# Loop Coupling and Field Distribution in Earth for Horizontal Positioning in VLF/ELF Through-The-Earth Wireless Mine Communications

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***Abstract*—A through-the-earth (TTE) wireless communication system is the system most likely to survive after a mine disaster because its signal penetrates the earth directly and does not use wires connecting the surface and underground components. Typically, the transmit (Tx) and receive (Rx) antennas are vertically separated by the earth overburden in a coaxial arrangement. In this paper, we show that there are advantages to separating the Tx and Rx antennas horizontally (co-planar arrangement), hence, communicating within the mine itself, and offering the advantage of mobility for one of the antennas. In this paper, we present a two-layer model, with both Tx loop and Rx loop antennas buried at the same depth underground. The magnetic field distribution results at the Rx loop are obtained for various conditions, such as earth conductivity, conductivity contrast between two layers, and co-planar and co-axis for the same Tx and Rx separation distance, providing us with an understanding of the parameters that control the performance and a concise method to predict the performance of a co-planar TTE loop communication system.**

## I. Introduction

One of the requirements of the Mine Improvement and New Emergency Response Act (MINER Act) is the installation of post-accident two-way communications and electronic tracking for all coal mines. The through-the-earth (TTE) system usually utilizes a large loop antenna as the transmit (Tx) and ferrite-cored multi-turn wires as the receive (Rx), and operates at a very low frequency (VLF) or extremely low frequency (ELF). For TTE communication, one of the greatest challenges lies in the signal attenuation which is largely controlled by the conductivity of earth medium, the operating frequency, and the overburden depth. The performance and reliability of such a system is also highly dependent on additional properties of the earth such as the strata layer structure and conductivity associated with each layer. Therefore, to understand the performance limitations of TTE systems, we need to understand the impact of these layers on TTE propagation. Typically, the Tx and Rx antennas are vertically separated by the earth overburden, which is a coaxial arrangement. In this paper, we show that there are advantages to separating the Tx and Rx antennas horizontally (co-planar arrangement), hence, communicating within the mine itself. The co-planar TTE configuration offers the advantage that one unit can be in a relatively fixed location while the other can move as the mining face progresses. The fixed position unit can then be used as a relay to a surface unit, which can also be in a fixed location. Mines do not always have access rights to all areas on the surface, so the fixed position surface unit can be in an area to which the mine does have access. In this paper, we present a two-layer earth model, with both the Tx loop and Rx loop antennas buried at the same depth underground. The magnetic fields are calculated based on potential theory. The magnetic field distribution results at the Rx loop are presented for various apparent earth conductivities.

## II. 2-Layer Co-Planar Model

For a two-layer earth model as depicted in Fig. 1, both transmitting loop and receiving loop are buried underground horizontally at depth $h$. They are within the same homogenous and isotropic layer, i.e., the second layer, and are separated by a distance $\rho$. The coal is assumed to have a low conductivity compared with that of the surrounding rock above the seam. The top layer (layer 1), with a thickness of $h_1$, usually has higher conductivity and less depth than that of lower layer (layer 2) [1]. Here we set $h_1 = h/300$.

With the aid of magnetic Hertzian potential [2, 3], the magnetic fields in layer 2 can be obtained by applying the appropriate boundary conditions. The field components in the cylindrical coordinate system $(\rho, \varphi, z)$ are given in (1)–(6). $z$ is the vertical position of the point of interest ($z = -h$ for the present case).

$$\{\mathrm{H}_{\rho 2}, \mathrm{H}_{z2}\} = b\{P_{2,} Q_{2,}\}, \tag{1}$$

in which

$$P_2 = \frac{h^3}{2}\int_0^\infty \left(\lambda^2 e^{-k_2(h+z)} - \lambda k_2 R_2(\lambda) e^{k_2 z}\right) \mathrm{J}_1(\lambda\rho) d\lambda, \tag{2}$$

$$Q_2 = -j\mu\omega\sigma_2 \frac{h^3}{2}\int_0^\infty \left(\frac{\lambda}{k_2} e^{-k_2(h+z)} + R_2(\lambda) e^{k_2 z}\right) \mathrm{J}_0(\lambda\rho) d\lambda + \frac{h^3}{2}\int_0^\infty \left(\lambda k_2 e^{-k_2(h+z)} - {k_2}^2 R_2(\lambda) e^{k_2 z}\right) \mathrm{J}_0(\lambda\rho) d\lambda. \tag{3}$$

$$R_2(\lambda) = \frac{{R_2}'(\lambda)}{{R_2}''(\lambda)}, \tag{4}$$

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$$R_2'(\lambda) = e^{-(h-2h_1)k_2} \times \{-e^{2h_1k_1}(k_0+k_1)(k_1-k_2)\lambda + (-k_0+k_1)\lambda(k_2+k_1)\}, \quad (5)$$

$$R_2''(\lambda) = e^{2h_1k_1}(k_0+k_1)k_2(k_1+k_2) + (-k_0+k_1)k_2(k_2-k_1). \quad (6)$$

In (1), $b = M/2\pi h^3$ is the normalizing factor and M = NIA the magnetic moment of the transmitting loop. N is the number of wire turns in the loop; I the rms value current through a single wire; and A the area formed by the circular loop. $P_2$ and $Q_2$ are dimensionless functions and can be viewed as transmission losses due to attenuation by the conducting earth. In (2) and (3), $k_1$ and $k_2$ satisfy $k_i = \sqrt{\lambda^2 + \gamma_i^2}$, which are the complex wavenumbers in layer 1 and layer 2, respectively. $\gamma_i^2 = j\mu\omega\sigma_i$ is the intrinsic propagation constant of layer *i*. $J_0(*)$ and $J_1(*)$ are Bessel functions of the first kind. *j* is the square root of -1. $\sigma_i$ and μ are the conductivity and magnetic permeability of the corresponding layer, respectively. Note that μ is assumed to be the same as the free space value. ω is the angular frequency.

