Direct Optimization of Electrically Large Reflectors and Feed Chains

Peter Meincke, Michael Palvig, Niels Vesterdal, Erik Jørgensen
TICRA, Copenhagen, Denmark
pme@ticra.com

***Abstract*— The combination of a higher-order Method of Moments formulation and the Multi-Level Fast Multipole Method constitutes the foundation of an efficient direct optimization of antenna systems consisting of feed chains and electrically large reflectors. Through a numerical example it is illustrated that the direct optimization approach gives better results than those obtained using traditional approaches, in which the reflectors and feed chains are optimized separately.**

***Keywords*— Optimization, feed chains, reflector antennas, higher-order Method of Moments.**

I. Introduction

The RF optimization of large reflector-antenna systems is typically performed using two separate software tools: One tool is used for the optimisation of the reflector and another is applied for the feed chain, consisting of waveguide components and feed horns. This multi-tool optimization approach is tedious and it also results in sub-optimal designs, since intermediate optimisation goals must be introduced in the feed-chain, although these goals are not design goals of the combined feed-chain/reflector-antenna system. These parameters are merely introduced to decouple the feed chain optimization from that of the reflector. Typical intermediate goals are feed taper and feed phase centre. The drawbacks of the multi-tool optimization approach are eliminated by using an integrated tool for which the entire antenna system, i.e., all reflectors, feeds, and waveguide components can be analyzed and optimized as a single model. However, for electrically large structures the typical calculation time for an accurate analysis is typically measured in minutes or hours and an optimization with many variables is thus generally not possible.

In this paper, a fast and accurate hybridised analysis method, which is well-suited for large scale optimization of the entire feed-chain/reflector system, is presented. The underlying approach, that allows for accurate analysis for electrically large reflectors with very little memory usage and computation time, relies on a newly developed higher-order (HO) Method of Moments (MoM) formulation, accelerated with the Multi-Level Fast Multipole Method (MLFMM). In the hybridized approach, a Generalized Scattering Matrix (GSM) technique is used to decompose the problem into smaller regions, each solvable with an efficient method suitable for the specific subproblem. The feed and waveguide components are, for instance, analyzed using fast dedicated analysis methods suitable for optimization, e.g., MoM, mode-matching or analytical expressions depending on the component to be analyzed. Thus, a rigorous solution of the entire feed chain can be obtained by combining the generalised scattering matrices of the individual components.

With this hybridized approach available, large-scale optimization can be performed on the single model, and the need for intermediate optimization goals is no longer present. A *direct* optimization technique can be used, where the influence of all geometrical changes is measured only on the performance parameters that matter, e.g., the radiation pattern, or the return loss before all waveguide components in the feed chain.

The paper is organised as follows. In Section II the HO MoM is introduced as well as the accelerated version, HO-MLFMM. These methods are used in Section III in a numerical example to show that better performance is obtained when optimizing, as a single system, the feed chain in presense of the reflector.

II. Higher-Order Method of Moments

A popular discretization scheme for MoM when solving the underlying integral equation for the unknown surface current density on perfectly electrically conducing (PEC) structures is the one based on the RWG basis functions [1]. This is a low-order polynomial expansion, in which the geometry discretization relies on a mesh consisting of small triangular flat patches, typically with a side length of 0.1λ, λ being the wavelength. The RWG basis functions, used to expand the unknown surface current density, are first-order polynomials.

There exist, however, more efficient and HO discretization schemes that give rise to a lower number of unknowns, and therefore less memory consumption and computational time. One of these HO schemes is the one in [2]. Herein, the geometry discretization relies on curved quadrilateral patches of side length up to 2λ and the HO basis functions, used to discretize the surface current density, is based on modified Legendre Polynomials. The difference between the lower- and higher-order geometry discretization is shown in Figure 1. The discretization scheme of [2] generally reduces the number of unknowns with a factor of 5 as compared to the RWG basis, corresponding to a memory reduction of 25 times.

Although the above-mentioned HO scheme offers a large memory reduction as compared to the low-order one, it still suffers from the inherent $O(N^2)$ memory complexity associated with the storage of the full MoM matrix. With this complexity even large work stations easily run out of memory when electrically large structures are analyzed. A better memory complexity, $O(N \log N)$, can be obtained by using

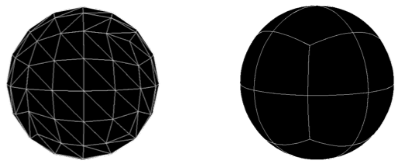

Fig. 1. Meshing of a sphere. Left: Lower-order flat triangular patches. Right: Higher-order, curved quadrilaterals.

the MLFMM acceleration of the MoM [3]. However, this acceleration scheme is developed for low-order discretization schemes and can therefore not successfully by applied directly to a HO discretization. This explains the explicit conclusion from [4], [5], [6], [7] that going beyond second order is not beneficial for MLFMM, either due to memory or accuracy concerns. This conclusion is, however, challenged in [8] in which the first successfull adaption of MLFMM to HO-MoM is presented. Herein it is shown that HO convergence can be achieved while simultaneously maintaining an efficient, low-memory and high-speed MLFMM implementation, and going beyond second order is indeed advantageous.

