Measurements and Modeling of Through-the-Earth Communications for Coal Mines

Lincan Yan, Joseph A. Waynert, and Carl Sunderman

***Abstract*—This paper presents modeling results from the National Institute for Occupational Safety and Health research into through-the-earth (TTE) communications technology for underground coal mines. Research focuses on the factors controlling the propagation and coupling of radio signals between transmit and receive antennas separated by earth or coal. Most TTE systems use single or multiturn loops of conductor for the transmit antenna. We compare the magnetic field distribution predicted from analytical formulas to the predictions of a method of moments computational electromagnetic (CEM) code. The predictions are compared in free space, in a homogeneous earth, and with the effect of the presence of the surface of the earth. The evaluations are done with the transmit loop buried in the earth and with the loop above the surface. The analytic results are shown to agree reasonably well with the more detailed CEM predictions for the situations considered, reducing the need for expensive and complicated CEM codes in analyzing simple TTE configurations. The predictive methods are applied to TTE measurements made in 94 different coal mines by the Bureau of Mines in the 1970s, and the implications for the apparent conductivity of the earth are discussed.**

***Index Terms*—Loop antenna, magnetic field sensing, mine communication, through-the-earth (TTE).**

I. Introduction

IN June of 2006, the U.S. Congress passed the Mine Improvement and New Emergency Response (MINER) Act. One of the aims of the MINER Act is to enhance the rescue of underground coal miners following an accident by providing wireless communications between surface personnel and miners trapped underground. Through-the-earth (TTE) communications systems, in which the radio signal passes directly through the mine overburden, offer the potential to be highly survivable in a coal mine environment. Therefore, the National Institute for Occupational Safety and Health (NIOSH) is performing research in TTE systems. The propagation of radio-frequency (RF) signals is highly attenuated in the somewhat conducting earth, but frequencies from roughly 10 Hz to 10 kHz can propagate significant distances. This paper considers and compares some of the modeling approaches that can be used to analyze TTE propagation.

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It is important to have numerical or analytical methods to predict the magnetic field distribution from a TTE transmitter operating in various environments. For uplink and downlink TTE communications, both analytical and numerical predictions are considered. These methods are necessary considering that *in situ* measurements are not always practical. Hence, several predictive methods are presented in this paper and their accuracy is evaluated.

In 1970s and early 1980s, the U.S. Bureau of Mines (BOM) measured detection of the TTE electromagnetic signals produced by a source either at the surface or underground using frequencies ranging from 630 to 3030 Hz [1]. These data were taken at 94 representative coal mines distributed throughout the U.S. In this paper, the TTE data are analyzed using several techniques to arrive at some conclusions about the apparent conductivity of the intervening overburden. The effect of the presence of the earth–air interface is discussed and, in particular, its effect on uplink versus downlink RF propagation.

II. Description

A. Magnetic Fields of a Current Loop in Free Space

The radiated magnetic fields of a small circular loop antenna carrying a current I_0 in spherical coordinates are given by [2]

$$H_r = \frac{jM\omega\mu\cos\theta}{2\pi\eta r^2}\left[1+\frac{1}{jkr}\right]e^{-jkr} \quad (1)$$

$$H_\theta = \frac{-kM\omega\mu\sin\theta}{4\pi\eta r}\left[1+\frac{1}{jkr}-\frac{1}{(kr)^2}\right]e^{-jkr} \quad (2)$$

where $M = NAI_0$ is the magnetic moment (A is the area of the loop; N is the number of turns in the loop), η is the intrinsic impedance in the air, μ is the magnetic permeability, ω is the angular frequency, k is the wavenumber, and $j = \sqrt{-1}$.

Along the loop axis, $\theta = 0$. The radial and azimuthal components disappear, and the z-component (vertical component) becomes

$$H_z = \frac{jM\omega\mu}{2\pi\eta r^2}\left[1+\frac{1}{jkr}\right]e^{-jkr} \quad (3)$$

$$H_\rho = H_\varphi = 0. \quad (4)$$

B. Magnetic Fields of a Current Loop in Homogenous Earth

For the loop buried in a homogenous medium such as earth, the intrinsic impedance and wavenumber in (3) and (4) will be changed due to the presence of the medium. The presence of earth conductivity will introduce a skin depth. It will also decrease the wave propagation speed (phase velocity). The

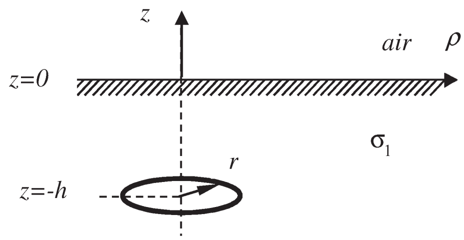

Fig. 1. Loop antenna with radius r buried in a homogeneous earth at depth h.

wavenumber is complex because of the lossy medium, and thus, its magnitude will increase. The conductivity of the medium introduces an exponential attenuation factor, further reducing the fields as distance increases, as compared to free space. We discuss the governing equations explicitly in the next section.

