Improvement of Accuracy of Extraction of Radiation Patterns from FDTD Modelling of Axisymmetrical Antennas

M. Olszewska and W. Gwarek

Institute of Radioelectronics
Warsaw University of Technology, Warsaw, 00-665, Poland
M.Olszewska@ire.pw.edu.pl, W.Gwarek@ire.pw.edu.pl

Abstract **─** This paper presents a discussion on the accuracy of extraction of radiation patterns of BOR antennas from FDTD simulations. The effect of the "main beam shadow" causing errors in extracted back radiation is explained. The methods of its elimination are proposed.

Index Terms **─** Accuracy, BOR structures, electromagnetic simulations, FDTD method, validation.

I. INTRODUCTION

The FDTD method has proven very useful and accurate in many applications [1]. Mainly software implementations of the FDTD method on classical computer CPUs are known, but recently also hardware accelerated versions are gaining in importance [2]. One of the possible variations of the FDTD method is its version applicable to axisymmetrical problems, denoted also as body of revolution (BOR) problems [3 - 5]. In BOR FDTD, the angular variation of fields is assumed to be known and the general 3D problem is reduced to a computational Vector 2D (or V2D) problem [4]. Reduction of the physical 3D problem to a computational V2D problem results in a drastic reduction (typically by almost two orders of magnitude) of the computing time and memory, without loss of accuracy. Alternatively, we can obtain much better accuracy with a reasonable computing time. Very high accuracy of the simulation results obtained with the BOR FDTD, applied to one or two-reflector antennas, fed by corrugated horns, has been confirmed by experiments. There is however one aspect, which causes our concern. We have found that in antennas with large reflectors (and thus having a large directive gain) the back radiation obtained in simulation is significantly higher than the measured one. Thus, we have launched an investigation to find the reasons for that discrepancy. In this paper, we propose an approach leading to more precise results of the simulation of back radiation.

II. PROPOSED APPROACH EXPLAINED ON AN EXAMPLE OF A DOUBLE REFLECTOR ANTENNA

Consider a double reflector antenna with an operating band from 5.2 GHz to 5.8 GHz, shown in Fig. 1. The radiation pattern obtained for this antenna in BOR FDTD simulations is shown in Fig. 2(a) and (b) (continuous line). It can be seen that the calculated back radiation is about 40 dB lower than the main beam. Having compared the results of simulation and measurements for many similar cases, we suspect that the results might not be accurate. Thus we will investigate in detail possible causes of errors.

A. Method of extraction of the radiation pattern

First of all, we will concentrate on the method of extraction of the radiation pattern. For that purpose, the near-field to far-field transformation, which has been widely studied for the FDTD method [6,7], is performed. It is based on extraction of fields at the so called near-to-far (NTF) surface (also called sometimes a Huygens surface). At that closed surface, the H and E fields (tangential to the "walls" forming the surface) are extracted from the FDTD simulation and used for

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projection of the fields to the far zone. In the case of BOR (V2D) simulations, the NTF walls are reduced to lines and in Fig. 1 we can see them presented as dashed lines. The antenna shown in Fig. 1 radiates predominantly to the right. Thus, the accuracy of extraction of the fields detected at the right NTF line is crucial. However, it is well known that the FDTD analysis provides values of E and H fields at different points of space. Thus, at the right NTF line we can have the accurate value of only one of them. Let us assume that the E-field is extracted exactly at the NTF line, as schematically presented in Fig. 3. Thus, the H-field must be obtained by averaging of the fields extracted half of the FDTD cell to the left and right. Let us try to estimate an error caused by such an averaging.

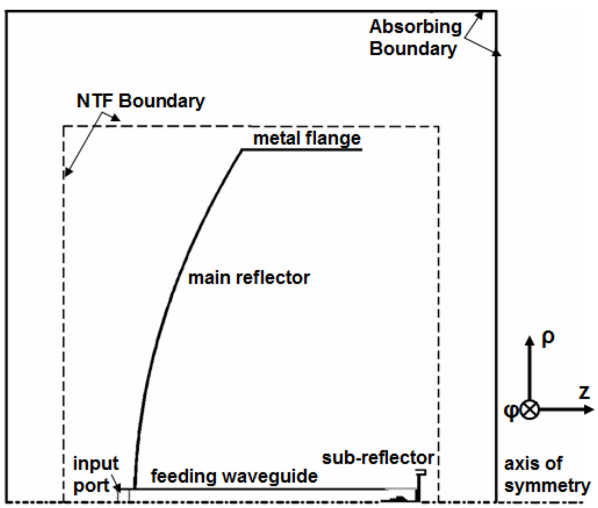

Fig. 1. A sketch presenting the type of simulation scenarios as appearing in a BOR FDTD software. Half of the long section of the structure is considered and meshed.