In this work we use the HO-MLFMM implementation from [8] to obtain accurate analysis in so short computational time that optimization is possible even for electrically large structures. Moreover, the before-mentioned GSM framework ensures that only the scattering matrices of components being modified in one iteration of the optimization are recalculated, thus further reducing the computational time of the optimization.

III. Optimization Example

The capability of the new approach is illustrated for an offset reflector configuration operating at 14 GHz. The feed is a corrugated circular horn excited with the fundamental TE_{11} mode, see Figure 2. The co- and cross polarization far-field patterns in the $\phi = 90$ degree plane are shown in Figure 3. The directivity is 42.1 dBi and a significant cross polarization level, caused by the offset geometry, at 22.4 dBi is observed, giving rise to a cross polarization discrimination (XPD) of 19.7 dB. In order to reduce the inherent cross polarization associated with the offset geometry, a matched-feed concept is used [9]. With this technique a mode converter is applied at the input of the circular horn so that a higher-order TE_{21} mode is excited, thus compensating the geometry-introduced cross polarization. Figure 4 shows the applied mode converter with two grooves. According to [9] the TE_{21} mode excited by the mode launcher should be so that

$$\frac{S_{21,\mathrm{TE21}}}{S_{21,\mathrm{TE11}}} = 0.1j. \tag{1}$$

Herein, $S_{21,\mathrm{TE21}}$ ($S_{21,\mathrm{TE11}}$) denotes the scattering parameter relating the TE_{11} mode of the input of the mode converter to the TE_{21} (TE_{11}) mode in the aperture of the horn. Hence, the relation (1) for the scattering parameters is used as goal for optimizing the length of the grooves of the mode converter, as well as the length of the mode converter, yielding in total two

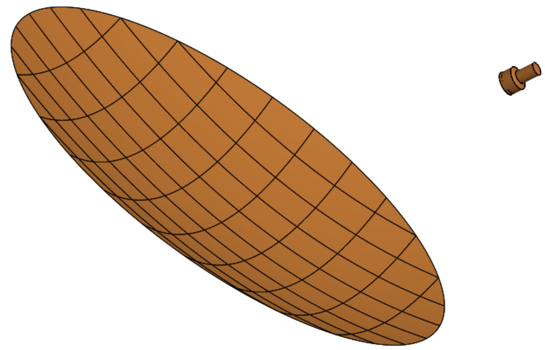

Fig. 2. The considered offset reflector configuration in which the feed is a corrugated horn.

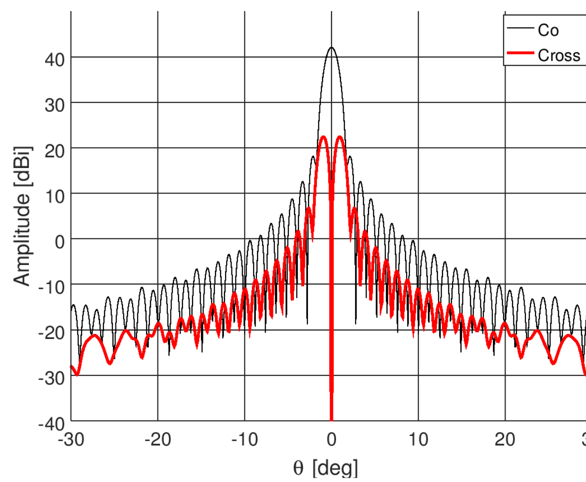

Fig. 3. The co- and cross polarization radiation patterns in the 90 degree plane when the feed is excited by the fundamental TE_{11} mode.

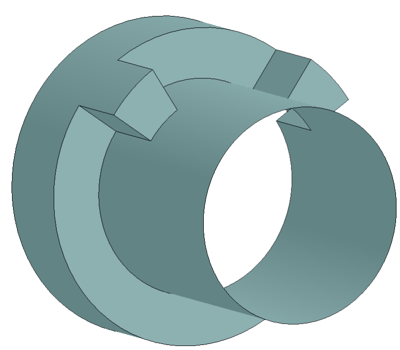

Fig. 4. The mode converter generating the higher-order TE_{21} mode. The length of the grooves as well as the mode converter length are optimized.

optimization variables. Figure 5 shows the obtained radiation pattern after the optimization and it is observed that the cross polarization level has dropped as compared to the original radiation pattern in Figure 3 without the mode converter. The XPD has increased to 24.2 dB.

