Efficient Implementation of BOR FDTD Algorithms in the Engineering Design of Reflector Antennas

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***Abstract*—This work presents a modelling-based methodology for the design and evaluation of axi-symmetrical antennas, including horns, compact and large dual-reflector antenna systems. The starting concept of the antenna is an educated guess stemming from the engineer's experience; however, further evaluation and optimization of that concept continue in a computational loop that involves a conformal FDTD algorithm in a BOR formulation. Our BOR FDTD retains the advantages of general-purpose 3D FDTD software, providing full-wave solutions and delivering key engineering parameters of antenna systems together with an insight into the distribution of the electromagnetic near-field, a useful feature to assess the mismatch of the horn due to the subreflector interaction. At the same time, the unique BOR formulation accelerates the analysis by orders in magnitude, making it practical to evaluate many designs within a manual or automatic optimization loop. We also show that BOR FDTD compares favourably with the Mode Matching Technique, being computationally fast while obviating the MMT inherent structural assumptions.**

***Index Terms*—axi-symmetrical antenna, BOR, FDTD, dual-reflector antenna, horn antenna.**

I. Introduction

Axially symmetrical reflector antennas are of importance in cosmic research and telecommunication base stations. Practical examples include many unconventional and complex designs, like the horn shown in Fig. 1 and further considered herein. In delivering such designs, antenna engineers are assisted with two basic types of commercial electromagnetic software: fast but structure-tailored mode matching techniques (MMT, e.g. [1]), or general-purpose 3D finite element (FEM, e.g. [2]) or finite difference time domain (FDTD, e.g. [3][4]) methods, which allow the modelling of arbitrarily-shaped and inhomogeneous structures, but are computationally expensive. Our collaboration between design engineers and software developers aims at proposing and validating a competitive compromise between the two approaches.

We note that structures with axial symmetry of boundary conditions, also named Bodies of Revolution (BOR), belong to the class of vector two-dimensional (V2D) problems [5]. In this class, the total electromagnetic field is a composition of orthogonal modes exhibiting $\sin(n\varphi)$ or $\cos(n\varphi)$ angular field dependence, where n=0,1,.. and φ stands for the angular variable of the cylindrical coordinate system. As a result, numerical analysis of BOR structures can be performed in 2D space, over only one half of the long-section of the structure, with the angular field dependence enforced analytically and n being a predefined parameter of the analysis. As explained in [6], in comparison with 3D discretization in general purpose EM software, the conformal BOR FDTD method allows achieving over two order of magnitude savings in both RAM and computing time, on both central and graphical processing units (CPU and GPU). Thus with a computer workstation equipped with 64 GB of RAM, assuming variable meshing enforcing basic cell size of $\lambda/20$, it will be possible to analyze a simulation scenario of 1300 by 1300 wavelengths, thereby an antenna-diameter of at least 2600 wavelengths. Employing a GPU card with 11GB of memory, like the popular video game card nVidia GeForce GTX 1080 Ti, enables the analysis of antennas of at least 1200 wavelengths in size, taking additional advantage of calculation acceleration as proven in [7-8].

It this work, we evaluate BOR FDTD performance for the complicated but representative horn as in Fig. 1 and the same horn supplemented with two reflectors, on popular computer hardware. We show the analysis to be fast enough for setting up a time-efficient optimization loop, which supplements the engineer's practical experience and allows reaching the design goals in a short time-frame - for example, by 120 design iterations within 1 hour for the horn itself. We also demonstrate how the insight into EM field distributions, provided by the FDTD method in general and specifically exploited by its implementation after [4], facilitates detecting possible causes of undesired performance and providing remedies. Our numerical experiments are conducted within the computational environment of QuickWave software [4], by its QW-V2D version, but essential conclusions remain valid for other BOR FDTD codes with appropriate postprocessing and visualisation functionalities.

II. Optimization of the Horn

In this section we will focus on the application of the BOR FDTD method to the analysis of the axi-symmetrical horn of Fig. 1. The classical FDTD algorithm implements stair-case approximation of material boundaries, significantly decreasing the accuracy of the geometry modelling, which is of high interest in case of modelling horn antennas for example, as they commonly have complicated shapes. Our BOR FDTD simulations take advantage of the advanced conformal meshing algorithms (Fig. 2), which do not require

FDTD time step reduction [9], thus do not deteriorate the calculation time. To further increase the modelling accuracy, BOR FDTD may impose stereoscopic field singularity corrections to EM field components that are adjacent to metal edges and corners [10].

