Integrated Design and Analysis of Large Reflector-Antenna Systems

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Abstract—For efficient integrated design and analysis of antenna systems consisting of waveguide harness, feed horns, and electrically large reflectors, a hybrid software has been developed. Herein, a higher-order Methods of Moments formulation using the Multi-Level Fast Multipole Method and a set of dedicated algorithms for solving electromagnetic problems inside waveguide geometries are combined with Physical Optics and a set of optimization algorithms. This allows for direct optimization of the complete antenna systems based on the far-field performance.

An example illustrating the superior antenna designs achievable with this approach compared to traditional approaches, in which the components of the antenna system are optimized individually and then combined into a complete system, is presented.

I. Introduction

Optimization of large reflector antenna systems is typically performed using two or more software tools: One tool for the optimization of the reflector, another for the feed chain, consisting of waveguide components, and often a third for the feed horns. This multi-tool optimization approach is tedious and often results in sub-optimal designs, since intermediate optimization goals based on approximate or assumed behavior of the other components are introduced in the design-chain, although these goals are not design goals of the combined feed-chain/feed-horn/reflector-antenna system. These metrics are introduced to achieve the necessary decoupling between the feed chain, the feed horn, and the reflector that are necessary to be able to use two or three different tools for designing the complete antenna system.

Typical intermediate goals are taper, phase centre, and cross polarization of the feed. 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 measured in minutes or hours and an optimization with many variables is therefore not feasible.

In this paper, a fast and accurate hybridized analysis method, which is well suited for large scale optimization of the entire feed-chain/reflector system, is presented. The accuracy and speed of the method rely on: 1) State-of-the art analysis methods tailored for each component of the system and 2) a rigourous coupling between the components (hybridization). The Generalized Scattering Matrix (GSM) based hybridization scheme [1] and some of the dedicated analysis methods will be introduced in Section II. In a numerical example in Section III it is shown that better performance is obtained when optimizing the feed chain in presence of the reflector in a single hybridized model.

II. Analysis Methods

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 generalized scattering matrices of the individual components.

The ability to optimize a system relies on a fast forward analysis. Our goal is to optimize a full reflector system, including waveguide feed network, horn, and scattering of the reflector, but including all of this in a single full-wave simulation is inefficient. Analyzing each component of the system with a dedicated method suitable for that type of component is much more efficient. It requires, however, that the analysis methods are rigorously coupled to each other. We have achieved this using a GSM description of the components, with separation at waveguide port interfaces. Some of the specific analysis methods are briefly introduced below.

A. Mode Matching and Analytical Methods

Many waveguide components consist of straight waveguide sections with different dimensions, or they can be accurately modeled as such. The coupling from modes in one waveguide piece to the next can be found by Mode

Matching, that is, imposing the continuity of the electric field at the interface of the two. Other waveguide junctions can be solved analytically, which is even more efficient than the Mode Matching.

B. Higher-Order Method of Moments with MLFMM

The scattering matrices of waveguide devices of general shape may be found using the Method of Moments (MoM). The MoM is also essential for coupling the closed waveguide problem to open radiating antennas.

The currents of the MoM problem is often discretized using RWG basis functions [2] on flat triangular patches. The flatness of the patches and the low order of the basis functions means that many coefficients must be used to accurately represent the currents — typically with a side length of $\approx 0.1\lambda$, λ being the wavelength.

To reduce memory consumption, we instead employ the higher-order discretization scheme presented in [3]. The basis functions are modified Legendre polynomials of arbitrary order defined on curved quadrilateral patches. This scheme generally reduces the number of unknowns with a factor of 5 as compared to the RWG basis functions [2] on flat triangular patches, corresponding to a memory reduction of 25 times.

For exact coupling from the waveguide region to electrically large and huge structures such as the reflector surface, support structures and even a full satellite body, we use the Multi-Level Fast Multipole Method (MLFMM) implementation of [4], which is the first work to successfully combine the advantages of both higer-order basis functions and MLFMM.

C. Physical Optics

For electrically large and smooth surfaces such as reflectors, physical-optics (PO) algorithms yield superior performance in comparison to full-wave algorithms such as the Method of Moments, Finite Element Method by providing only negligible differences in the calculated far-field patterns but at vastly lower computational costs. By further improving the PO algorithms, this difference can be made even more pronounced [5].

III. Optimization Example

To illustrate the capability of the new approach, an offset reflector system operating at 14.25 GHz with diameter $D = 1\,\mathrm{m}$ and focal length $f = 0.6\,\mathrm{m}$ is optimized (see Figure 1). The aperture diameter corresponds to 47.5 wavelengths and the f/D ratio is 0.6. The initial feed is an axially corrugated horn with extremely low cross polarization at the design frequency (more than 50 dB below peak).

The far-field patterns of the reflector system in the plane of maximum cross-pol are shown in Figure 3. Cross polarization lobes with the original feed (blue curve) are observed less than 20 dB below the peak of 42 dBi. This cross polarization is caused by the offset geometry, in spite of the near-perfectly polarized feed.

