Effect of Antennae Polarization Relative to Tunnel Orientation on Electromagnetic Wave Scattering due to Underground Tunnels

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Abstract: Illegal immigrants and smugglers frequently use underground tunnels to avoid border security and checkpoints. In addition, the threat of international terrorism has recently made the effort to detect tunnels a national security priority. No single technology and sensing modality is capable of detecting tunnels in all heterogeneous soils environments. There is a variety of promising technologies and sensing modalities for tunnel detection. However, each of these modalities faces the challenge of balancing the trade-off between image resolution and penetration depth, especially in case of deep small tunnels. Use of broadband antennas at different polarizations with respect to tunnel orientation, seems very promising to overcome this challenge. The goal of this research is to study and evaluate the feasibility of this approach via a 3D simulation using a finite element method (COMSOL) validated by experimentation. Both simulation and the experimental setup are 1/100 scaled. A versatile tunnel detection technology requires above surface transmitting and receiving antennas. However, to avoid surface roughness at this stage, cross-borehole depth profiling approach is used to simulate the above surface reflection and transmission modalities. The soil used in the experiment is dry fine Ottawa sand, which is a very challenging environment to detect air-filled tunnels using electromagnetic-based sensing. PVC-cased ferrite-bead jacketed borehole monopole antennas are sued as the source and receiver for the experiment. Not all the studied cases fit within this paper, and only samples of a few are presented here.

1. Introduction:

In this paper, the challenge of underground tunnel detection, with potential applications of preventing prison escapes, illegal immigration, and drug trafficking is studied. Human and drug trafficking at the border have always been a concern. Real-time monitoring of the ground around the borders and prisons has always been a need. Underground tunnels have also become a homeland security threat recently, especially due to an ever-emerging threat posed by international terrorism. In the past, more than forty clandestine border tunnels have been discovered by the United States border control (Welch 2006).

Previous research has shown a strong potential for tunnel detection using radar with detecting deep and small tunnels as most challenging cases.

Small deep tunnels are extremely difficult to find, due to the trade-off between image resolution and wave penetration depth. However, lower frequency electromagnetic (EM) waves can penetrate deep, and may not be able to discriminate the cross-section of the tunnel; while they may be able to discriminate the infinite length of the tunnel. The goal of this project is to study the effect of antennae polarization relative to tunnel orientation and its use as a tool to overcome the challenge of detecting small deep tunnels. Most tunnels are usually horizontal or slightly sloped, but their orientation may not be known. Therefore, a versatile tunnel detection technology requires above surface transmitting and receiving antennas with rotating horizontal polarizations. At first, the problem is theoretically explored by producing an RF model using a finite element (FEM) by COMSOL-Multiphysics. Then, the results will be validated through the experimental results.

2. Methodology, Experimentation and Simulation:

To experimentally study the wave propagation and scattering in soil surrounding tunnels and eliminate soil-surface roughness, the problem is modeled via a cross-borehole depth profiling approach. Two PVC-cased ferrite-bead jacketed monopole antennas (Farid et al. 2006) are placed vertically across the ground profile and tunnel. Although, this experimental configuration may be most desired, it is not easily practical. Therefore, an equivalent configuration of the setup (Figure 1) is generated by rotating the field configuration by 90 degrees. In this configuration, the horizontally polarized field antennas are equivalent to the vertically polarized ones in the lab (Figure 1). The tunnels placed parallel, inclined (35^{o}), and perpendicular to the plane of the two antennas simulate different orientations of the horizontal tunnel (in a plane parallel to the ground surface and antennas plane. . .

