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Characterization of Indirect Coupling Mechanisms from Lightning to Underground Cavities

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Introduction

Electromagnetic energy can propagate through solid material as well as through the air. Everyday occurrences of this are transmission of cell phone calls and radio signals through homes and buildings. However, the presence of solid material, in this case hundreds of feet of soil and rock, affects the propagation. When a lightning strike attaches to the ground the current flows in all directions along the surface of the ground and into the soil. Presuming that current flows near the surface of the earth as limited by the skin depth determined by the frequency of the current and the permeability and conductivity of the soil and rock, then electric fields can be induced inside an underground cavity of a mine with no metallic penetration from the outside of the cavity. The methodology used to measure this effect is to simulate lightning current flowing in the earth by connecting a frequency variable voltage source via straight wires on the surface between ground rod fields at either end of the wires. The ground rods are placed a significant distance, approximately 100 m on either side of the region where the electric fields are measured. The electric field is measured over a frequency range from 10 Hz to 100 kHz. At this point we have the electric field in the underground cavity from a known current distribution on the surface. Two steps are involved in calculating the response of a lightning flash attachment at a distance from the cavity. The first step involves modeling the surface current above the sealed area from a lightning flash attachment to the ground at a distance from the sealed area. The second step involves translating the electric field measured from current from a wire on the surface to that that would be caused by a uniform current flow on the surface from a distant flash attachment to the earth. Once these connections are made with data in the frequency domain, then the Fourier transform of the lightning flash can be multiplied by the transfer function and the inverse Fourier transform of the product can be taken to determine the peak electric field that would be caused by a lightning flash attachment of a given amplitude at a given location with respect to the sealed area.

Test Methodology and Configuration

The method used to characterize indirect electromagnetic coupling into an underground cavity is shown in Figure 1. The current from the audio amplifier (which is driven by the output from the network analyzer) is driven on to a long wire above the ground which is terminated at each end with ground rods. The ground rods are placed so as to produce a current distribution in the ground that simulates a linear current drive, which then can be related to the lightning current distribution.

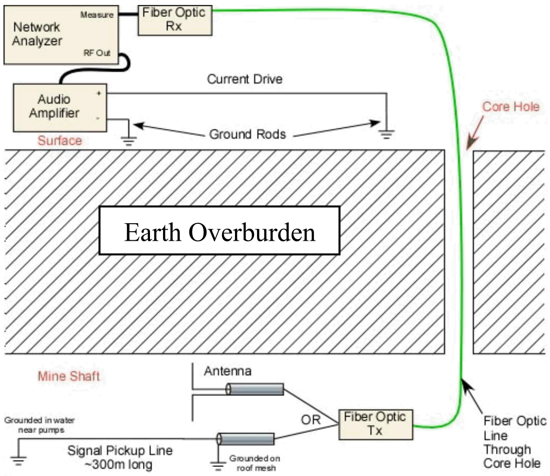

Figure 1 In-Direct Drive Conceptual Drawing.

Two current drives were used for the indirect drive measurements. One current drive was through ground rods placed so as to drive the current parallel to the length of the underground cavity and over the center of the cavity. The surface drive wire was approximately 500 m long. A second current drive was through ground rods placed so as to drive the current perpendicular to the length of the underground cavity. In this case the surface drive wire was only 200 m long.

Figure 2 Sandia dipole antenna in vertical polarization inside underground cavity.

The electric field at various locations in the sealed area of the mine was measured with an active dipole antenna connected to a receiver via fiber optics. The fiber optic receiver is connected to the network analyzer measurement port so that the signals are phase-locked in order to measure very small signals in the microVolt/meter range. The three polarizations of the electric field were measured at a total of 15 locations for both the parallel and perpendicular wire current drives. The positions were P2 through P8 and X1 through X8, where the P stands for parallel to the length of the cavity and the X stands for transverse to the length of the cavity. A photo of the dipole antenna in horizontal and vertical polarization is shown in Figure 2. The locations of the measured electric field where approximately centered around the middle of the current drive and the distance between locations was approximately 10 m. There were 17 total desired locations; however positions P1 and P9 were not measured due to water hazards and time constraints. The three polarizations measured were the vertical, P-directed (parallel to the length of the cavity), and X-directed (transverse to the length of the cavity).

Indirect Electromagnetic Coupling Model

To calculate the electric fields in the earth induced by a current on the surface, the problem is simplified by representing the earth as a homogeneous material with a constant resistivity. The calculations for the indirect coupling model are shown below where the current drive is assumed to be of infinite length and time-varying, as more appropriate for lightning currents on the surface. These results are used to compare to the indirect measurements of the electric field in the sealed area as a function of the drive current on the surface.

