Electrical Impedance Sensor to Detect Tunnels and Infrastructure in Soil

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Abstract: Tunnels and their detection have been a problem in warfare since the ancient world when they were employed to destroy fixed fortifications and provide secret means of ingress and egress. Recent events have highlighted the ongoing problems of tunnels and the difficulties in locating them, not only in military situations, but also in law enforcement and homeland security applications as well. "The news has recently reported the discovery of tunnels in current U.S. combat zones, under U.S. borders, and under the borders of our allies. Almost all of these tunnels were discovered through human intelligence assets rather than by technology" (Sabatier, 2006). This introduction highlights the national interest in a technology solution to the difficult problem of tunnel detection in unstructured environments. The Sabatier Report also concluded that the ultimate solution will involve sensor fusion and new mathematical approaches. Electromagnetic and acoustic or seismic techniques may provide the significant advantage of a mobile non invasive solution. Surface based sensing of volumetric properties introduces complexity in the form of underdetermined and ill-posed inversion problems. This paper will focus on the forward modeling aspect to the solution of the overall problem.

Keywords: clandestine tunnels, subsurface imaging, numerical methods, forward modeling, impedance sensing

1. Introduction

The overall objective of the NSF project funding this work was to extend the utility of electromagnetic sensors for detection of underground tunnels. A detailed forward model would be used to design and optimize the sensor configuration and provide simulated data to validate a new shape based inversion approach. The forward model would be detailed enough to simulate the "real world" spatial noise sources (clutter) that typically provide the practical limitations to the technology. This paper will describe the methodology used for sensor design and optimization as well as the approach taken to model the tunnel and soil in a realistic way to facilitate validation of candidate inversion algorithms.

1.1 Sensing Requirements

A typical clandestine tunnel may be up to one meter in diameter and up to 7-10 m. deep. While larger and deeper (up to 30 m.) have been found, they are rare. Therefore, this study addressed the common tunnel configuration. In a typical application, such as locating clandestine tunnels across a border, the desire is for a mobile, covert (non-invasive) method for identifying "probable tunnels". Boreholes are then made to confirm or refute the tunnel's existence. The sensor must either operate at a sufficient standoff from the surface not to be affected by surface clutter (roughness and surface objects such as vegetation, fallen trees, etc.) or conform to the surface.

1.2 Sensor Configuration

The most practical configuration for the desired sensor is a ground hugging 1D multi-element geo-referenced sensing array. The 1D array would be scanned over the surface to produce a 2D array of data over suspected tunnel locations. The 2D surface data would be inverted to produce a representation in 3D of anomalies in the subsurface volume.

2. Theory & Modeling Approach

For tunnel detection, two simplifications to Maxwell's equations can be made resulting in a quasi-static formulation. First, the soil is considered to be a lossy dielectric with unit permeability. Second, the wavelength of the electromagnetic excitation used is large compared with the sensor/media geometry features. Therefore the coupling between the electric and magnetic fields can be ignored and the governing partial differential equation is:

$$-\nabla \cdot \left((\sigma + j\omega\varepsilon_0)\nabla V - \left(J^e + j\omega P\right)\right) = 0$$

where σ, ω, ε, *V, J, P* are the conductivity, angular frequency, permittivity of free space, electric potential, current density, and polarization respectively. The soil specific permittivity and conductivity will be modeled as empirically defined functions of frequency (f) and vertical spatial location σ (z, f), ε(z, f).

Other aspects of the sensor/soil interaction, such as surface effects and bulk inhomogeneities and the tunnel objects will be modeled using spatially dependent permittivity and conductivity functions.

COMSOL Multiphysics has developed the *emqvw* "small electric currents" application mode for this type problem in which the field strength is small and the response is linear. For improved resolution, the highest frequency that provides adequate penetration and sufficient field intensity (using relatively inexpensive components) will be used. At 200 kHz, the skin depth is ~50 m and inexpensive integrated circuits are available the will produce sufficient excitation voltage.

3. Model Geometry

The expectation for the tunnel detection application is that signals will be on the edge of detectability. As a result, possible sources of modeling errors had to be identified and minimized.