The example horn antenna analyzed in this paper (Fig. 1) is designed to work in the X-band, with the receiving band covering 7.25 – 7.75 GHz and the transmit band 7.9 – 8.4 GHz. The polarization of interest is circular polarization and the horn is meant to be a part of a dual-reflector system. The overall length is 1320 mm, comprising a circular "feed-tube" around 920 mm long and a corrugated section about 400 mm long. The diameter changes from about 40 mm in the feed tube to about 252 mm at the aperture. The corrugated part of the horn is made of 82 corrugations, which accurate modelling is crucial for the overall antenna performance. Meshing applied for BOR FDTD model enforces FDTD cell size of $\lambda/40$, resulting in the simulation project comprising 1 million FDTD cells. This corresponds to a GPU memory occupation of only 50 MB, as only half of a long-section needs to be analysed. The EM simulation, taking advantage needs to be analyzed. The EM simulation, taking advantage of a graphic card (GPU) acceleration on nVidia GeForce GTX 1080 Ti takes 21 s to give a well converged radiation pattern and reflection coefficient results (Fig. 3). For a comparison, calculations using multiprocessor/ multicore processing require 70 MB of RAM memory and take 1 min 57 s on popular Intel i7 4930-K processor, which is still a reasonable simulation time, and 49 s on an advanced Xeon Silver 4116 processor.

The accuracy of BOR FDTD calculation is confirmed by comparing its simulation results with results obtained with a Mode-Matching Technique (MMT) software [1] (Fig. 4). The small differences in pattern and reflection characteristics are attributed to the fact that MMT does not account for the structure outside (in this case, assuming an approximation of a finite flange at the aperture) and for the mismatch to free-space at the aperture.

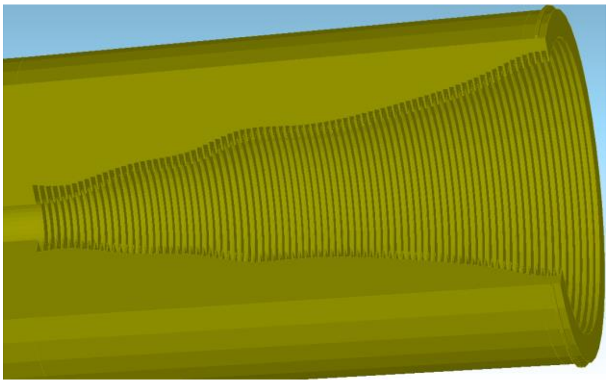


Fig. 1. An example of conformal BOR FDTD meshing as in QuickWave [4].

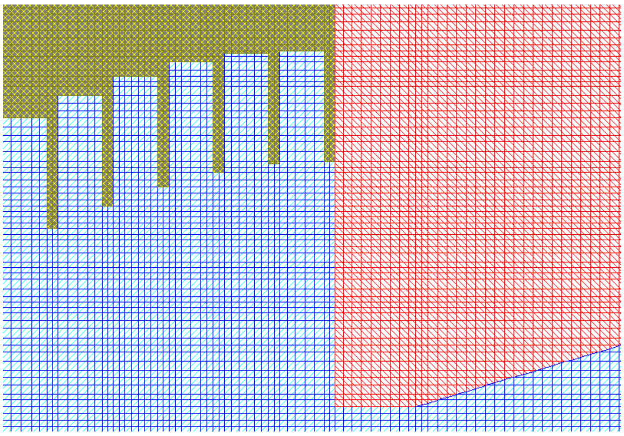
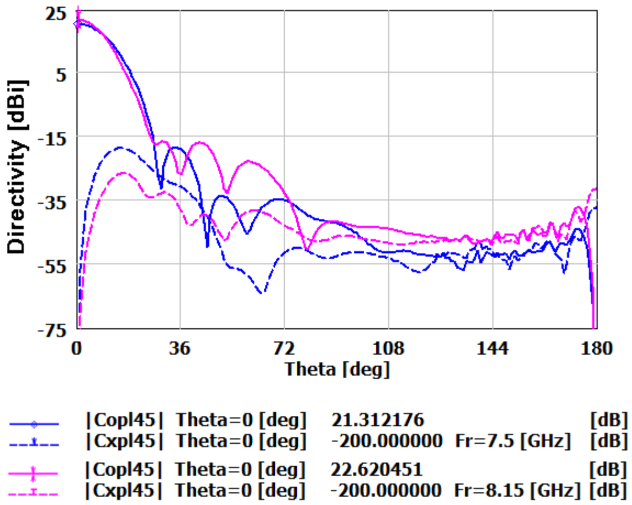
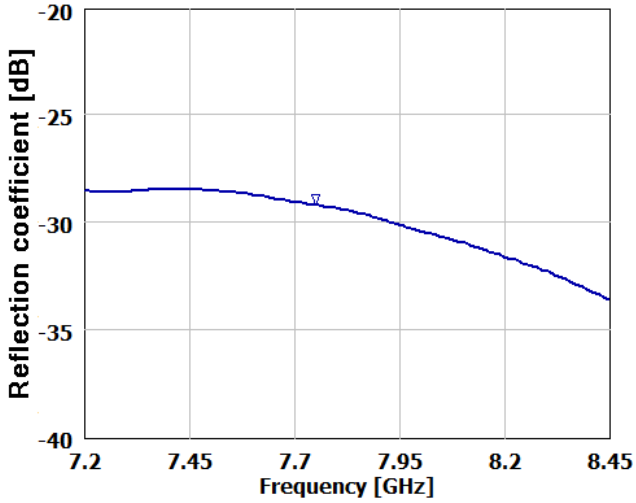


