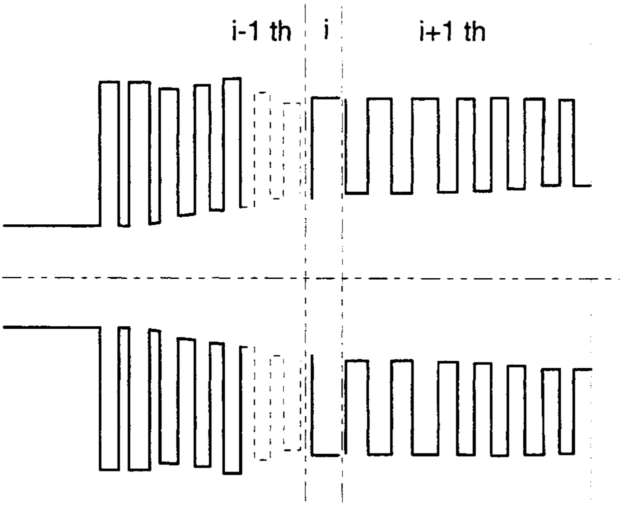

Figure 1: Generalized Scattering Matrices stored for each discontinuity.

3 Results

A sample of the most significant projects developed with the CAD environment presented are shown below. Some of them have already been manufactured, tested, and are currently employed in telecommunication satellite systems of major importance. For each of them, the following data are presented:

- major electric and mechanic features;
- sketch of the longitudinal section;
- polar and crosspolar radiation patterns along the plane $\phi = 45°$.

The first feeder, the INT8AA (Table I, Figs. 2 and 3), is a corrugated horn with constant flare angle proposed in the INTEL 1444 Steerable/Reconfigurable Antenna Study [5], suitable to be employed in double reflector Gregorian antenna systems. Its features are the very low crosspolarization level and low return loss in the 10.95–14.50GHz frequencyrange. The HBF feeder (Table II, Figs. 4 and 5), has a wide flare angle and is employed for the grating antenna of the HotBird 2 and 3 satellites. It shows good electrical characteristics and extremely compact geometry. The third feeder, the V5A, is a profiled circular horn used in the rotable - steerable beam antenna of the W24 EUTELSAT satellite (Table III, Figs. 6 and 7). It provides high electrical performance with a compact envelope.The THAI feeder (Table IV, Figs. 8 and 9) has been designed for the on-set antenna of the THAICOM satellite and it features high performance with a extremely compact geometry.

Table I - INT8AA major electrical and mechanical features

APPLICATION	Dual Gregorian Spot Antenna
FREQUENCY BAND (GHz)	10.70 ÷ 14.50
RETURN LOSS (dB)	≤ -35.0
DIRECTIVITY (dBi)	19.3 ÷ 22.1
MAX. CROSS POL. LEVEL (dB)	≤ -41.4
ENVELOPE (length x outer diameter - mm)	298 x 114
DEVEL. STATUS	EBB Manufactured and Tested