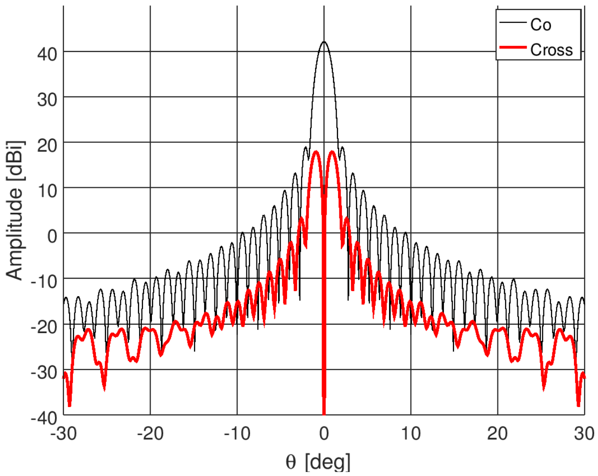

Fig. 5. The co- and cross polarization radiation patterns in the plane of maximum cross polarization ($\phi = 90$ degrees) after the mode converter is optimized for the scattering parameter ratio in (1).

The above result is obtained entirely by optimizing the horn without taking into account its radiation. The applied goal in (1) for the scattering parameters is intermediate, since what matters is the cross polarization level in the far-field pattern. Therefore, a better cross polarization reduction can be obtained by using a direct optimization with goals on the cross polarization level in the radiation pattern. To this end a new optimization is performed, in which the combined system consisting of mode converter, corrugated horn, and reflector are treated as a single model using the GSM hybridization and the HO-MoM/MLFMM. Optimization goals are to minimize the return loss at the input of the mode converter as well as the far-field cross polarization level. The radiation pattern resulting from this optimization is seen in Figure 6. With this direct optimization approach the XPD is 37.5 dB, which is 13.3 dB better than when the feed is optimized alone. By including the depths of the 4 first horn corrugations in the optimization as well, the result in Figure 7 is obtained with an additional improvement of 10.3 dB. Due to the efficient HO-MoM, each cost function evaluation takes only 3 seconds to calculate on a standard laptop computer.

IV. Conclusion

A hybridized approach based on the generalized scattering matrix technique and a higher-order Method of Moments accelerated with the Multi-Level Fast Multipole Method is presented that allows for fast and direct optimization of combined feed chains and reflectors with goals on the secondary radiation pattern. Through a numerical example it is illustrated that such direct optimization gives better

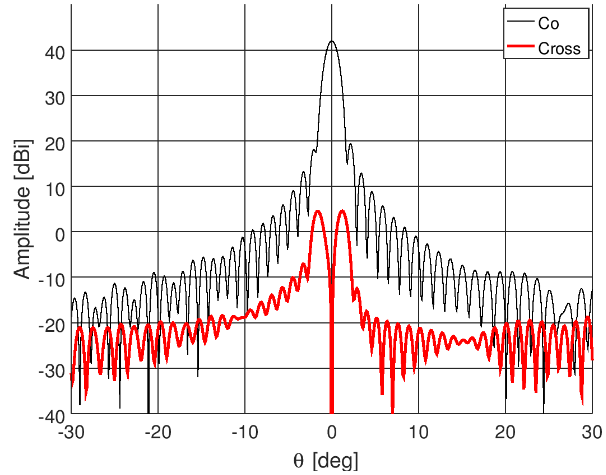

Fig. 6. The co- and cross polarization radiation patterns in the plane of maximum cross polarization ($\phi = 45$ degrees) after a direct optimization of the mode converter with minimum cross polarization level in the secondary pattern as goal.

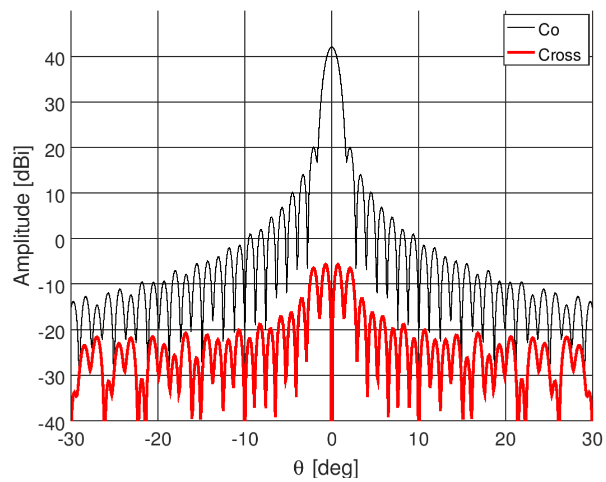

Fig. 7. The co- and cross polarization radiation patterns in the plane of maximum cross polarization ($\phi = 90$ degrees) after a direct optimization of the mode converter as well as the first four horn corrugations with minimum cross polarization level in the secondary pattern as goal.

results than the traditional approach in which feed chains and reflectors are optimized separately using two different software tools.

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