Fig. 2. An example of conformal BOR FDTD meshing as in QuickWave [4].



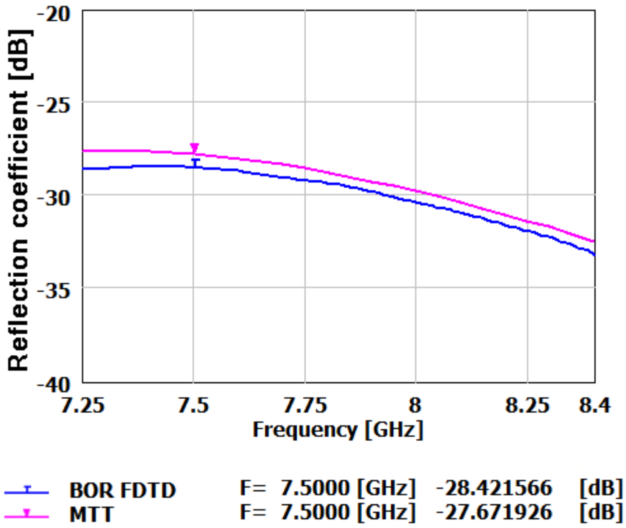
(a)



(b)

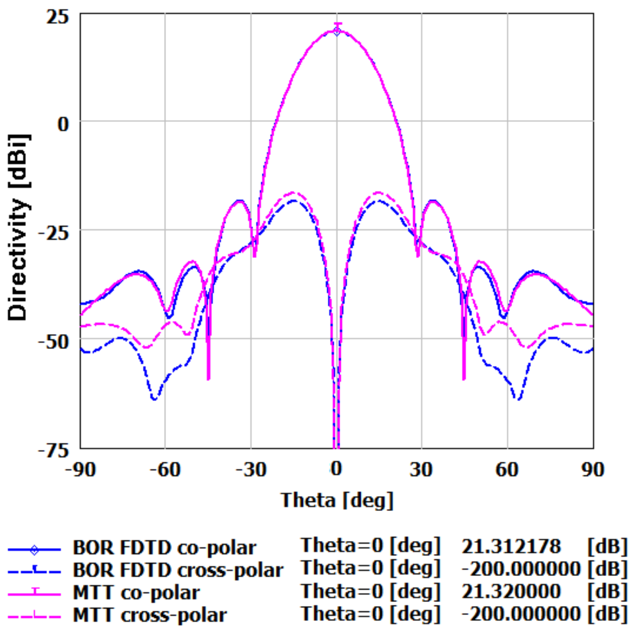
Fig. 3. Simulated radiation patterns at the center frequencies of the receiving and transmit bands (a) and reflection coefficient (b), results obtained with BOR FDTD.

We then set an optimization loop (either internal to [4] or an external optimization tool, like e.g. Matlab), in which the horn return loss and radiation patterns are goal functions. For the considered horn, within one hour of the optimization process around 120 consecutive models can be simulated, which is typically sufficient for an antenna engineer to achieve the design goals.