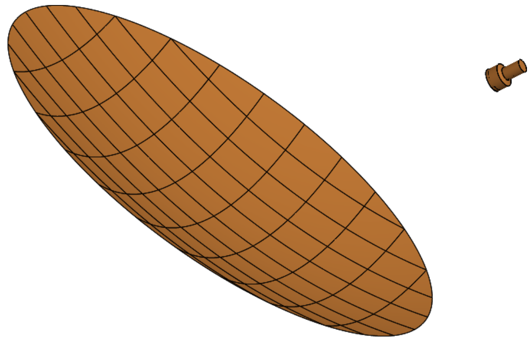

Fig. 1. The considered offset reflector configuration. $D = 1\,\mathrm{m}$, $f/D = 0.6$.

The cross polarization may be reduced by exciting specific modes in the horn [6]. The relevant mode for a circular horn is the TE_{21}. According to [6] the TE_{21} mode should be -20 dB to -30 dB below the fundamental mode and in phase quadrature with it.

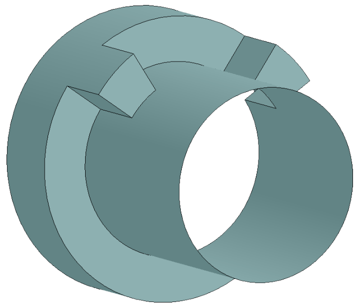

Fig. 2. The mode converter generating the higher-order TE_{21} mode.

A TE_{21} mode may be excited by an asymmetric waveguide mode converter. A mode converter of the type shown in Figure 2 is attached to the throat of the original horn.

If the multi-tool approach were the only available, we would first optimize the horn and mode converter alone to the specifications given in [6] (in this work using a gradient-based optimization approach). That is, the groove size and the length of the mode converter are optimized such that the TE_{21} mode content in the aperture of the horn is -20 dB below and 90° behind the fundamental mode.

Evaluating the secondary pattern with this modified feed, we get cross polarization shown as the orange curve in Figure 3. The peak cross polarization is reduced by 4.5 dB.

The above result is obtained entirely by optimizing the horn without taking into account its radiation. The applied goal for the mode amplitude and phase is intermediate, since what matters end is the cross polarization level in the reflector far-field pattern.

The improvement achieved above is moderate. We could amend the intermediate goals and do another iteration,

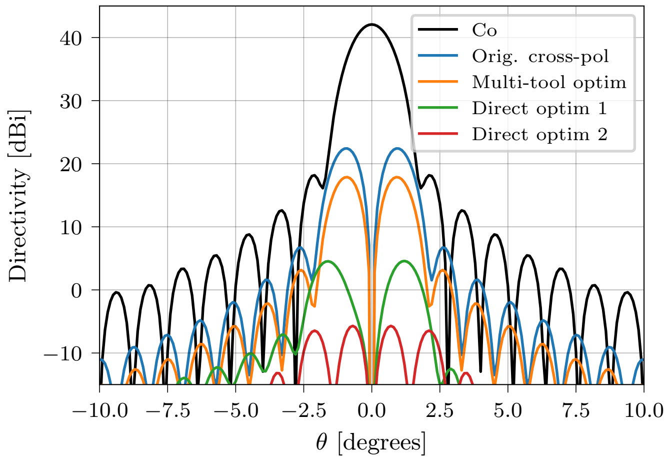

Fig. 3. The radiation pattern (in the plane of maximum cross) of the system after the three different feed optimizations. The multi-tool optimization imposes goals on the feed scattering parameters, while the direct optimizations impose goals directly on the far-field pattern. The co-polar pattern is virtually unchanged and thus plotted as one.

but instead we perform a new optimization, in which the combined system is optimized directly.

The mode converter, corrugated horn, and reflector are treated as a single model combining analytical methods, mode matching, and the HO-MoM/MLFMM using the GSM-based hybridization. The optimized variables are still the mode launcher dimensions, but now the optimization goal is to directly minimize the far-field cross polarization level. The resulting cross polarization pattern is plotted as the green curve in Figure 3, showing an additional 13 dB of reduction compared to the multi-tool optimization.

By including the depths of the 4 first corrugations in the optimization as well, the red curve in Figure 3 is obtained with an additional 10 dB improvement. Due to the highly efficient analysis method, each cost function evaluation takes only 3 seconds to calculate on a laptop computer.

IV. Conclusion

A rigorous hybridized approach based on several analysis methods combined with the generalized scattering matrix scheme and a higher-order Method of Moments accelerated with the Multi-Level Fast Multipole Method is presented. It allows for fast and direct optimization of combined feed chains and reflectors with goals directly on the secondary radiation pattern. Through a numerical example it is illustrated that such direct optimization can give superior results compared the traditional approach in which feed chains and reflectors are optimized separately using two or more software tools.

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