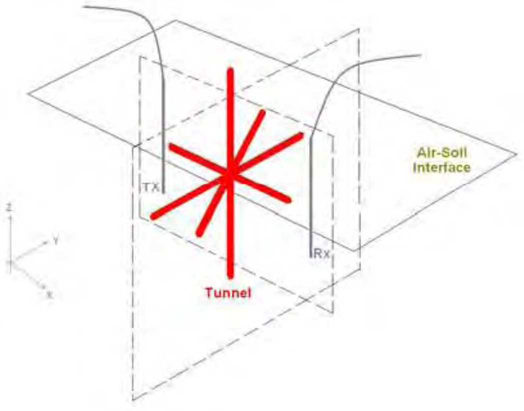


Figure 1. A schematic of experimental setup

COMSOL RF-module is used to model the experiment with a dipole source as the transmitting antenna, which is later placed in spherical PML boundaries of the type spherical as the absorbing boundary condition.

The model uses a vertical ideal electric dipole source (5cm long), which was modeled using the Perfect Electric conductor boundary condition, and the voltage was supplied using the Lumped Port Boundary condition. The (infinitely long) tunnel was placed at x=10 cm parallel to the transmitter. Finally, the magnitude of the electric field was measured at different depths of 13cm through 37 cm at 4 cm intervals at x= 30 cm virtual receiver locations.

A spherical PML (perfectly matched layers) condition was used to absorb waves in all directions to produce a well-defined truncated electromagnetic space. Dielectric properties of air and soil were selected from the COMSOL material library and published values (von Hippel 1954 and Hipp 1974).

The tunnel dielectric constant is 1.0 and conductivity of 0.0 S/m. The soil is described by a dielectric constant of 7.0 and conductivity of 0.001 S/m. The incident radiation source is a vertically polarized ideal dipole emitting EM waves at 1.093 GHz.

Finally, the simulated scattered field is validated with the experimental measurements. A picture of the experimental setup is shown in Figure 2.

In this experiment a small-scale preliminary study of antennae polarization with respect to the tunnel orientation was conducted before the main research (i.e., in the field) in order to check the feasibility and to improve the design of the research. The problem was also theoretically simulated in COMSOL. PVC-cased ferrite-bead-jacketed monopole antennas were installed in the dry fine Ottawa sand parallel to a long vertical PVC-cased tunnel with a diameter of 1”, buried between the antennas, to experimentally simulate an infinite tunnel. The tunnel was placed in a vertical plane, perpendicular to the plane of the two antennas and at first perfectly parallel to the antennas. The tunnel is later rotated at different orientations in the same plane (35 degree and 90 degrees). As for our preliminary work, the data is presented for few cases only. The box was covered with a well-grounded aluminum foil to insulate the experiment from outside, and in order to create an absorbing domain that would serve as a truncated electromagnetic space.

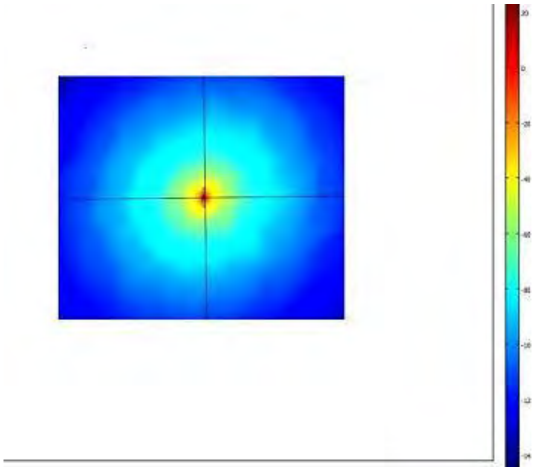
Figure 2. Soil filled box insulated with grounded tin foil

A removable tunnel was filled with soil and air at different incidents, to replicate the closest conditions to the incident (background soil without tunnel) field measurements. The tunnel was then emptied to simulate the case of air-filled void to measure the total (background soil with tunnel) field.