We assume that the angular E_φ field captured in the FDTD cell centre is equal to:

$$E_\varphi = E_{\varphi 0}\cos(\omega t - \beta z)\,. \qquad (1)$$

The magnetic field, which significantly changes along the direction of the wave propagation, has to be calculated as an average of two values captured at both sides of the cell. Assuming that in the axial z-direction wavelength is λ_z and the FDTD cell size is a, a phase shift corresponding to wave propagation over a distance equal to half of the FDTD cell is:

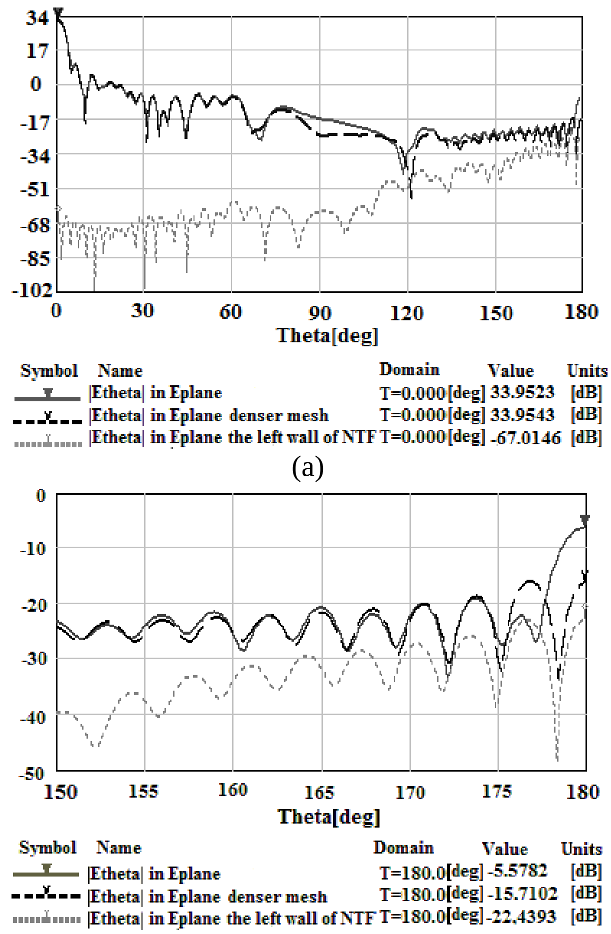

Fig. 2. Simulated radiation patterns for E_θ polarisation presented in the entire angle range (a) and in the range 150° - 180° (b); a typical scenario (continuous line), denser mesh in the right NTF boundary region (dashed line), integration only on the back NTF surface (dotted line).

$$\phi = \frac{360^\circ}{\lambda_z}\frac{a}{2}\,. \qquad (2)$$

For a pure travelling wave with the wave impedance equal to Z_0, we thus obtain the H_ρ field averaged at the cell centre as:

$$H_\rho = -\frac{E_{\varphi 0}}{2Z_0}\left[\cos(\omega t - \beta z - \phi) + \cos(\omega t - \beta z + \phi)\right] = -\frac{E_{\varphi 0}}{Z_0}\cos(\omega t - \beta z)\cos(\phi)\,. \qquad (3)$$

The H field estimation error can be expressed as:

$$\delta_H = \cos\phi\,. \qquad (4)$$

In the considered scenario, the cell size is about 3 mm, which means that the half-cell, at 5.2 GHz corresponds to 9.4° of the phase shift. This modifies the amplitude of the magnetic field by about 1.34%. Since δ_H further corresponds to a modification of the wave impedance, we get:

$$Z_0{}' = \frac{E_\phi}{H_\rho} = 1.0134 Z_0 \,. \qquad (5)$$

When the wave impedance deviates from Z_0, it means that the software detects a partially standing wave. The detected standing wave ratio VSWR is equal to that deviation:

$$\frac{Z_0^{'}}{Z_0} = SWR = \frac{1+|\Gamma|}{1-|\Gamma|} \cong 1+2|\Gamma| \,, \qquad (6)$$

where Γ is a hypothetical reflection coefficient detected at the NTF surface. In the considered case, we get the corresponding reflection coefficient equal to 0.0067. That way the NTF surface produces in the back direction a "shadow" of the main beam. The "shadow" appears at the level of about -43 dB.