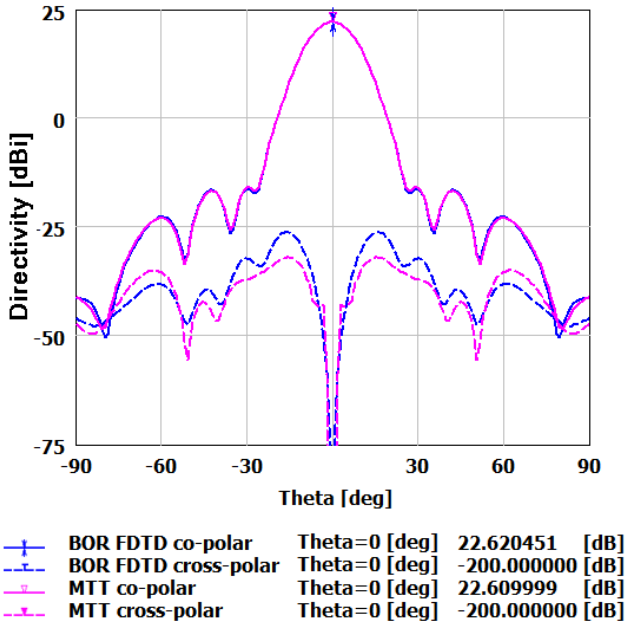
Reflection coefficient [dB]
-20
-25
-30
-35
-40
7.25
7.5
7.75
8
8.25
8.4
Frequency [GHz]
BOR FDTD F= 7.5000 [GHz] -28.421566 [dB]
MTT F= 7.5000 [GHz] -27.671926 [dB]

(a)



Directivity [dBi]
25
0
-25
-50
-75
-90
-60
-30
0
30
60
90
Theta [deg]
BOR FDTD co-polar Theta=0 [deg] 21.312178 [dB]
BOR FDTD cross-polar Theta=0 [deg] -200.000000 [dB]
MTT co-polar Theta=0 [deg] 21.320000 [dB]
MTT cross-polar Theta=0 [deg] -200.000000 [dB]

(b)



(c)

Fig. 4. Comparison of horn reflection coefficient (a) and radiation pattern at 7.5 GHz (b) and 8.15 GHz (c) obtained with BOR FDTD and MTT software.

III. Design of the Dual-Reflector Antenna System

The optimized corrugated horn antenna, analyzed in Section II, is now introduced into the dual-reflector antenna system as a feeding horn. The antenna consists of a 9 m-diameter main reflector and a 0.7 m-diameter subreflector attached to the feeding horn with a dielectric support tube (Fig. 5) (being a low-loss, low dielectric constant, structural foam), reaching a size of 250 wavelengths. This is just an example of a possible dual reflector system, but one of the design goals of that particular example was to minimize the sidelobes.

Similarly to the horn analysis, a variable meshing of $\lambda/40$ cell size is enforced, resulting in 33 million FDTD cells and a GPU memory occupation of 2 GB. EM simulation with BOR FDTD on an nVidia GeForce GTX 1080 Ti card takes 8 minutes and the radiation pattern calculations at a total of 24 frequencies of interest, with step angle of 1 degree, requires only 5 seconds. Here again, the times are short enough to allow running multiple iterations in an optimization loop. In our case, the final radiation patterns at the centre frequency of the transmit band is shown in Fig. 6.

BOR FDTD may provide many useful functionalities, which support the antenna design process, e.g. giving an insight into the EM near-field, which may be helpful in investigating the causes of undesirable performance. Figure 7a shows the field distribution, in which side and backward radiation, due to diffraction at the main reflector edge, is clearly visible. This kind of supporting functionalities enabling catching such behaviour, allows an experienced antenna designer to consider possible improvements, like, for example, adding a metallic baffle along the reflector edge to decrease the leakage (Fig. 7b, Fig.8a,b).

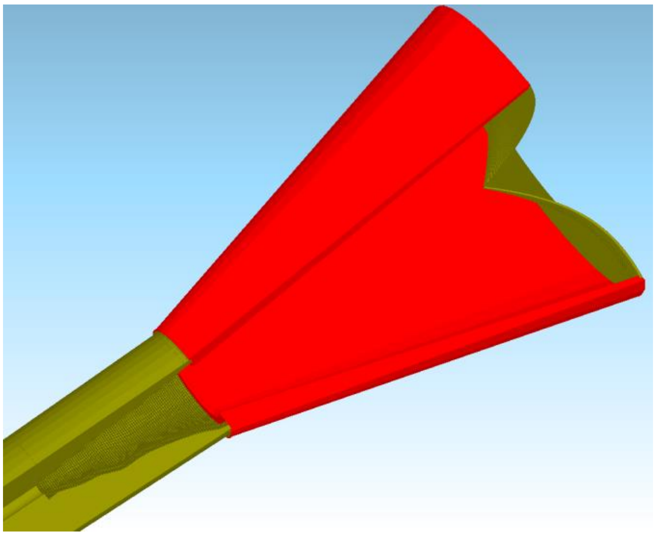


Fig. 5.   Secondary reflector (subreflector) of the dual-reflector antenna system with the feeding horn and the dieletric supporting tube (low-loss, low dielectric constant, structural foam).