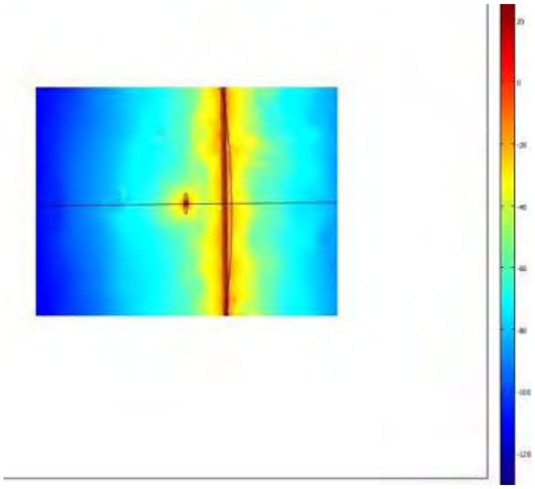
A vector network analyzer (Agilent E5071C) was used to collect the response of the background dry sandy soil with and without the air-filled tunnel. To collect depth-profiling data, the transmitter was kept at fixed depth, while the receiver was moved between the depths of 13 cm and 37 cm. The frequency-response data is measured between 0.3 GHz and 3 GHz (S_{11}: Reflection, S_{21}: Transmission). The magnitude of S_{21} is measured and plotted for the soil with and without the tunnel at a frequency of 1 GHz only, since this is the initial stage in our research and for the sake of assessing the degree of agreement between the COMSOL model and the experimental results. The scattered field due to the tunnel was obtained by subtracting the incident field (soil background without the tunnel) from the total field (soil background with the tunnel). Figure 2 illustrates a picture of soil-filled box and PVC-cased antennas and the tunnel.

3. Summary and Results:

As known, the EM waves propagating through the dry sandy soil are scattered due to the dielectric contrast present between the soil and the air-filled tunnel. This is well visible through the simulation using RF module in COMSOL. Figure 3 shows the incident and total and scattered field (dB) for a case with the tunnel parallel to the antennas.



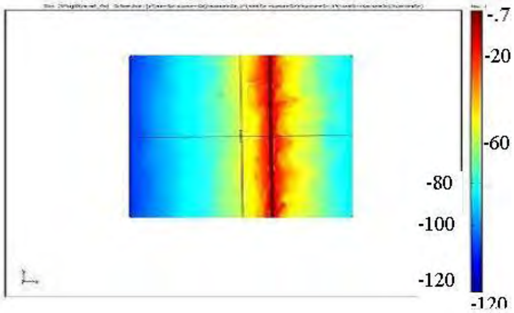
(a)



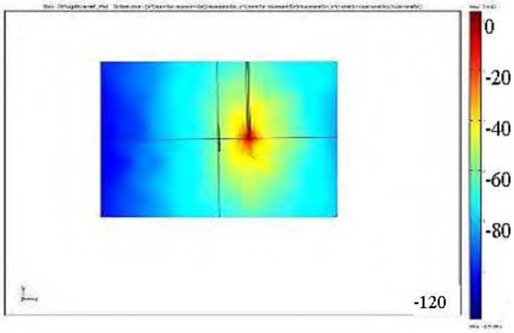
(b)

Figure 3. Magnitude of Y-component (dB) of the electric field from a 30 cm deep source and *f* = 1.093 GHz: a) Incident, b) Total field due to the tunnel at x=10 cm, and c) Scattered field due to the tunnel.

The scattered field can be calculated by subtracting the incident field from the total field. Figure 4 shows the scattered field (dB) for the tunnels respectively at 0° (parallel), 35° and 90° (perpendicular) to the antenna orientation.



(a)