According to the above discussion, it is concluded that, in the considered example, the calculation of the back radiation at the levels of 40 dB or less below the main beam is unreliable and can be explicable as a numerical error. It should be mentioned that an imperfect absorbing boundary at the right of the computational domain may also cause some standing wave effects contributing to the "main beam shadow" effect.

B. Methods of eliminating the main beam shadow

To verify the above hypotheses, additional simulations with denser meshing (cell size about 1.5 mm) close to the right NTF boundary and the right absorbing boundary region are performed. The results are shown in Figs. 2(a) and (b) (dashed curves). The calculated back radiation is about 10 dB lower than in the original scenario, which confirms our hypotheses and improves the accuracy of backward radiation extraction. However, in practical calculations the remaining level of errors may still be unacceptable. Moreover, the software user may find it difficult to distinguish the physical result from the parasitic one. Can that error be eliminated at its source? In principle, the effect of H-field averaging could be

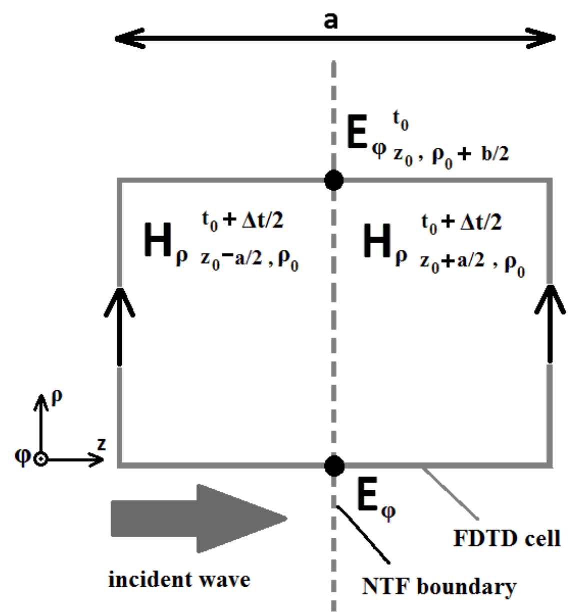

Fig. 3. Scheme of the extraction of the fields at NTF boundary.

eliminated, dividing the H-field value as in equation (3) by a correction factor defined by equations (2) and (4). However, this is impractical in a general case, since the direction of wave propagation at the NTF surface needed for calculating λ_z in equation (2) is unknown. Furthermore, such a correction would not suppress standing wave errors due to numerical reflections from absorbing boundaries.

In this work, we propose an alternative method of eliminating the "main beam shadow". The method consists of comparing the radiation patterns calculated using all three NTF lines with the radiation patterns calculated using only the contribution of the left NTF line. The results obtained in the one-line simulation are presented by dotted curves in Figs. 2(a) and (b). The obtained radiation pattern is naturally wrong for angles within the main forward beam, but it is correct for 180°. It indicates the back radiation of about 56 dB down from the main beam. The results of all the performed simulations are summarized in Table 1.

C. Periodic behaviour of the back radiation pattern

In Fig. 2(b), we can see that the back radiation close to 180° is composed of periodic minima and maxima. The question to be asked is, whether this is a numerical effect or a physical one. While analyzing the field distribution of the considered antenna, we have concluded that the main source of the back radiation is the outer edge of the parabolic main reflector. We can therefore say that the source has a shape of a circle of diameter equal to 900 mm.

Consider a loop antenna, approximating such a backward radiation source. At its opposite sides we would have two maxima of the current. In the Cartesian coordinate system, the current will have the same directions at those points, as it is shown schematically in Fig. 4.

