

Wire-grid modelling of metallic targets for Ground Penetrating Radar applications

Fabio Mangini^{1,2}, Pietro Paolo Di Gregorio¹, Marco Muzi¹, Lara Pajewski¹, Fabrizio Frezza¹

¹*Department of Information Engineering, Electronics and Telecommunications, "La Sapienza" University of Rome, Via Eudossiana 18, 00184, Roma, Italy.*

²*Enrico Fermi Center - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Piazza del Vinimale 1, 00184, Roma, Italy.*

Abstract – This work deals with the electromagnetic modeling of metallic cylindrical objects, buried in the soil or embedded in a structure, by means of a suitable set of wires. The most widely used criterion for choosing the wire size is the so-called same-area rule, coming from empirical observation and stating that the total surface area of the wires has to be equal to the surface area of the object being modeled. Recent studies have shown that the same-area criterion yields affordable results but is quite far from being the optimum: better results can be obtained with a wire radius shorter than what is suggested by the rule. This motivated us to carry out an investigation of the accuracy of the rule. We carried out simulations by using a commercial software implementing the finite-element method and found that the best accuracy is achieved with wires having a radius about 10-15% shorter than what is suggested by the rule. In particular, when a higher number of wires is used in the model, the radius needs to be shortened more.

I. INTRODUCTION

Ground Penetrating Radar (GPR) is a non-destructive technique that uses low-power wide-band electromagnetic waves to produce high-resolution images of the subsurface and structures [1]. GPR has gained broad acceptance internationally and nowadays is employed for a great variety of tasks, including archaeological investigations and inspection of ancient buildings, statues and further items of cultural or historical interest [2].

In the GPR field, a lot of research focuses on the development of electromagnetic-modelling tools, which help to understand how target structures get translated into radar-grams [3, 4]. Electromagnetic simulators can support the choice of the most proper equipment for a survey and are especially useful in the interpretation of experimental data.

This work deals with the electromagnetic modelling of cylindrical conducting targets embedded in a half-space by

means of a suitable set of small circular-section cylinders (wire-grid modelling).

Wire-grid modelling of conducting objects was introduced by Richmond in 1966 [5] and, since then, this method has been extensively used over the years to simulate arbitrarily-shaped objects and compute radiation patterns of antennas, as well as the field scattered by targets. The most widely used criterion for choosing the wire size is the so-called same-area rule [6], coming from empirical observation and stating that the total surface area of the wires has to be equal to the surface area of the object being modelled.

Ludwig [7] studied the reliability of the same-area rule by examining the canonical radiation problem of a transverse magnetic field by a circular cylinder fed with a uniform surface current, compared with a wire-grid model. Paknys [8] considered the wire-grid modelling of a circular cylinder with a uniform current on it, or illuminated by a transverse magnetic monochromatic plane wave. Both investigations concluded that the rule is optimum.

More recently, a circular cylinder in a dielectric half-space was studied, illuminated by a transverse magnetic monochromatic plane wave [9]; the scattered field was calculated in the spectral domain by using the cylindrical-wave approach and results obtained for different wire-grid models were compared with the exact solution. Such comparisons showed that the same-area criterion is affordable but higher accuracy is obtained with smaller wires. The open-source tool `gprMax` [3], implementing the finite-difference time-domain technique, was used in [10] to study the wire-grid modelling of conducting objects embedded in a half-space or in a multilayer; the source was a line of current, with Ricker waveform. Results obtained in [10] confirmed the conclusions drawn in [9], notwithstanding a different numerical method was used and simulations were performed in the time domain. The highest accuracy was obtained by shortening the radius of about 10%.

All those studies motivated us to further investigate the accuracy of the same-area rule. In this paper, we present

simulation results that we obtained for the wire-grid model of a metallic cylinder in a half-space. We used COMSOL Multiphysics to perform our simulations, which is a commercial software implementing the finite-element method. We obtained results in both the spectral and time domains. Our results are in agreement with [9] and [10].