C. Surface Fields of a Current Loop in Earth

The presence of the surface of the earth introduces additional effects on the propagating magnetic field. Electromagnetic surface fields due to a loop antenna buried in a homogeneous earth can be calculated using an analytical method [3]. Fig. 1 illustrates a current loop buried at depth h in a two-layer medium of earth (medium 1) and air (medium 0). The cylindrical coordinates (ρ, φ, z) are used in this case since the problem is symmetrical about component φ. Solutions describing the magnetic field distribution can be found by using Maxwell's equations and applying the appropriate boundary conditions.

The component magnetic fields above the surface for a buried Hertzian dipole [4] can be expressed as

$$H_{z0} = -bQ_0 \tag{5}$$

$$H_{\rho 0} = bP_0 \tag{6}$$

where $b = M/(2\pi h^3)$ is the vertical magnetic field strength in free space directly above the loop on its axis. $M = INA$ is the magnetic moment, where I is the current through the loop, N is the turns of wire, and A is the loop area. P_0 and Q_0 in (5) and (6) can be viewed as transmission losses due to attenuation by the conducting earth where

$$Q_0 = \int_0^\infty \frac{x^3 e^{-(x^2+jH^2)^{1/2}+x(1-Z)} J_0(xD)dx}{x+(x^2+jH^2)^{1/2}} \tag{7}$$

$$P_0 = \int_0^\infty \frac{x^3 e^{-(x^2+jH^2)^{1/2}+x(1-Z)} J_1(xD)dx}{x+(x^2+jH^2)^{1/2}} \tag{8}$$

and $D = \rho/h$, $Z = z/h$, and $H = (\mu\omega\sigma_2)^{1/2}h$, i.e., the ratio of source depth to skin depth. J_0 and J_1 are Bessel functions of the first kind.

D. Subsurface Fields of a Current Loop Located Above Ground

As illustrated in Fig. 2, a cylindrical coordinate system (ρ, φ, z) is chosen again. A loop antenna with magnetic moment M and radius r is located at $z = h_0$, where $z = 0$ indicates the earth's surface and positive z is upward. The homogeneous half-space earth has conductivity σ.

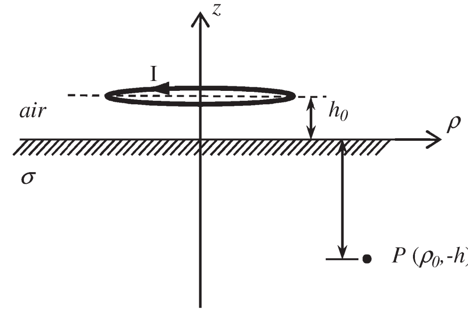

Fig. 2. Circular loop antenna with radius r located above ground with height h_0. Observation point P located at depth h underground.

At an observation point P at depth $h(z = -h)$ and radial coordinate ρ, the subsurface field components are [4]

$$H_\rho = -b\hat{P} \tag{9}$$

$$H_z = b\hat{Q} \tag{10}$$

where

$$\hat{P} = \int_0^\infty \frac{J_1(Ax)}{\frac{Ax}{2}} \frac{x^2(x^2+jH^2)^{\frac{1}{2}}}{(x^2+jH^2)^{\frac{1}{2}}+x} e^{-Zx} e^{-(x^2+jH^2)^{1/2}} J_1(Dx)dx \tag{11}$$

$$\hat{Q} = \int_0^\infty \frac{J_1(Ax)}{\frac{Ax}{2}} \frac{x^3}{(x^2+jH^2)^{\frac{1}{2}}+x} e^{-Zx} e^{-(x^2+jH^2)^{1/2}} J_0(Dx)dx \tag{12}$$

where $A = a/h$, and $Z = h_0/h$.

