Modeling of Medium Frequency Propagation Along a Thin Wire Parallel to a Lossy Return Path

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Abstract: The National Institute for Occupational Safety and Health has been investigating the performance of medium frequency (MF) communications systems in which electromagnetic waves are known to couple parasitically to conductors present in underground coal mine tunnels. In an effort to understand the MF signal behavior and factors that might control the attenuation and coupling of signals to the conductors, a representative computational electromagnetic model using the planar multilayered Green's function is developed and compared with analytic approximations available in the literature. Results are discussed for return path dissipation factors ranging from that of a good dielectric to that of a good conductor at MF. Finally, the approximate analytic forms, in conjunction with the computer model calculations, are used to construct equivalent transmission line representations for a given set of wire geometries and return path material parameters.

1. Introduction

Recent disasters have emphasized the need for reliable communication systems in the mining industry. In response to these tragedies, the United States Congress passed the MINER Act (Mine Improvement and New Emergency Response Act) in 2006, which is considered to be the most significant mine safety legislation since the Federal Mine Safety and Health Act of 1977. As part of the MINER Act, funding was appropriated to the NIOSH Office of Mine Safety and Health Research (OMSHR) to improve existing technologies and develop new solutions for robust communications and tracking. Moreover, in an effort to create redundancy in communications and tracking systems, multiple frequency ranges are to be examined. Medium frequencies are of particular interest because of their ability to parasitically couple into conductor infrastructure within a mine shaft and propagate large distances through various room-and-pillar architectures [1, 2]. To aid in the understanding of how MF signals propagate in a coal mine environment and determine what factors most influence their behavior, extensive numerical and analytical modeling is required. Many of the full-wave formulations for MF propagation in coal mines [3, 4] develop complex modal equations, requiring sophisticated numerical methods to produce accurate calculations. Furthermore, when utilized, these numerical methods can be time consuming. Alternatively, constructing representative models using commercial method of moments (MoM) codes presents a different but equally distinct challenge due to the computational resources required to model full-scale mines.

In order to make a logical progression towards the more complex, aforementioned procedures for modeling MF propagation in coal mines, a geometry closely related is examined and discussed for the remainder of this paper. The geometry at hand is represented in Fig. 1, which shows an electrically thin wire of radius, a, placed in free space a distance, h, above a lossy earth material. There are several justifications for using this geometry as a starting point and crucial stepping-stone toward understanding the behavior of MF propagation in coal mines. To start, this geometry reduces complexities in both analytical and numerical modeling, facilitating faster calculations while evaluating the impact of the varying dielectric media. Additionally, once predictions are made, it is of primary interest to test them through measurement. The experimental setup and control of the geometry depicted in Fig. 1 is significantly less complex than similar experiments established within a coal mine, where there can be numerous uncontrollable features and unknowns. Lastly, it is expected that for wire heights much less than one wavelength, a transmission line (TL) mode will be established between the wire conductor and the parallel ground return path, largely confining the fields therein. As a result, the geometry shown in Fig. 1 should be directly related to a wire placed in close proximity to a single tunnel boundary with identical material constituents.

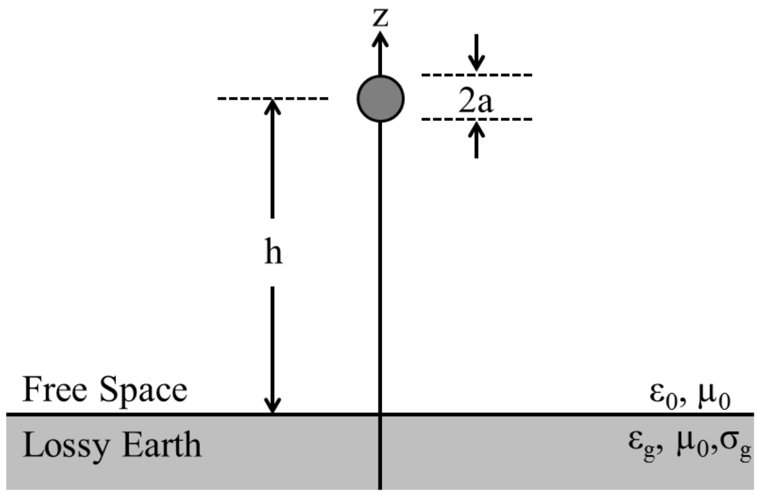

Fig. 1. Geometry and material metrics of wire over a homogenous half-space.