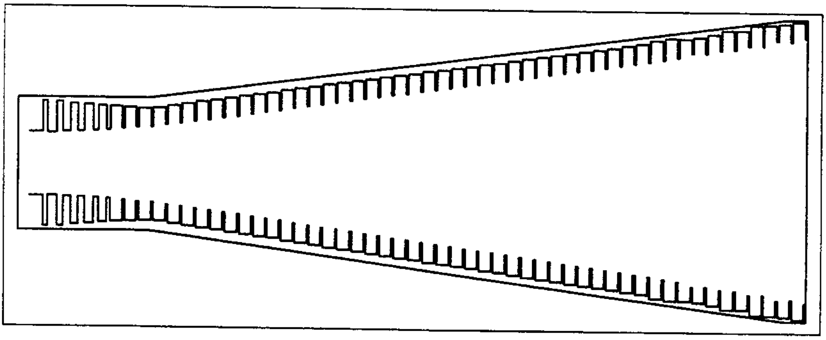

Figure 2: INT8AA feed - longitudinal section

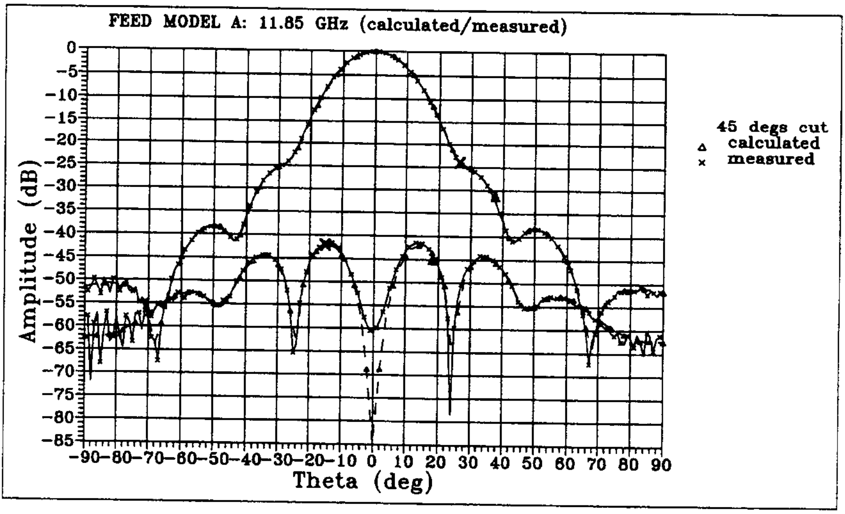

Figure 3: INT8AA feed - measured and calculated patterns at 45 degs ϕ-cut

Table II - HBF major electrical and mechanical features

APPLICATION	Single Offset Shaped Reflector Antenna (HB2)
FREQUENCY BAND (GHz)	13.80 ÷ 14.50 & 17.30 ÷ 18.10
RETURN LOSS (dB)	≤ -34.0
DIRECTIVITY (dBi)	17.1 ÷ 18.0
MAX. CROSS POL. LEVEL (dB)	≤ -34
ENVELOPE (length x outer diameter - mm)	64.7 x 84.0
DEVEL. STATUS	EBB Manufactured and Tested

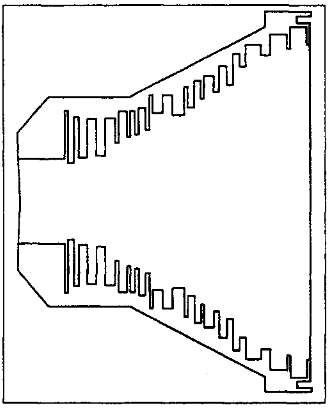

Figure 4: HBF feed - longitudinal section

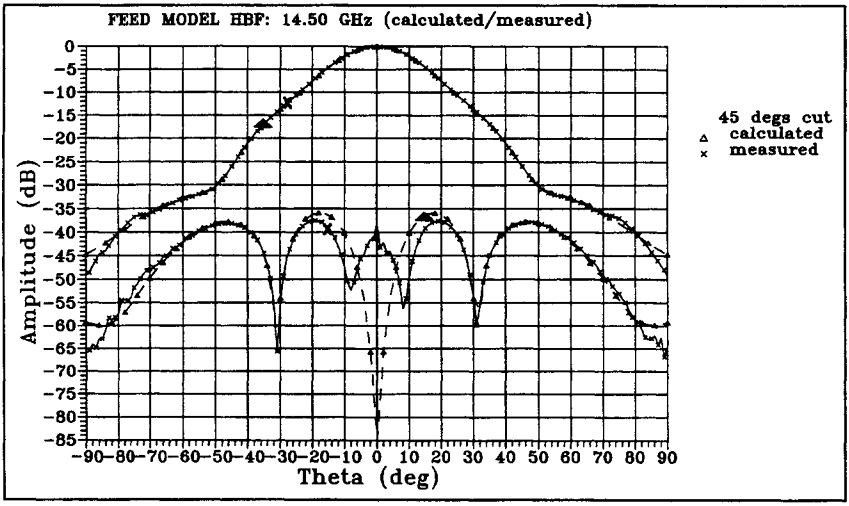

Figure 5: HBF feed - measured and calculated patterns at 45 degs ϕ-cut

Table III - V5A major electrical and mechanical features

APPLICATION	Dual Gregorian Rotatable Coverage (W24)
FREQUENCY BAND (GHz)	Tx 11.10 ÷ 11.70; Rx 13.00 ÷ 14.00
RETURN LOSS (dB)	≤ -33.0
DIRECTIVITY (dBi)	19.3 ÷ 21.2
MAX. CROSS POL. LEVEL (dB)	≤ -41.5
ENVELOPE (length x outer diameter - mm)	185 x 114.0
DEVEL. STATUS	EBB Manufactured and Tested