III. Results and Comparison

In this paper, we compare the magnetic field strength calculated by numerically integrating the formulas above to a FEKO[1] simulation. FEKO [5] is a computational electromagnetics software product that primarily uses the method of moments (MOM) integral formulation of Maxwell's equations.

A. Underground Loop, Uplink

For illustrative purposes, we chose a loop antenna with a radius of 20 m buried in a homogeneous half-space earth of 0.01-S/m conductivity and relative magnetic permeability of 1. The antenna has ten turns of wire with 10-A RMS current in each turn. The vertical component of the magnetic field is normalized by the loop's magnetic moment to make the results independent of the details of the transmit loop. The field to moment ratio is evaluated at the earth's surface as a function of the frequency using (5). Fig. 3 shows that the vertical magnetic field component changes with radial distance ρ from the loop axis at the earth's surface for a loop located a representative distance of 250 m underground. Note the appearance of a null at around

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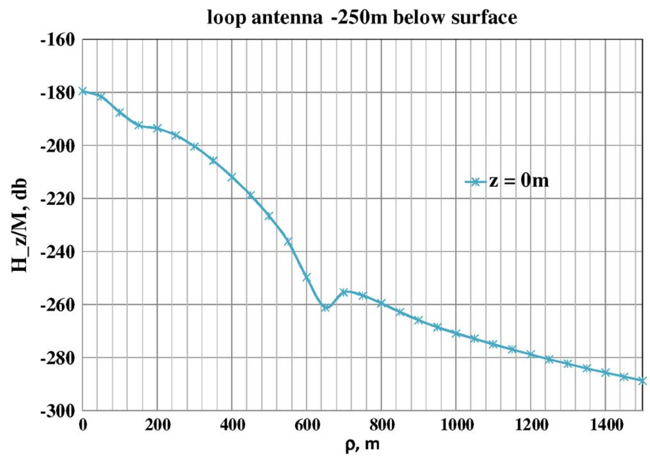

Fig. 3. Vertical magnetic field component at surface ($z = 0$ m); transmit loop underground.

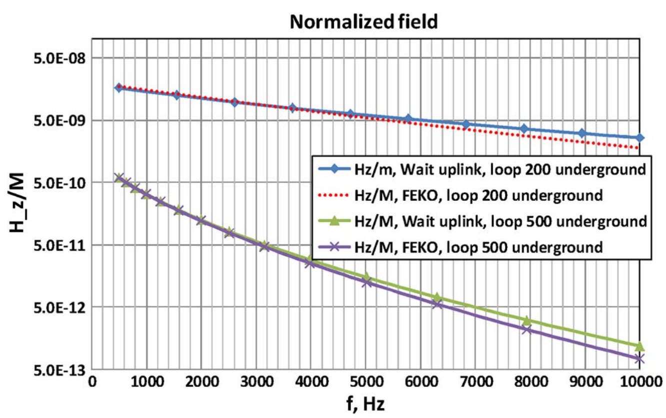

Fig. 4. Vertical field component changing with frequency f; transmit loop underground.

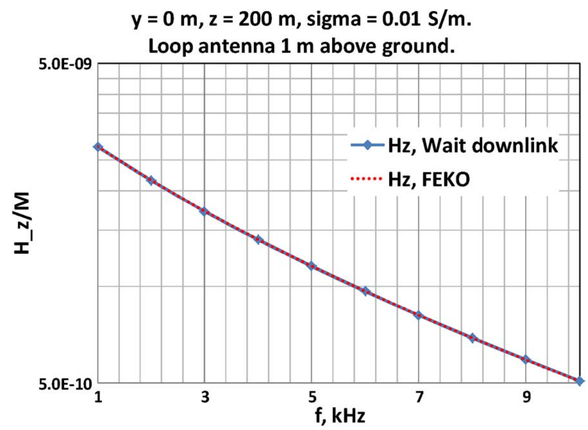

Fig. 5. Vertical field changing with frequency f; transmit loop on the surface.

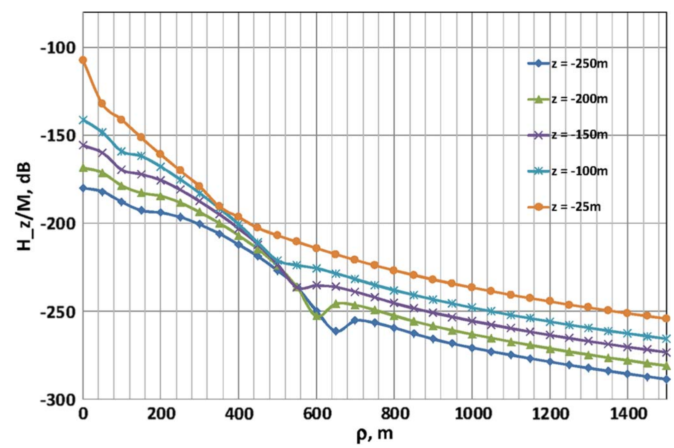

Fig. 6. Vertical field component (in decibels) changing with radial distance ρ from the loop axis at different depths; transmit loop on the surface (Wait).