II. WIRE-GRID MODELLING OF A METALLIC CYLINDER IN A HALF-SPACE

A perfectly-conducting (PEC) circular cylinder embedded in a dielectric half-space is considered. The cylinder has radius $R = 50$ mm and is located at a depth of 100 mm below the separation surface between the air and a host material with relative permittivity $\varepsilon_r = 4$. The wire-grid model consists of N perfectly-conducting circular cylinders with radius r , uniformly-spaced; each wire has the axis on the perimeter of the cylinder to be modelled (see Fig. 1). Two cases are studied in this paper: $N = 16$ and $N = 32$. The same-area rule suggests to use $r = R/N = 3,125$ mm and $r = R/N = 1,562$ mm, respectively, for 16 and 32 wires.

Finite-element method results are presented in Fig. 2, in the case of 16 wires. In the upper panel, the absolute value of the scattered electric field is shown as a function of frequency for different values of the wire radius; the scattered electric field is calculated immediately above the interface between air and soil, over the cylinder axis. In the bottom panel, the absolute error of the scattered electric field is plotted as a function of time, for the same values of the wire radius and probing position. The absolute error is defined as the magnitude of the difference between the exact A-scan (calculated in the presence of the circular cylinder) and the A-scan obtained for the wire-grid model. According to a nomenclature widely accepted by the GPR community, the term A-scan here refers to an array of electric-field values calculated in a fixed spatial point and in a series of consecutive instants (a GPR trace). The curves in Fig. 2 show that best accuracy is achieved when the wire radius is shortened of 10% with respect to the value suggested by the same-area rule. This is in agreement with results presented in previous studies.

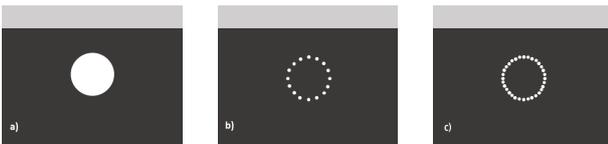


Fig. 1. a) A circular-section cylindrical object in a half-space; b) Wire-grid model of the object with 16 wires; c) Wire-grid model of the object with 32 wires,

A refinement of this analysis is presented in Fig. 3. Here, we considered different values of the wire radius ranging from 85% to 91% of the value suggested by the rule of thumb. The results that we obtained suggest that the best accuracy is achieved when the radius is shortened of 12% with respect to the value suggested by the same-area rule.

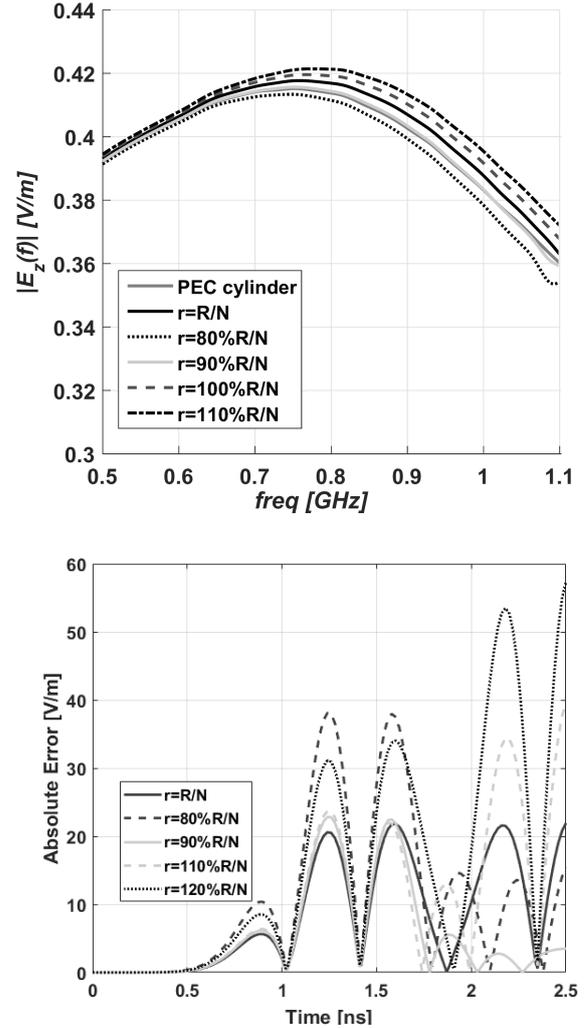


Fig. 2. Wire-grid modelling of a metallic circular cylinder by means of 16 wires: results in the spectral (upper panel) and time (bottom panel) domains.