2. Electromagnetic Modeling with FEKO

To initiate investigations for the geometry in Fig. 1, a FEKO [5] model was constructed using a planar multilayered Green's function to represent the free space/lossy earth interface. At both ends of the model, the wire conductor was grounded into the layer representing the lossy earth. At one end, an ideal voltage source was positioned opposite to the load which, for TL analysis, was typically considered as being open, shorted, or matched. It should be noted that, in practice, any source could be used in order to represent different experimental setups. For example, future measurements may utilize inductively coupled antennas systems, in which case the voltage source described above could be replaced accordingly.

In these FEKO models, the following metrics were considered: wire height from the free space/ground interface, grounding rod length/penetration, wire radius, and the ground's permittivity and conductivity. Fig. 2 shows this geometry with material characteristics. Previous studies have indicated that wire height and ground conductivity have a much larger effect on the propagation characteristics than wire radius and ground permittivity [6]. The last metric to consider is the length of the grounding rods, affecting the termination impedance and, in turn, input impedance seen at the source. In future work, the authors intend to characterize the termination impedance associated with various grounding rod geometries (*i.e.* length and radius) and ground material properties through computational electromagnetic

(EM) modeling and measurement.

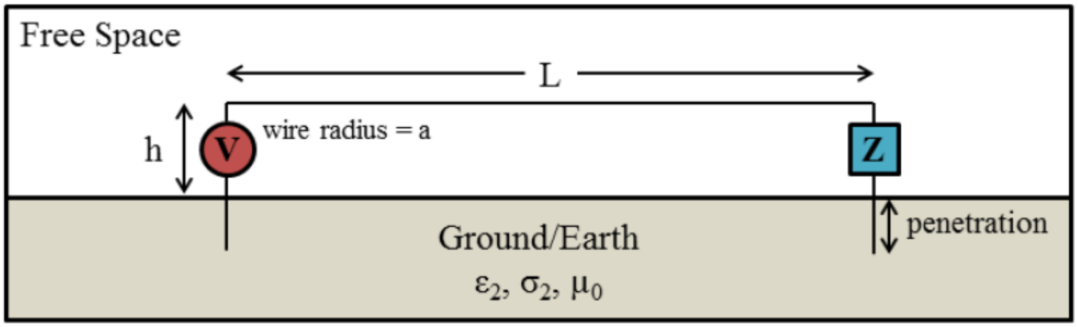

Fig. 2. FEKO model geometry.

3. Analytic Approximations

A. Theoretical Background

As previously mentioned, the calculations made with the described FEKO model were compared with analytic approximations reported in the literature. The wire with earth return has been a fundamental problem of interest for almost a century. First reported in 1926 [7], Carson derived approximate, TL solutions under the assumption that the wires are thin, placed in close (*i.e.* much less than one wavelength) proximity to the ground, and that the ground return dissipation factor is characteristic of good conductors ($\sigma/\varepsilon\omega >> 1$). In effect, Carson's approximation provides straight-forward calculations, but requires low frequencies of operation and/or the return path to have high conductivity, which may not be the case for the ground materials of interest. Significant improvement was made in 1972 [8], when J. R. Wait's full-wave analysis provided the exact modal equation for all ranges of both electrical and geometric parameters. Wait's model showed that the propagation constant, $j\gamma$, could be written in terms of the standard TL modal equation given by

$$j\gamma = \sqrt{ZY} \tag{1}$$

where *Z* and *Y* are the equivalent series impedance and shunt admittance, respectively, and are functions of γ.

The difficulty with Wait's approach is that γ is a function of itself and therefore requires advanced numerical methods to compute solutions. To avoid the challenges associated with solving the exact modal equation, attempts to improve on Carson's original approximation have been reported that introduce corrective terms to account for displacement currents associated with lossy dielectrics. The approximation used here, reported in 1996 by D'Amore and Sarto [6], still assumes thin wire diameter and wire heights much smaller than a wavelength. When applied, the approximate form of the propagation constant in (1) is given by

$$\gamma^2 \approx \mathrm{k}_0{}^2\left(\frac{2\pi * Z_{\mathrm{int}}/(j\omega\mu_0) + \ln\left(\frac{2h}{a}\right) + 2S_1(h)}{\ln\left(\frac{2h}{a}\right) + S_2(h)}\right), \tag{2}$$

where Z_{int} is the wire's internal impedance, while S_1 and S_2 are the small argument, logarithmic approximations for the associated Sommerfeld integrals given by

$$S_1(h) = \frac{1}{2}\ln\left(1 + \alpha r^{-1}\right) \tag{3}$$

$$S_2(h) = \frac{k_0^{\ 2}}{k_g^{\ 2} + k_0^{\ 2}} \ln\left(1 + \beta r^{-1}\right). \tag{4}$$