$y = 600$ m. This null also appears in the FEKO simulation results and is an artifact of the z-component magnetic field of a dipole. The magnetic field lines must form continuous loops. Hence, the field must transition from vertically up to vertically down and, in the process, must go through a zero value as the radial distance increases. This is the origin of the null.

Fig. 4 shows a comparison between FEKO results and (5) of the normalized vertical magnetic field on the loop axis as a function of frequency at two different loop depths. The antenna is 500 m and is located 200 m underground. The homogeneous earth has an assumed conductivity value of 0.01 S/m. The field is measured at $\rho = 0$ m and $z = +5$ m. Instead of evaluating the field right above the surface, we choose some distance from the surface $(z \neq 0)$ to avoid any possible calculation error caused by a singular point. (Later calculations indicated that this was not necessary.) As can be seen, the analytical equations predict slightly higher field strengths than FEKO and the difference increases with increasing frequency, becoming 60% or 4.1 dB at 10 kHz.

B. Surface Loop, Downlink

Again, we choose a circular loop of 20-m radius and 100 A of wire. The homogenous earth half-space has an assumed conductivity value of 0.01 S/m. The normalized magnetic field strength at 200-m depth underground for a transmit loop on the surface is evaluated by using both Wait's downlink formulas, i.e., (9) and (10), and FEKO software simulation. Fig. 5 shows the vertical component of the field as a function of frequency f for a transmitting loop 1 m above ground. The results from the Wait's downlink formula and FEKO are in good agreement with each other. The difference, as shown in Fig. 5, is very small (less than 0.1% for conductivity of 0.01 S/m).

In Fig. 6, the vertical field component in decibels (relative to 1 A/m) is plotted with radial distance ρ from the loop axis at different depths for a loop located $+1$ m above ground. The earth conductivity is again 0.01 S/m. The transmit antenna operates at 8 kHz. As shown in Wait's uplink results (loop antenna underground) in Fig. 3, nulls also appear in Wait's downlink results in Fig. 6.

C. Uplink Versus Downlink

From (5) and (10), the z-components of the magnetic field in air from an underground source are nearly equal to those in the opposite direction given the same separation. The difference is less than 2% or 0.18 dB for all depths at a representative frequency of 8 kHz and earth conductivity of 0.01 S/m. Fig. 7 shows an example of the effect of conductivity. The lower conductivity case is shown with the lower curve and the higher conductivity case with the upper curve. Fields here are expressed as those produced by a loop underground relative to those from a loop above ground and measured at the same distance (300 m)

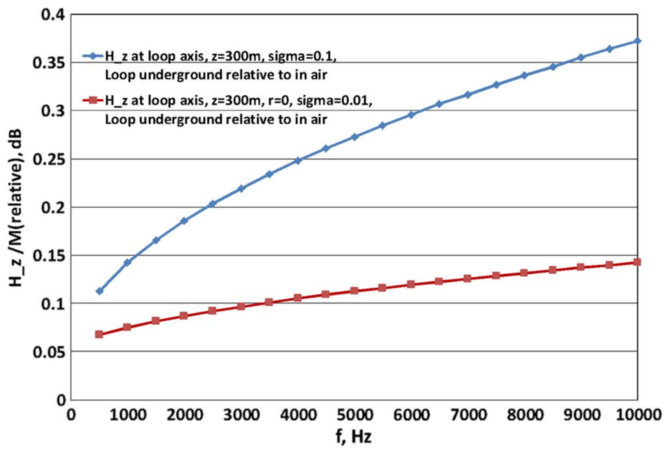

Fig. 7. Comparison of surface and underground transmitted fields at 300-m separation for different earth conductivity values.