3.1 Model Dimensionality

Due to the ill-posed nature of the tunnel detection application, inversion methods will be sensitive to and magnify high frequency noise. Initially, it was decided to model the problem in 3D using fine enough mesh density to reduce solution variability to below the expected sensor resolution. When modeling in 3D using fine mesh granularity, computational burden (both speed and memory usage) can quickly increase to impractical levels. Even using Version 3.4 multi-core solvers and preconditions on a dual core machine, the solution time for a single solve for one tunnel size and location combination was 540 seconds. As ~2000 solves were required to simulate a complete scan of the sensor over the tunnel for the range of tunnel diameters and depth, over 12.5 days would be required to generate one forward dataset. Many datasets would be required to simulate candidate sensor configurations and soil surface and volumetric inhomogeneities. As a tunnel has nominal symmetry along its axis, it is tempting to consider a 2D slice through the tunnel. Two of the expected spatial noise sources (layering and surface effects) are horizontal structures and therefore would be captured in a 2D slice through the tunnel orthogonal to the tunnel axis. The third noise source, large inclusions (such as rocks) require 3D to model rigorously, a 2D slice was felt to provide an idea of the magnitude of the perturbation to the inversion that inclusions might induce. As a result, it was decided that using 2D simulation would be sufficient for the initial feasibility evaluation. The solve time for the 2D model was reduced to 2 seconds per solve for a total of just under 2 hours per dataset.

The proposed 1D sensing array consisted of a 15cm x 15cm planar transmit (Tx) electrode and three similar sized receiver (Rx) electrodes. Tx to Rx separation is 3 meters while Rx to Rx separation is one meter. Shield electrodes confine the field in the air above the sensor. Field director electrodes direct the electric field to penetrate deeply into the soil. This configuration was developed by scaling designs from previous applications and using the qualitative results from the forward model to improve the configuration for penetration, resolution, and sensitivity. Figure 1 depicts the sensing geometry.

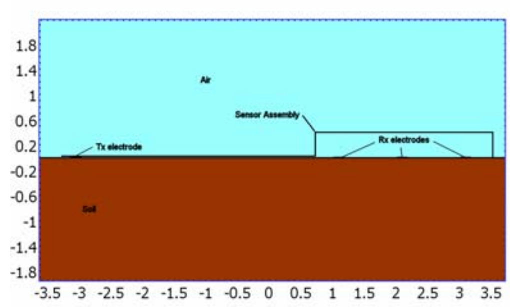

Figure 1. Tunnel Sensor Geometry

Critical portions of the measurement circuitry external to the sensor were modeled using the *Spice Import* feature in the **Physics** menu. The output of the model is the measured complex voltage on each of the Rx electrodes. Using this approach, the model outputs can be assessed against known electronic noise sources (wideband and quantization). This assessment provided an indication of whether the electronics sensitivity and selectivity needed to be improved for this application.

4. Modeling Challenges

In sensing problems with expected signals at the limit of detectability, proper selection of boundary conditions, meshing strategy, and mesh density can significantly influence the computational results if not correctly specified. In this task each of these issues was evaluated with known cases to assess the influence on accuracy for detecting tunnels.

4.1 Model external boundary conditions

When solving open boundary radiation problems using the finite element method, the computational domain must be truncated with an artificial boundary to limit the computations required. The truncated boundary must be terminated in such a way that the solution is not changed by any artifacts introduced by the boundary conditions on the truncated boundaries. In initial modeling of the tunnel detection problem, it was observed that the electric field did not decay to zero far way from the excitation as must happen to conserve the energy in the system. In order to permit model truncation without the introduction of artifacts, absorbing boundary conditions have been developed (Zienkiewicz, 1983). For electrical impedance problems, the effect is equivalent to a ground plane at infinity. The COMSOL AC/DC module has implemented the infinite element layer (IEL) boundary condition to address this situation. To use the IEL technique, a series of sub-domains are built completely surrounding the model adjacent to the desired physical extent of the computational domain. The IELs are initialized using the "*Infinite Elements*" tab in "*Subdomain Properties*". The model geometry show in Figure 1 was tested with and without IELs. Without the IELs, the electrical potential was observed not to decay to zero as expected at large distances from the sensor electrodes.

4.2 Meshing effects

Finite element modeling (FEM) techniques used a discretized version of the problem space for computation. The meshing process breaks up the solution space up into discrete computational nodes using various strategies to maximize accuracy using the smallest number of mesh points. For any particular model, there will generally be a minimum mesh density and optimum mesh strategy that will produce the required accuracy with minimum computational burden. In the current project, the forward model will be used to predict the sensor data to be used by the inversion algorithms. In operation, the sensor will be scanned in two dimensions over a suspected tunnel. To simulate the scanning in the forward model, the model is solved for various positions of the tunnel with respect to the sensor. Each time the tunnel is moved in the model a new mesh results with a new set of computational nodes that will in general be different from the previous set. This variability in the computational mesh can be a noise source. This potential modeling noise, which will not exist in real sensor data, may influence the results obtained by the inversion algorithm. In this activity the meshing density and strategy will be optimized to so as not to influence the inversion algorithm.