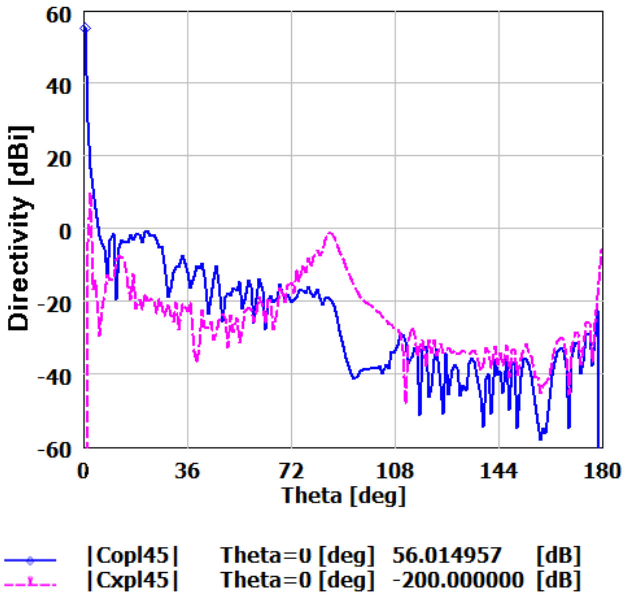
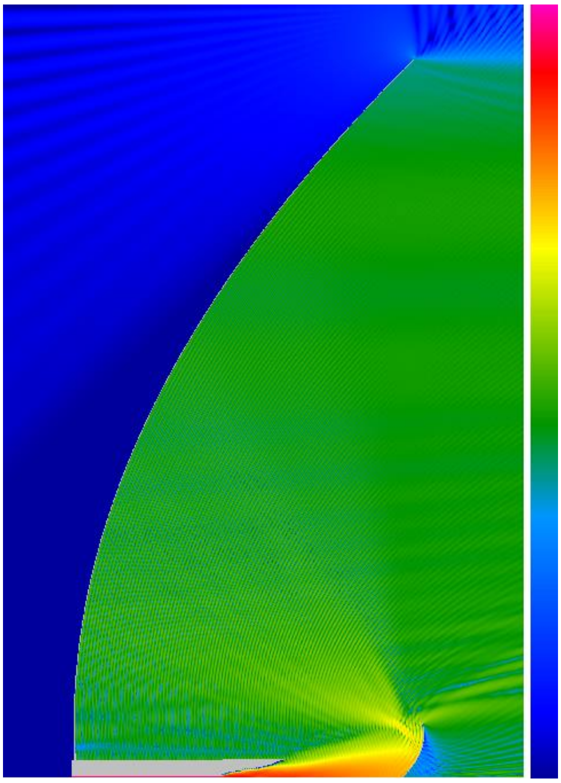
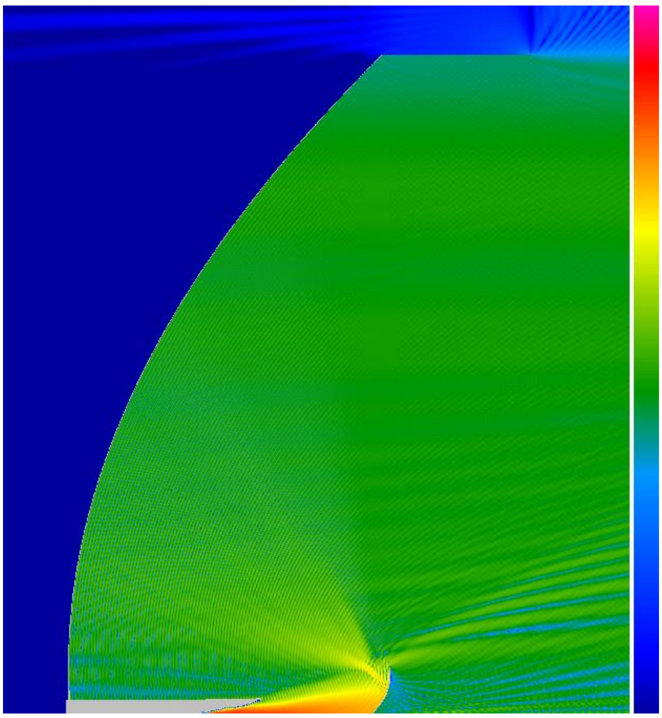


Fig. 6.   Radiation pattern of the dual reflector antenna at 8.15 GHz calculated with BOR FDTD.