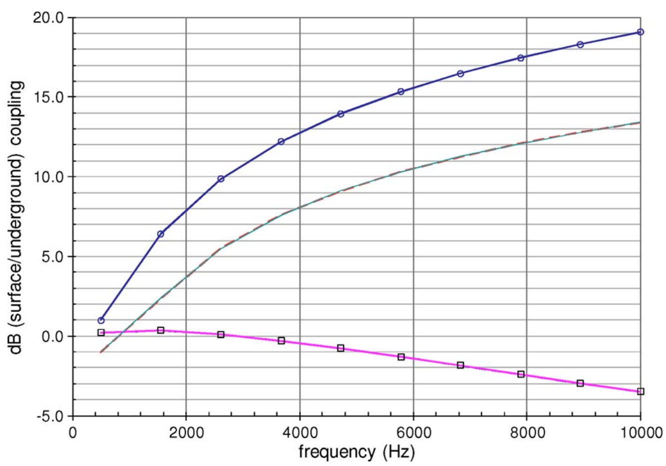

Fig. 8. Decibel difference in coupling between downlink and uplink loops in FEKO. (Upper curve) $\sigma = 1$-, 100-, and 500-m separation, loops coaxial. (Middle curve) $\sigma = 0.1$- and 100-m separation, coaxial loops, and (cannot be distinguished) loop axes offset by 100 m. (Lowest curve) $\sigma = 0.01$-, 100-, 250-, and 500-m separation, coaxial loops.

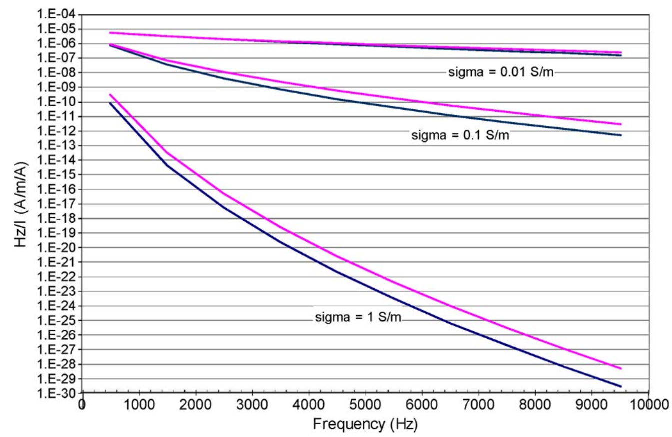

Fig. 9. Decibel difference in normalized field between downlink and uplink loops in FEKO. (Pink) Loop on the surface. (Blue) Loop underground; 300-m separation, loops coaxial.

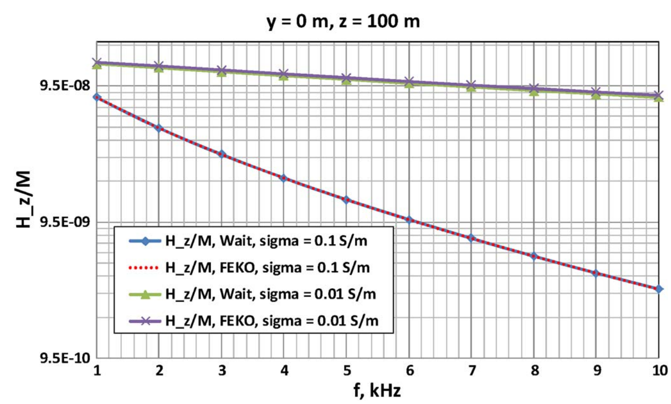

Fig. 10. Normalized magnetic field 100 m below surface transmitter on the loop axis for conductivity values of 0.01 and 0.1 S/m.

from the source for both cases. As shown in Fig. 7, there is a greater difference between the uplink and downlink H_z (vertical component of the field) for a higher conductivity earth.

Comparing only H_z on the axis does not give the actual coupling between two loops, which is the important parameter for TTE communications when the receive antenna is another loop. Actual coupling is determined by integrating the normal component of the field over the loop area. FEKO calculations indicate the ratio of the induced voltage in the receiving loop to the current in the transmitting loop. A measure of the coupling between loops can be quite different for uplinks and downlinks, as shown in Fig. 8, for several values of earth conductivity. For low conductivity, there is a minimal difference between uplink versus downlink couplings. Coupling may not be an appropriate metric because it will depend on many factors that are not related to the field itself. For example, many TTE systems use a wire-wound iron core antenna as the receiver. Thus, we investigated the difference in the normalized magnetic field strength using FEKO for uplink versus downlink, as shown in Fig. 9. Again, at higher conductivity values, there appears to be a significant difference between the uplink and downlink field strengths.