It was found that a global selection of "*extra fine*" in the *Free Mesh Parameters* dialog box was required for the mesh density not to influence the measured voltages. In addition, an additional mesh refinement was required in the region through which the tunnel was moved to provide a smoothly varying output. The resulting model had 144,000 DOF in the solution.

5. Model Validation

The current application has neither an analytic solution nor a prototype sensor for model validation. A twofold approach was taken to assess the reasonableness of the model output. First, extensive experience with surface based capacitance systems was used by analogy. In these systems, used to sense material properties, COMSOL *emqvw* models and actual hardware produce very similar results (Gamache, 2007). In addition, use of the forward model described here with the inversion algorithms developed in this project provided and end-to-end validation. For this validation, the forward model produced simulated sensor data (for various tunnel and clutter conditions) that was then used by the inverse algorithm to reconstruct the tunnel. The RMS error between the modeled tunnel and the reconstructed tunnel was taken as a measure of performance of both the forward model and the inverse algorithm. To establish a baseline for evaluation of the effects of noise, surface, and volumetric inhomogeneities, a series of runs were made at ~2000 combinations of tunnel location (x), depth (y), and radius (r). For the baseline runs, the soil surface was flat and the soil homogeneous. For a typical case with (x,y,r) = (0,-2,0.5), the difference between the reconstructed tunnel and the model was (0.0041, 0.0004, 0.0021) m. While this is not an independent validation of the accuracy of the model, it does indicate that noise introduced by the model itself is very low.

Figures 2-4 show the predicted values of the sensed voltages for parametric scans of tunnel horizontal location, depth, and radius.

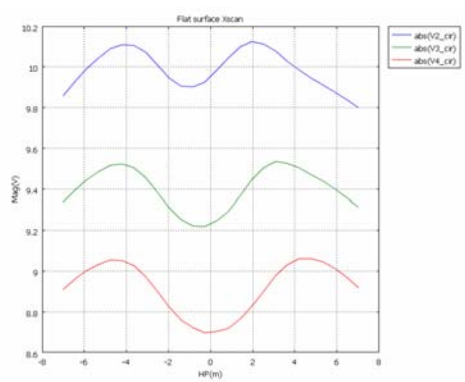

Figure 2. Tunnel Position Scan

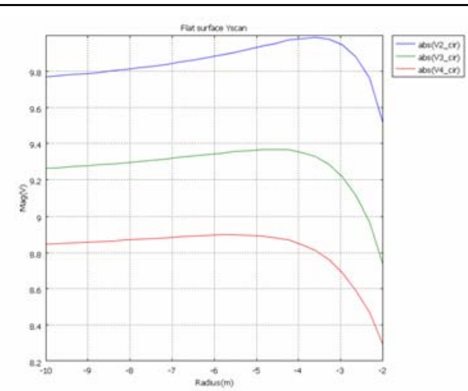

Figure 3. Tunnel Depth Scan

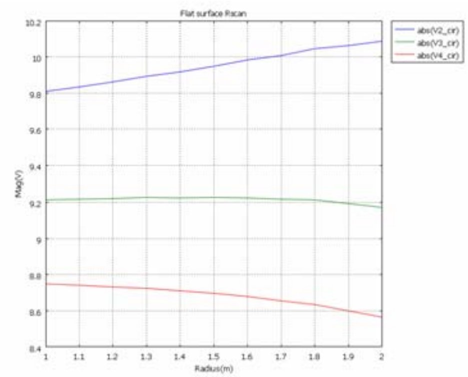

Figure 4. Tunnel Radius Scan

6. Modeling the Clutter

6.1 Surface clutter

The practical limitation of surface based electromagnetic sensing applications is generally not the technology itself but rather the spatial noise associated with the non-uniform soil medium (layering, water table, in-homogeneities (rocks, organic material) and the typically rough surface. In microwave applications (for example mine detection), the surface is particularly troublesome due to the similarity of the radiation wavelength, surface features, and the objects under detection (Gamache, 2006). Surface roughness was modeled by placing a square wave shaped surface with variable amplitude and spatial wavelength between the sensor and the soil below. Solutions for the baseline tunnel scans were compared with data from simulation of the rough surface to determine the limits of performance of the inversion algorithm. The wavelength range (0.4-4.8 in.) and the peak amplitude range (0.125-1.5 in.) were chosen to reflect an estimate of the soil surface that would not be in contact with the proposed conforming sensor.