## III. Results and Discussion

Since the transmitting and receiving loop lie at the same level within the mine tunnel, the field at the receiving loop then can be evaluated by setting z = -*h* in (2) and (3). Similarly as in [3, 4], we use the variable replacements: $x = \lambda h; D = \rho/h; Z = z/h$, in which *x* and λ are the integration variables, D the normalized radial distance (dimensionless), z the vertical position of the point of interest (z = -*h* for the present case), and Z the normalized vertical position.

The field expressions above can then be evaluated numerically for a range of parameter values. The conductivity of the lower layer is assumed to be 0.005 S/m, 0.01 S/m, and 0.1 S/m. For most coal mines, the overall conductivity value of 0.005 S/m and 1 S/m are, respectively, the lower limit and upper limit. However, the value near the surface of the ground can increase due to moisture in the soil or metal infrastructure nearby. We increase its value by setting the upper conductivity to be ten times of the value of the lower layer.

The normalized fields plotted against the separation distance between transmitting and receiving antennas (normalized by overburden depth, *h*) for various conductivities are shown in Fig. 1. The upper plot in Fig. 1 shows that the radial component of the field decreases dramatically with radial distance when the conductivity of the lower layer is high. For $\sigma_2 = 0.1$ S/m and $\sigma_1 = 1$ S/m, the radial field strength drops about -31 dB from D = 0.5 to 1.5. Meanwhile, the radial field will be much stronger at lower conductivity values (0.01 S/m and 0.005 S/m) than at higher values (0.1 S/m).

In the lower plot in Fig. 1, earth conductivities of the given layer structure have a more prominent effect on the vertical component of the magnetic field strength compared with the radial field. The vertical field is much stronger than the radial field (about 30 dB difference) in the range D < 0.5. It is also obvious that the conductivities have less effect on vertical field strength at near distances (D < 0.5) compared with far distances. Similarly as seen in vertically separated loops [5], there are nulls around D = 2.5 for $\sigma_2 = 0.1$ S/m, D = 3.3, 3.7 and 4.8 for $\sigma_2 = 0.01$ S/m and 0.005 S/m.

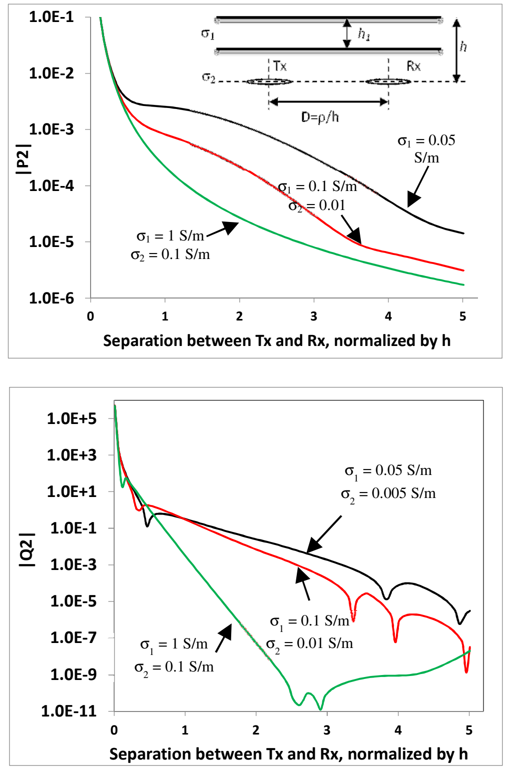


Fig. 1. Normalized radial (upper) and vertical (lower) fields plotted as function of radial distance (normalized by overburden depth *h*) for various conductivities.

The results for the magnetic field distribution provide us an understanding of the impact of the conductivity values for the earth and the thin layer, the layer thickness, and the depth of the loop on TTE performance. Concise results can be obtained using an analytical formula and do not require a commercial computational electromagnetics code.

## 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).

## References


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## 125: Propagation in Underground Environments

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Session Chair: Chenming Zhou, National Institute for Occupational Safety and Health (NIOSH)

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Lincan Yan; *NIOSH/OMSHR, United States*
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Bruce Whisner; *National Institute for Occupational Safety and Health, United States*
Nicholas Damiano; *National Institute for Occupational Safety and Health, United States*

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B. Haraoubia; *USTHB, Algeria*
Mourad Nedil; *University of Quebec (UQAT), Canada*
Salim Azzeddine; *University of Quebec (UQAT), Canada*
Nahi Kandil; *University of Quebec (UQAT), Canada*
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