Infinite Line Source above Homogeneous Half-Space

The current drive geometry of an infinitely long, horizontal wire placed a distance, h, above a conductive half-space is shown on the left side of Figure 3. A side view is shown on the right side of Figure 3. Similar configurations are analyzed in References 1 through 5.

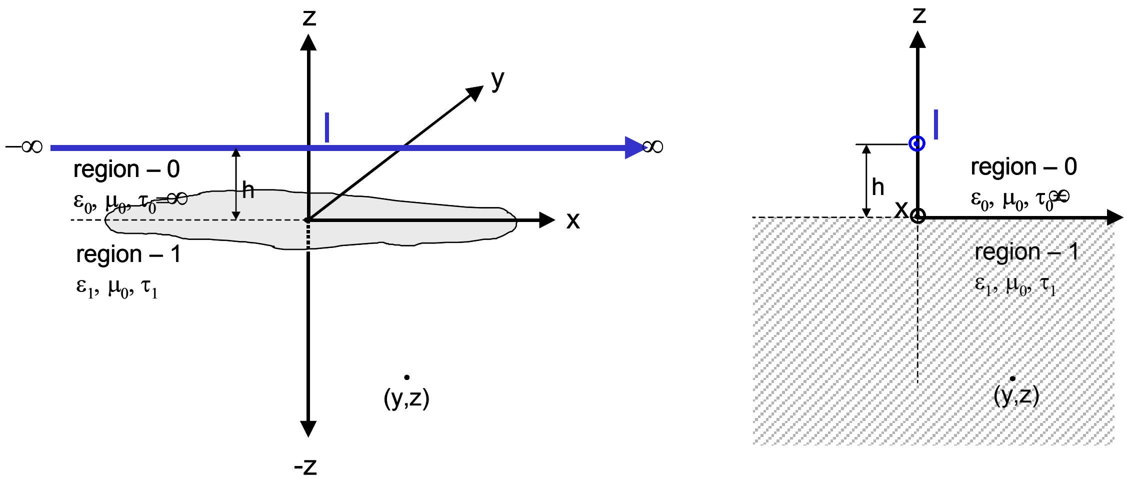

Figure 3 Infinite Length, Harmonically Time Varying Horizontal Current Drive Over a Conductive Half-Space

The current drive is harmonically time varying and is directed along the positive x-axis at height, h, above it. The upper half space has infinite resistivity and the lower half-space has resistivity, τ_1. If one neglects displacement current and relates current density, $i_x(x,y,z)$ and electric field, $E_x(x,y,z)$, in region-1 through, $E_x(x,y,z)=\tau_1 i_x(x,y,z)$, then the current density in the lower half-space, region-1, can be determined to be

$$E_x(y,z)=\frac{ik\varsigma_0}{\pi}\int_0^\infty \frac{e^{qz}e^{-uh}}{u+q}\cos uy\,du$$

where

$$k=\omega\sqrt{\mu_0\varepsilon_0}$$

$$q=\sqrt{u^2+ip^2}$$

$$p^2=\frac{\omega\mu_0}{\tau_1}=\frac{2}{\delta_1^2}$$

$$\delta_1=\sqrt{\frac{2\tau_1}{\omega\mu_0}}$$

Infinite Line Source at Surface of Homogeneous Half-Space

If the line current source is brought to the surface of the conducting homogeneous half-space, where h=0, integrating this result for y=0 to get the horizontal electric field immediately below the current source yields

$$E_x\left(y=0,z\right)=\frac{\tau_1 I}{\pi}\frac{1}{\delta_1^2}\left\{\left[\left(1+i\right)\frac{1}{\left(\frac{z}{\delta_1}\right)}+\frac{1}{\left(\frac{z}{\delta_1}\right)^2}\right]e^{-(1+i)\frac{z}{\delta_1}}-i2K_0\left[\left(1+i\right)\frac{z}{\delta_1}\right]-\left(1+i\right)\frac{1}{\left(\frac{z}{\delta_1}\right)}K_1\left[\left(1+i\right)\frac{z}{\delta_1}\right]\right\}$$

where K_0 and K_1 are modified Bessel functions. Note that we are now using positive z in the downward direction in the formula.

Results

The purpose of the electric field mapping of the underground cavity area was to first look for any field inhomogeneities due to geological features and secondly to compare to the analytical model. The electric field measurements are shown in Figure 4. The electric field results did show an enhanced electric field at the P5 and the X7 locations.