As already mentioned, we repeated the simulations in the case of a higher number of wires. In particular, in Fig. 4 spectral- and time-domain results are presented when $N = 32$. With this number of wires, the most accurate model is obtained when the radius is shortened of 14% with respect to what suggested by the same-area rule. Actually, it seems that the wire radius needs to be shortened more when a higher number of wires is used.

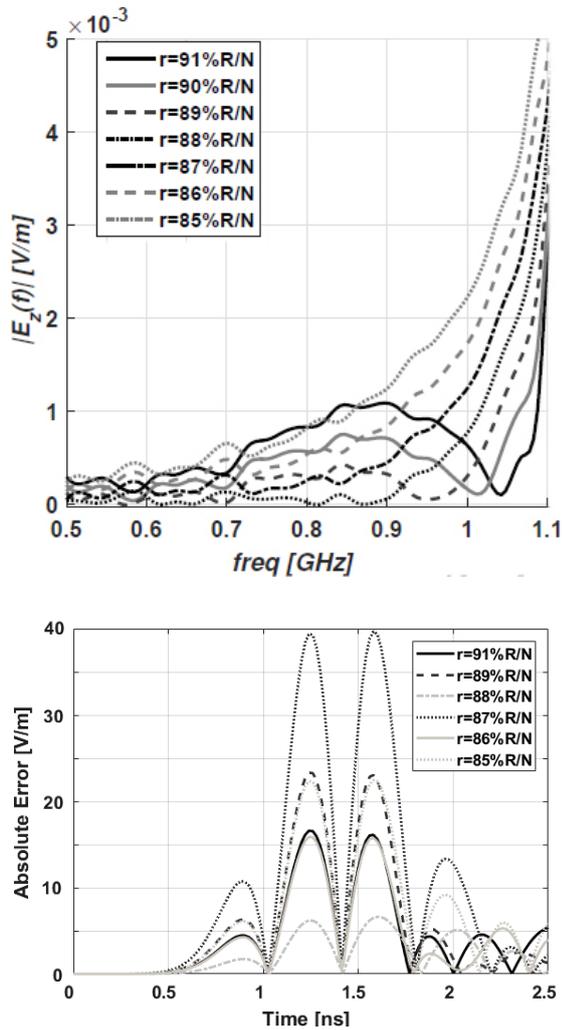


Fig. 3. Refinement of the analysis presented in Fig. 2.

III. CONCLUSIONS

In the framework of wire-grid electromagnetic modelling of buried two-dimensional objects, we investigated the accuracy of the same-area rule. We carried out simulations by using the commercial software COMSOL Multiphysics, implementing the fine-element method. We considered different wire-grid models of a metallic cylinder embedded in a dielectric half-space. Namely, models with 16 and 32 wires were simulated and the wire radius was varied. The best accuracy was obtained by shortening the wire radius of about 10% – 15% than what is suggested by the same-area rule.

Wire-grid modelling problems are of particular interest for the electromagnetic simulation of Ground Penetrating Radar (GPR) scenarios. We considered only a two-dimensional problem, but this is of practical interest. Indeed, in utility detection, quality controls of reinforced concrete, and many other GPR applications, the sought tar-

gets often are long and thin, hence two-dimensional methods can be employed to simulate them.

The wire-grid modelling technique is also useful for shielding applications and in the measurement of electromagnetic properties of materials through the use of coaxial cages.