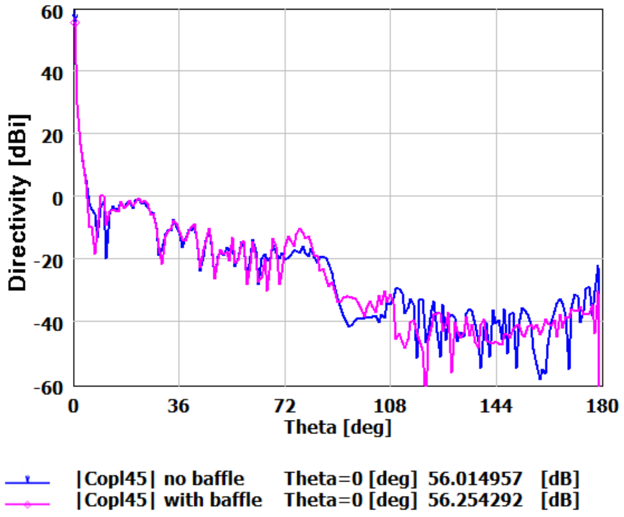


(a)

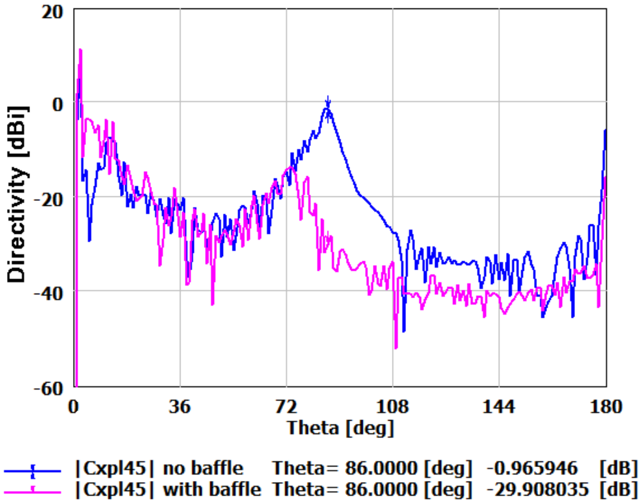


(b)

Fig. 7. Distribution of average value of *Eρ* component in logarithmic scale for the dual-reflector antenna (a), the dual-reflector antenna equipped with a 1 m-long metallic baffle (b), produced by BOR FDTD.



(a)



(b)

Fig. 8. Comparison of co-polar (a) and cross-polar (b) radiation patterns for the two antenna configurations (without and with metallic baffle), produced by BOR FDTD.

IV. CONCLUSIONS

This paper presents the key conclusions of long-term collaboration between the teams of antenna engineers and electromagnetic software developers, represented by the present authors. It demonstrates that the design of axi-symmetrical antennas can be accurately and efficiently performed by running BOR FDTD algorithms within optimization loops. With a single BOR FDTD analysis of a horn (and a horn with two reflectors) being completed within 1 minute (and 10 minutes, respectively), we are typically able to complete an optimization process within hours. The BOR FDTD approach retains the advantages of 3D FDTD in terms of wide-frequency-band modelling of complex geometries as well as inhomogeneous and lossy materials. Its efficiency stems from reducing the simulation of the axi-symmetrical structure to half of its long-section - whereas in the 3D approach at least one quarter of the volume needs to be considered.

It should be emphasized, however, that no simulation tools may replace the engineering experience, essential for proposing the initial design as well as for interpreting the EM field displays, so as to understand possible antenna misperformances and to propose improvements. More examples of such practical interpretations will be presented at the Conference. We shall also discuss selected BOR FDTD software developments relevant to axi-symmetrical antenna design, such as enhanced mesh generation algorithms and extraction of various optimization objectives.

ACKNOWLEDGEMENT

The work leading to this paper has received funding from the European Union Horizon H2020 Programme (H2020-NMBP-07-2017) under grant agreement n°761036.

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