The data collected for the indirect drive tests from the dipole antenna was only usable above 100 Hz. This was due to a very large 60 Hz clutter signal from surrounding power lines and the high noise level from the network analyzer below 40 Hz. Both of these factors could be overcome by reducing the IF bandwidth of the network analyzer from 10 Hz to 2 Hz. The reduction of the IF bandwidth lowers the noise floor considerably and reduced the sensitivity of the transfer function to the 60 Hz clutter, however the time for a single swept measurement increases from ~1.5 minutes to ~10 minutes. Due to time and budget constraints, the higher IF bandwidth was used for the majority of the data collected. As a result, only data from frequencies above 100 Hz are plotted for the dipole measurements in this paper.

The normalized composite electric fields from the dipole antenna at various locations are plotted in this section. The composite electric field is simply the root-sum-square or amplitude of the electric field vector. The measured electric field was normalized by the current in the drive wire on the surface, so that the units are V/m/A.

The normalized electric field inside the underground cavity, due to a wire current drive parallel to the P-direction, measured at locations P2 through P8 is shown in Figure 4. The normalized electric field for X1 through X9 is not shown. Similarly, the fields due to a wire current drive perpendicular to the P-direction, measured at locations P2 through P8 and X1 through X9 are not shown in this paper due to length restrictions.

Referring to Figure 4, note that the composite electric fields measured in a path parallel to and immediately below the drive are about the same amplitude. The presence of metal objects near the antenna affects the local fields somewhat. The measurement at P5 was made in the area between unconnected sections of roof mesh. The slight resonance at about 60 kHz in the P5 measurement was probably caused by a resonance of an abandoned piece of wire cable that was in the vicinity of the field measurements. This cable was not removed for the electric field measurements and high electric fields may have been induced on the disconnected end of the cable at resonance.

The models for diffusion coupling presented in the previous section are compared with the measured electric field. Using an effective soil resistivity of 80 Ω-m, the analytic model plotted in Figure 5 matches very closely the horizontal (P-directed) electric field measured with a parallel current drive. The correlation between model and measured data is extremely good from 10 to 100 kHz. This confirms that the major coupling mechanism from the surface to the sealed area is field diffusion coupling. The measured data is contaminated by 60 Hz resonances and clutter below 1 kHz for this polarization. There is a deviation from the model of coupling beneath an infinite line, at frequencies below 1 kHz, where the measured data stays at a constant level of approximately 0.0006 V/m/A, whereas the analytical model predicts a downward slope. Much of this deviation can be attributed to the field caused by the DC component from the finite spacing of the ground rods. An estimate of this component of the electric field is shown below 1 kHz where the skin depth is much larger than the depth to the measurement antennas.

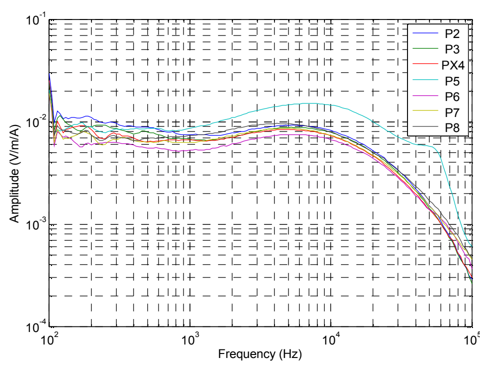

Figure 4 Composite Electric Field along P-direction with parallel line drive on surface.

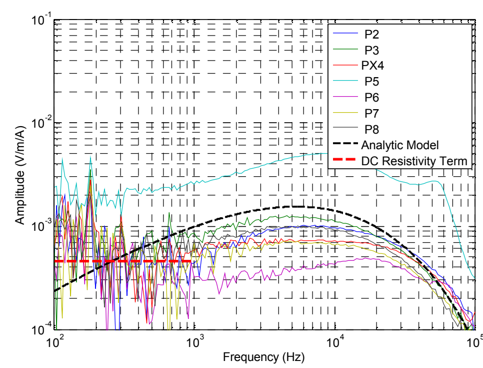

Figure 5 P-directed Electric Fields compared with the diffusion model with an effective resistivity of 80 Ω-m.

Conclusions

This series of experiments

- Very good quality data, well above noise floor
- Influenced by 60Hz and resonance clutter signals
- Clutter can be reduced by decreasing IF bandwidth, which increases measurement time

- Very good correlation between model and measured data.

Acknowledgment

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