Table 1: Values of the back radiation obtained for the considered scenarios

Scenario	Back radiation level (with respect to the main beam)
Typical	-40 dB
Denser meshing around right NTF and absorbing boundary	-50 dB
Considering the contribution of only left NTF line	-56 dB

Thus, we are essentially considering a set of two dipoles excited in phase and separated by the distance of 900 mm. At f=5.2GHz the dipoles form the radiation pattern with a maximum at θ_{max}=180° and the first minimum at θ_{min} such that:

$$\theta_{min} = \text{arc sin}\left(\frac{\lambda}{2D}\right) = 1.8° \, . \qquad (7)$$

Looking at the radiation patterns of Fig. 2(b), we find that the value from equation (7) corresponds to what we see. It can be concluded that the effect of ripples in the back radiation pattern is formally physical - and not numerical. However, "physical" does not mean "realistic" here. Our discussion has been based on an idealistic assumption that the external edge of the antenna is perfectly axisymmetrical. In the technological reality, the shape of the reflector edge is slightly perturbed and thus the sharp radiation ripples in back radiation do not appear. Thus, as a practically measurable level of the back radiation, we should take a kind of average of the pattern over a reasonable angle range. Having compared the results of simulation and measurements for the cases similar to the one considered here, we have concluded that the averaging angle should be about 3°.

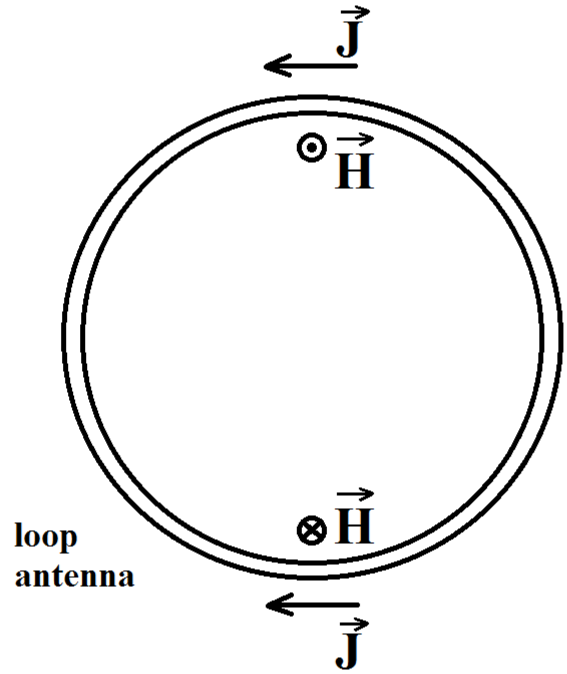

Fig. 4. Axial magnetic field and angular current in the loop antenna - a schematic view.

III. CONCLUSIONS

The paper has presented typical causes of errors in the extraction of back radiation of axisymmetrical antennas analyzed by the BOR (V2D) FDTD method. The effect of the "main beam shadow" has been investigated in detail and the approach for improving the accuracy of the analysis has been proposed.

The results presented in this paper have been obtained with working versions of our in-house V2D FDTD codes. Based on the resulting recommendations, a procedure for deleting user-selected walls of the Huygens surface from the near-to-far field transformation has been implemented in the QW-V2D software [8]. Its results coincide with those shown in the paper.

In future work, we shall validate our conclusions for general 3D (i.e., not necessarily axisymmetrical) high-directivity antennas and against commercial 3D FDTD packages, which are more abundant on the electromagnetic software market.

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Marzena Olszewska received the B.Sc. and M.Sc. degree from the Warsaw University of Technology. She is a Ph.D. student at the Warsaw University of Technology, Institute of Radioelectronics. Her research activity deals with double reflector antennas of a small size.

She is employed in QWED company, the vendor of QuickWave software for electromagnetic design.

Wojciech K. Gwarek graduated in 1970 from the Faculty of Electronics, Warsaw University of Technology. He obtained the M.Sc. degree from M.I.T. (EE'74). After returning to Poland he continued his work at the Warsaw University of Technology from where he received his Ph.D. (1977) and habilitation (1988) and where he is currently a professor. His teaching activities include lectures on electromagnetic theory, microwave technology and electromagnetic compatibility.

Professor Gwarek is the author of more than 200 technical papers and a text book on electromagnetic theory used in Poland since 1977. For the last 30 years, he has been reviewing papers for many of the leading archive journals and served as a TPC member for many international conferences. In 2008 and 2010, he was a co-chair of the TPC of the MIKON International Conference on Microwaves Radar and Wireless Communication. In the years 2003-2005, he served as a Distinguished Microwave Lecturer of the IEEE. Since 2001, he is a Fellow Member of the IEEE. He is a worldwide recognized expert on industrial design of microwave equipment involving electromagnetic modeling. In 2011, he obtained the IEEE Microwave Pioneer Award for his contribution to the theory and applications of electromagnetic modeling.