Here, jk_0 and jk_g are the propagation constants of unbounded EM waves in the free space and ground media, respectively. Lastly, $r = (4h^2 + a^2)^{1/2}$ with the α and β terms given by

$$\alpha = \frac{2}{\sqrt{k_0^2 - k_g^2}} \tag{5}$$

$$\beta = \frac{k_0^{\ 2} + k_g^{\ 2}}{k_0^{\ 2}\sqrt{k_0^{\ 2} - k_g^{\ 2}}}. \tag{6}$$

Note that the propagation constant, γ, is no longer a function of itself. When compared with Wait's exact modal equation, the D'Amore and Sarto approximation is remarkably simple and can be applied to perform rapid computations with a high degree of precision provided the appropriate conditions are met.

B. Numerical Examples

Next, it is instructive to consider numerical examples in order to compare the computational models constructed in FEKO with D'Amore's approximation outlined above. The first example, with results shown in Figs. 3 and 4, compares calculations of velocity factors and attenuation, respectively. Calculations were performed for varying ground conductivities (10^{-5} – 10^{-2} S/m) as a function of wire height above the air/ground interface. The wire conductor was modeled as copper, with a 1-mm radius, and driven by an ideal voltage source operating at 500 kHz. Permittivity of the ground was assigned as 10. Notice that the ground dissipation factor, σ/ωε ranges from 0.03, displacement current dominance, to 36, conduction current dominance. The results are in agreement for the entire range of wire positions, particularly for high ground conductivity.

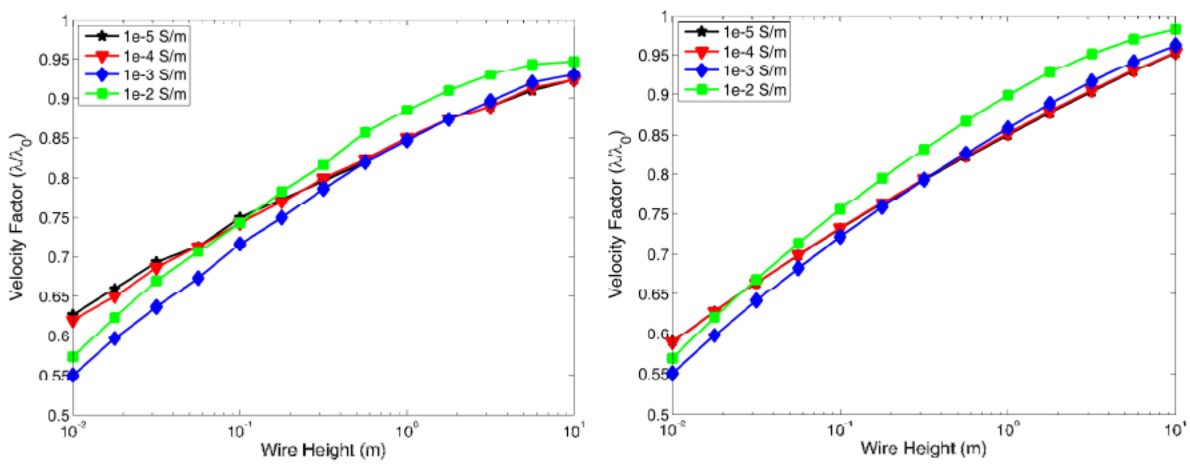

Fig. 3. Velocity factor as a function of wire height for a TL driven at 500 kHz.
Calculated using: FEKO (left) D'Amore approximation (right).