D. Apparent Earth Conductivity

The radio signal can be dramatically attenuated due to the conductivity of the earth at TTE frequencies. There are many factors that influence the conductivity of the earth. The principal ones are the soil type, moisture content, chemical composition, dissolved salt concentration, and temperature [6]. As shown in Fig. 10 for both FEKO and Wait calculations, higher earth conductivity dramatically increases the magnetic field attenuation.

Combining the TTE measurements made in 94 different coal mines by the BOM in the 1970s [6] with uplink field equation (5), we can determine the apparent conductivity of the overburden for each mine. Although the BOM measurements were performed at frequencies ranging from 630 to 3030 Hz, only the uplink results for 630 Hz are given in Fig. 11. As shown, most mine overburdens have apparent conductivity values in the range of 0.01 to 1 S/m.

Fig. 12 shows the normalized vertical magnetic field from FEKO at several different conductivity values at a frequency of 630 Hz for the downlink case. BOM data from a subset of the 94 different mine measurements are represented by the data points in Fig. 12. Although not explicitly shown in Fig. 12, the data seem to imply that lesser overburden depths have higher apparent conductivity values.

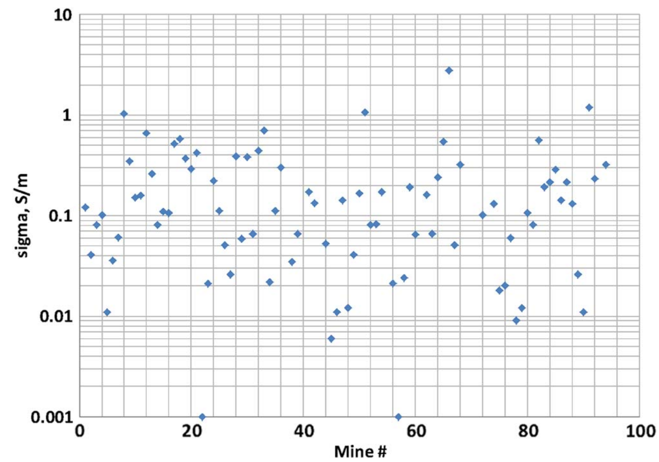

Fig. 11. Calculated conductivity values of 94 mines based on BOM TTE measurement data and Wait's uplink analytical solution. The frequency is 630 Hz.

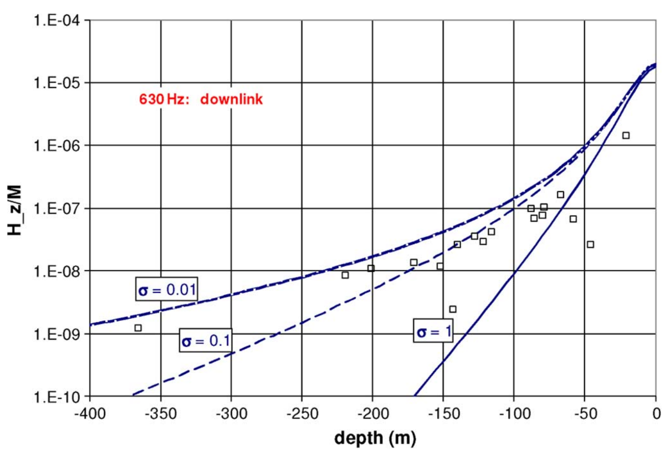

Fig. 12. Normalized field at different conductivity values (FEKO, curves) and BOM measurements (data points).

IV. Conclusion

The vertical component of the magnetic field has been evaluated using Wait's uplink and downlink formulas and FEKO MOM software. The predictions are fairly close. For a given frequency and separation distance, the magnetic fields have the same dependence on the radial direction for the homogenous half-space environment. For both downlink and uplink cases, the fields are about the same order of magnitude if the apparent earth conductivity is not too large; however, it can differ by 10–20 dB for mines that have overburden conductivity values on the order of 1 S/m.

There are nulls that exist as a function of radial distance for both uplink and downlink fields. Those nulls are an artifact of the magnetic flux distribution for a loop or magnetic dipole. Earth (overburden) conductivity values for a series of mines were calculated based on the BOM data. Most of the calculated conductivity values have a value between 0.01 and 1 S/m, with shallower mines appearing to have higher conductivity values. These conductivity values are several orders of magnitude greater than what would be expected from the conductivity values of the materials likely present in the overburden strata. At present, we have no explanation for the difference.

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