IV. ACKNOWLEDGEMENTS

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REFERENCES

- [1] A. Benedetto and L. Pajewski, Eds. *Civil Engineering Applications of Ground Penetrating Radar*. Springer, Book Series: Springer Transactions in Civil and Environmental Engineering,” 385 pp., 2015.
- [2] L.B. Conyers, *Ground-penetrating radar for archaeology*. Altamira Press, 2013.
- [3] C. Warren, A. Giannopoulos, and I. Giannakis, “gprMax: Open source software to simulate electromagnetic wave propagation for Ground Penetrating Radar,” *Computer Physics Communications*, vol. 209, pp. 163-170, 2016.
- [4] F. Frezza and F. Mangini, “Electromagnetic scattering by a buried sphere in a lossy medium of an inhomogeneous plane wave at arbitrary incidence: spectral-domain method,” *JOSA A*, vol. 33, pp. 947-953, 2016.
- [5] J.H. Richmond, “A wire grid model for scattering by conducting bodies, *IEEE Trans. Antennas Propagation*, vol. AP-14, pp. 782-786, 1966.
- [6] S.M. Rao, D.R. Wilton, and A.W. Glisson, “Electromagnetic scattering by surfaces of arbitrary shape,” *IEEE Trans. Antennas Propagation*, vol. AP-30, pp. 409-418, 1982.
- [7] A.C. Ludwig, “Wire grid modeling of surfaces,” *IEEE Trans. Antennas Propagation*, vol. AP-35, pp. 1045-1048, 1987.
- [8] R.J. Paknys, “The near field of a wire grid model,” *IEEE Trans. Antennas Propagation*, vol. 39, pp. 994-999, 1991.
- [9] F. Frezza, L. Pajewski, C. Ponti, and G. Schettini, “Accurate wire-grid modelling of buried conducting cylindrical scatterers,” *Nondestructive Testing and Evaluation*, vol. 27, pp. 199-207, 2012.

- [10] L. Pajewski, S. Adabi, and S. Prontera, "Electromagnetic wire-grid modelling for Ground Penetrating Radar applications," Proceedings of TU1208 Third General Meeting | London, UK, March 2015, Aracne, ISBN 978-88-548-8486-1.

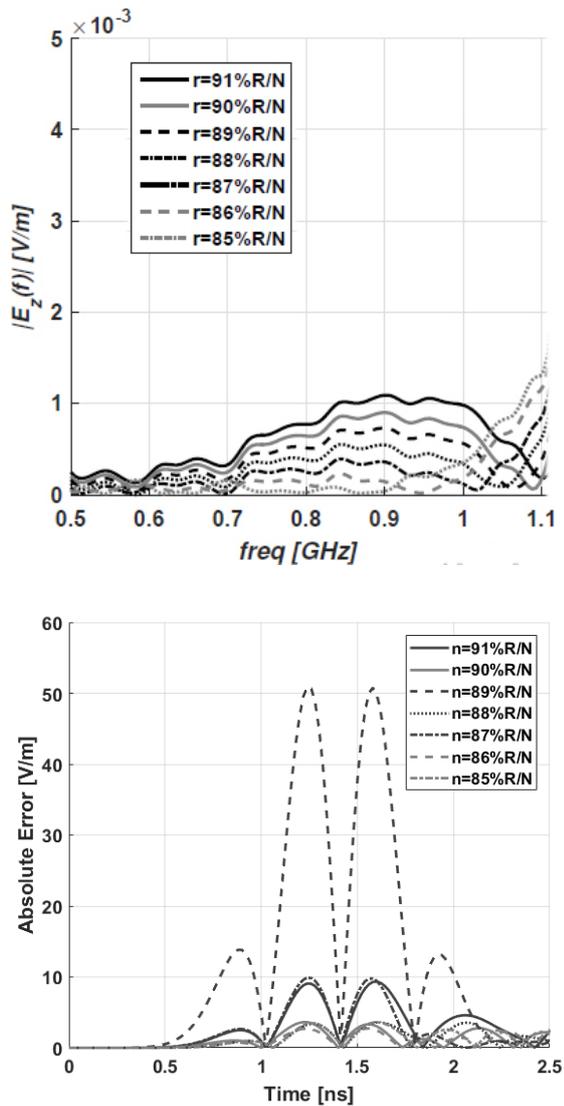


Fig. 4. Wire-grid modelling of a metallic circular cylinder by means of 32 wires: results in the spectral (upper panel) and time (bottom panel) domains.