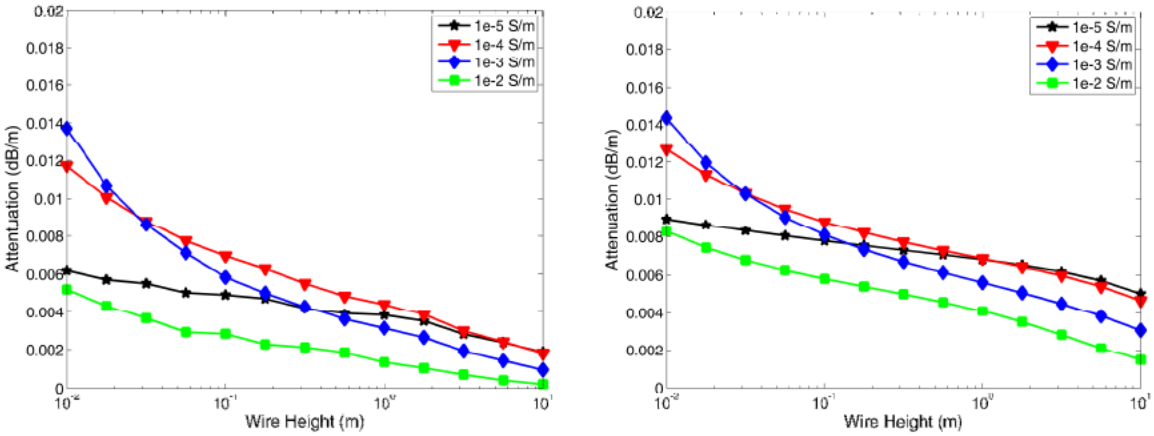

Fig. 4. Attenuation as a function of wire height for a TL driven at 500 kHz.
Calculated using: FEKO (left) D'Amore approximation (right).

The next numerical example compares phase constants and attenuation as a function of frequency for the same ground conductivities used in the previous example. The wire conductor and ground were assigned the same material and geometric properties as in the example above. Here, however, the wire position was fixed at 10 cm above the ground (ten cm is a representative distance for conductor spacing from a wall in a mine). The results for this comparison are shown in Fig. 5 and again are found to be in good agreement across the variations in both ground conductivity and frequency. In future work, the authors intend to make final comparisons with measurement results.

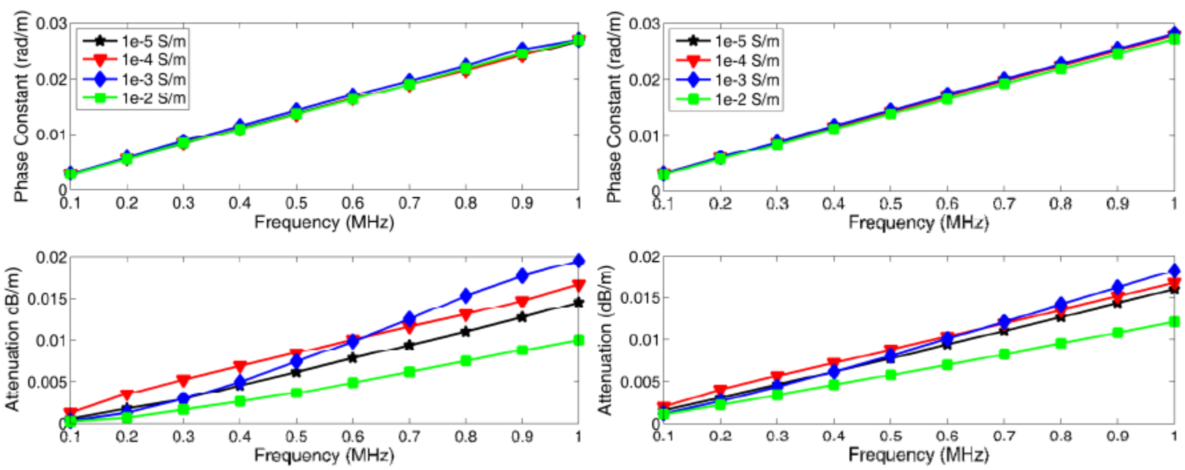

Fig. 5. Phase constant and attenuation as a function of frequency for a wire placed 10 cm above ground.
Calculated using: FEKO (left) and D'Amore approximation (right).

4. Conclusions

A representative computational EM model was developed and compared with D'Amore's approximate form of Wait's more general modal equation. The motivation for this work is to aid in the engineering of robust communication systems required for both emergency and daily mining operations. Specifically, the work presented in this paper is considered to be a crucial stepping-stone in the characterization of MF signal propagation in coal mines. To demonstrate the computational agreement between the models developed in FEKO and the D'Amore approximation, calculations were made and compared for propagation constants subject to varying ground conductivities, wire heights, and frequencies. In future work, the authors intend to make a third comparison with experimental measurements. The three methods combined will yield a powerful modeling package for understanding how MF signals propagate in underground coal mines.

Disclaimer: The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company name or product does not constitute endorsement by NIOSH.

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