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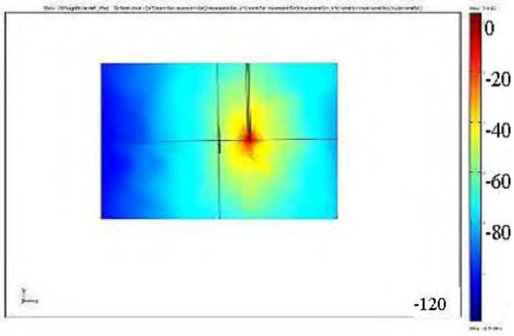
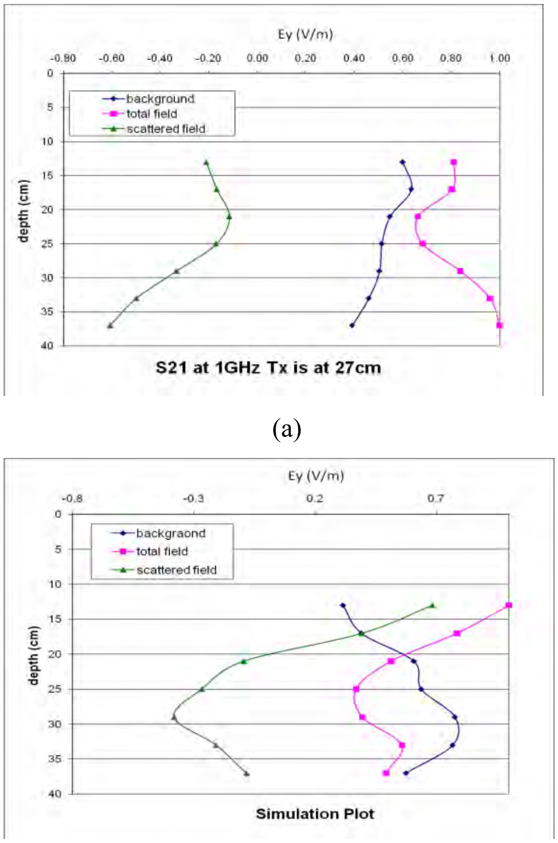


(c)

Figure 4. Scattered field (dB) for a tunnel at different angles wit respect to the antennas polarization: (a) 0°, b) 35°, and c) 90°



(a)

(b)

Figure 5. Incident, total and scattered Y-component of electric field and frequency of f = 1.093 GHz: a) Simulated in COMSOL, 27 cm deep transmitter; and b) Experimentation, 30 cm deep transmitter

Figure 5 shows the vertical (Y) component of the incident, total and scattered electric fields at a single frequency (1.093 GHz) along varying receiver depths (measured experimentally, and simulated using COMSOL). As seen in Figure 4, the peaks of the experimental and simulated scattered-field magnitudes approximately coincide with the depth of the transmitter with respect to the tunnel. Examining the effect of antenna polarization with respect to the tunnel is studied by rotating the tunnel at various angles and measuring the magnitude of the electric fields.

It is seen in Figure 5 that the experiment and the simulations due not agree well. This will be studied with a more controlled experiment.

4. Conclusions

The figures show the fact that the polarization of the antennas relative to the tunnel orientation has a strong effect on the scattered field strength. Therefore, it is most likely that the scattering effect on a low frequency incident field due to a tunnel parallel to the antenna polarization. In other words, while high frequency signals capable of discriminating the tunnel cross-section cannot penetrate deep enough to reach the tunnel, lower frequency signals capable of penetrating very deep (but incapable of discriminating the tunnel cross-section) can detect the tunnel larger dimension (infinite length). The effect of frequency was studied but do not fit in this paper. However, a combination of broadband antennas at different orientations should be capable of detecting small tunnel in deeper layers. This strategy may work for very lossy soil environment such as clayey soils. It is seen in Figure 5 that the experiment and the simulations due not agree well. This will be studied with a more controlled experiment.

5. References

1. Arvin Farid, A.M. ASCE, Jose A. Martinez-Lorenzo, Akram N. Alshawabkeh, A.M.ASCE, and Carey M. Rappaport, "TUNNEL DETECTION USING CROSS-WELL RADAR", 2006

2. Farid, A. M., Alshawabkeh, A. N., and Rappaport, C. M. (2006), "Calibration and Validation of a Laboratory Experimental Setup for CWR in Sand," *ASTM*, Geotechnical Testing Journal, Volume 29, Issue 2, pp. 158-167

3. Welch, W.M. (2006). "In the age of terror, U.S. fears tunnels pose bigger threat." Article in the *USA TODAY*