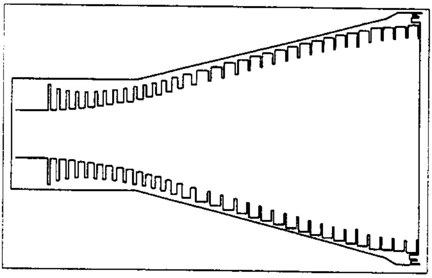

Figure 6: V5A feed - longitudinal section

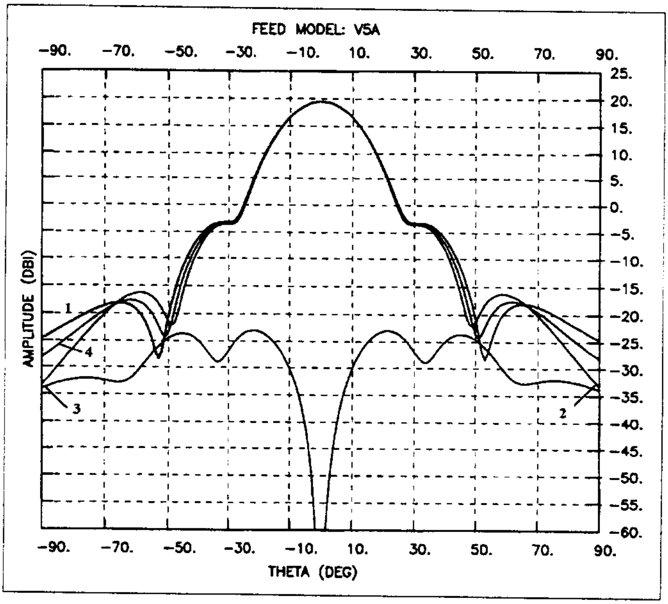

Figure 7: V5A feed - calculated patterns: 1), 2), 4) co-polar component, 0 , 45 and 90 degs ϕ-cuts, respectively; 3) cross-polar component, 45 degs ϕ-cut.

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Table IV - THAI major electrical and mechanical features

APPLICATION	On-Set Reflector (W24)
FREQUENCY BAND (GHz)	12.25 ÷ 12.50 & 14.00 ÷ 14.40
RETURN LOSS (dB)	$\leq$ -28
DIRECTIVITY (dBi)	-28 ÷ 11.50
MAX. CROSS POL. LEVEL (dB)	$\leq$ -40.5
ENVELOPE (length x outer diameter - mm)	28 x 36
DEVEL. STATUS	EBB Manufactured and Tested

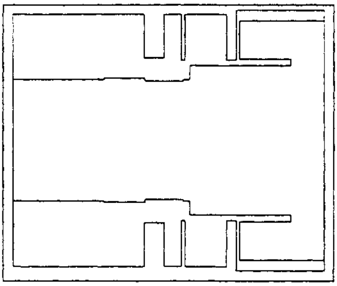

Figure 8: THAI feed - longitudinal section

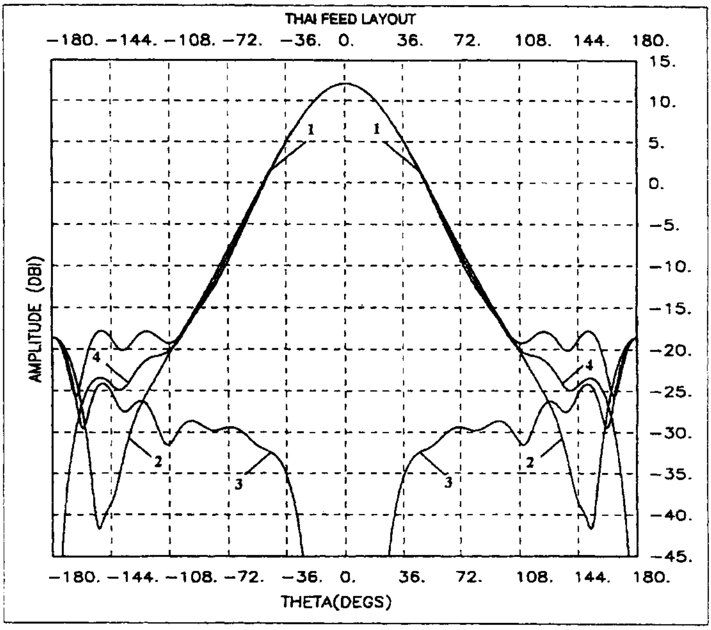

Figure 9: THAI feed - calculated patterns: 1), 2), 4) co-polar component, 0 , 45 and 90 degs ϕ-cuts, respectively; 3) cross-polar component, 45 degs ϕ-cut.

4 Conclusions

A design and optimization procedure for circular corrugated feeders has been presented. The potentialities of the developed CAD environment has been shown through many samples of realized horns. The accuracy and reliability of the electromagnetic model on which the CAD is based, is proved by the considerable number of feeders manufactured and tested.

5 Acknowledgments

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