For the case of tunnel detection, use of wavelengths much larger than both the tunnel and any likely surface features was expected to minimize scattering, but at the loss of spatial resolution. Spatial resolution would be recovered using a 1D array of sensors scanned in 2D over an area of interest combined with a shape based inversion to reconstruct the definition of the objects of interest. For a typical case with (x,y,r) = (0,-2,0.5), the difference between the reconstructed tunnel and the model was (0.063, 0.0084, 0.0048) m.

For the case where the wavelength is large compared with the features of the surface roughness it is expected that the primary difference between the reference scans and the rough surface scans will be a simple offset. The rough surface is expected to produce a response equal to insertion of an air gap equal to the peak amplitude of the roughness. This is in fact what was seen. A simple offset is expected have no effect on the inversion algorithm. What is of interest, then, is shape differences from the flat surface case that may cause error in the inversion. To visualize the shape difference, the offset is removed and then the difference plotted. Figure 5 is an example of a difference plot for the case of a tunnel position scan. The variation observed is barely above the expected noise level of the system of 0.02 dB.

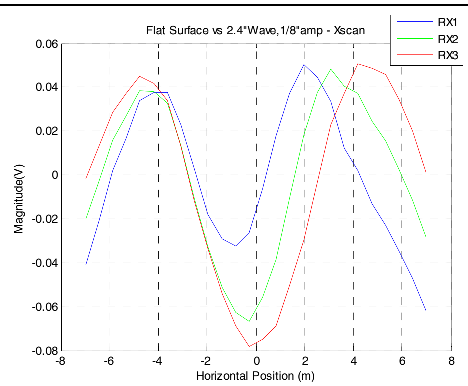

Figure 5. Rough Surface Effect

6.2 Volumetric clutter

Volumetric clutter can be due to geologic layering, variable saturation and water table location, as well as inclusions, such as voids, large rock masses, buried infrastructure, or organic material. Horizontal layered structures were modeled by setting the permittivity and conductivity to expressions of the depth variable, y, in *Subdomain Properties*. A common and distinct horizontal discontinuity present in soil is the water table. For some soils, the permittivity and conductivity changes associated with the water table will occur over a narrow vertical range. For other soils, the transition will be much more gradual. Both cases were simulated to cover the expected extremes. All the combinations of the tunnel parameters (x,y,r) previously conducted for the baseline were run with a range of positions of a sharp water table transition from 0-16 m below the soil surface. A second set of data was developed with a gradual transition from saturated to 30% saturated over the 16 meter depth range. Difference plots were made of all runs to determine the cases with the largest differences. An example, for the case of variable tunnel depth is shown in Figure 6. The variation due to layering is much larger than for the rough surface. The data for those sets were then processed by the inversion algorithm to assess the influence on the reconstructed tunnel parameters. For the diffuse transition case, the error varied from (0.01, 0.0006, 0.0087) for the transition 5 meters below the surface to (0.06, 0.03, 0.03) with the water table at the surface. The results for the sharp transition cases were poor with many instances of lack of convergence.

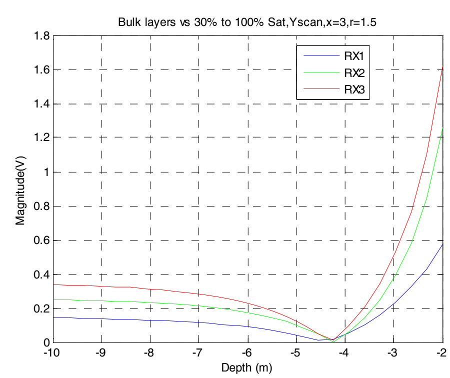

Figure 6. Diffuse horizontal Gradient Effect

7. Discussion & Conclusions

The capability to sense hidden objects within dielectric media using surface electromagnetic probing is an area of great research interest and social significance. Applications under current investigation range from cancer cells within the human body to mines, explosives, and tunnels within the soil. Electromagnetic, acoustic, and seismic methods have the significant advantage of mobile, non-invasive probing. Improvements to electronics, sensors, and computational methods are required to realize the true potential of these technologies.

COMSOL Multiphysics has been shown to be an effective tool to develop, design, an optimize sensors for tomographic measurements in dielectric materials.

8. References

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