# Remote Sensing of Electromagnetically Penetrable Objects: Landmine and IED Detection– (RSEPOLID)

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**Abstract:** The detection, characterization, and classification of underground environmental hazardous objects [mines, IEDs, and other unexploded military hardware] is a worldwide problem that needs urgent attention and solution. While electromagnetic sensor technologies have been applied to identify these hazards, increasingly low dielectric contrast between newer, sophisticated landmines, and complex surrounding soil geometric in-homogeneities acts as an increasingly major impediment to successful detection. The present study investigates the use of the Finite Element Method software COMSOL Multiphysics to model the propagation of electromagnetic waves introduced into the computational domain non-invasively. Four quantities of interest were investigated and analyzed numerically: depth, size, soil moisture, and frequency of incident waves, and the template generated by this research can be used to more safely determine vital feedback about buried IEDs to perform a more informed and successful demining process.

**Keywords:** Landmines, Subsurface, Detection, IEDs, Sensing

## 1. Introduction

The detection, analysis, and characterization of subsurface objects, especially landmines and other Improvised Explosive Devices (IEDs), has been a very important goal of the international scientific community in recent years. IEDs pose a lethal threat to innocent civilians, and have a detrimental and destructive impact on infrastructure in third world countries [1-18]. In fact, landmines pose this threat to over 70 countries around the world, two-thirds of which are some of the world's poorest nations, while innocent civilians in these countries, 40-50 percent children, are killed or maimed by these explosives [19-20, 21-24]. In addition, the cost to remove landmines ranges from $300 to $1000, making cheaper removal of IEDs in developing nations increasingly important [25].

### 1.1 Subsurface Sensing

Subsurface sensing and imaging is the noninvasive recovery of shape and topological characteristics of an object buried or embedded within a dielectric region. Electromagnetic imaging technique involves propagating electromagnetic waves of known frequency and amplitude on the computational geometry, measuring the fields scattered by the dielectric surface and the object, and quantifying the electromagnetic parameters of the scatter [25].

### 1.2 Current Detection Problems

In recent years, current subsurface detection technologies and methods, invasive and expensive, have grown obsolete and inaccurate as landmine cloaking technology advances [26]. Landmine technological improvements are impeding the successful sensing rates of traditional Ground Penetrating Radar (GPR) techniques and thus, a new means of detecting and identifying subsurface hazards through variations in the current electromagnetic wave scattering models is paramount to keeping up with this increasing sophistication. Many studies attempt to use Finite-Difference Frequency-Domain simulation technology to create computational templates for real world GPR data comparison, but FDFD methods are often flawed [27-33]. This research studies an alternative approach, Finite Element Modeling (FEM) in COMSOL Multiphysics, to simulate real world environmental situations to study IED scattering more accurately [34,35].

### 1.3 Objective

By generating this template of various situations involving subsurface sensing, variations and trends concerning GPR IED scattering can be better understood for implementation in actual real world landmine detection applications. The present study examines numerous simulations of many real world situations, especially those concerning the variables of GPR wave frequency, depth and



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shape of IEDs, ground moisture content and composition, and other relevant variations in hypothetical real world situations as modeled and tested in COMSOL. By developing graphs of the amplitudes of various reabsorbed backscattered waves for comparison of the interference and scattering effects of varying mediums, a more intelligent and versatile subsurface sensing template for real world detection and removal can be generated.

## 2. Methods

### 2.1 Model Development

The first step in developing a simulation to correctly portray a real-world environment is defining the geometry and shapes of the objects to accurately represent actual aspects of the real world buried landmine scenario. A basic 2D geometry was defined with the real-world dimensions of target objects and boundaries to differentiate the basic mediums involved in scattering. A homogeneous soil surface is adopted as a representative model because of its modularity and relevance to simple landmine detection applications. However, in order to account for the numerous surfaces with multiple disparate layers of earth, two homogeneous soil surfaces were defined in certain models.

### 2.2 Use of COMSOL Multiphysics

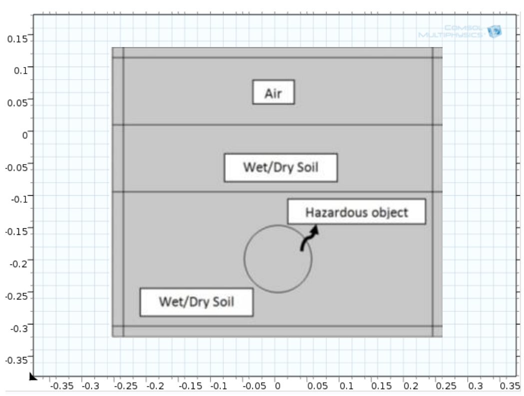


**Figure 1**. A 2D model used for the computational domain. The top domain is air and the bottom domain is the soil. The circle in the bottom domain represents the IED.

In order to more accurately simulate real world conditions, the geometry was surrounded by layer subdomains on all sides as seen in the model in Figure 1. These subdomains were defined as Perfectly Matched Layers (PMLs), absorbing layers with qualities that insure that incident waves would not be affected by the enclosed boundaries of our limited simulation size [36]. By absolutely reabsorbing all incident waves, the domains allowed our simulation the properties of infinite boundaries, completely removing all traces of reflection that would otherwise interfere with the scattering pattern results.

Finite Element Modeling was implemented for the successful and efficient modeling and testing of the entire complex solution over the larger environment domain without compromising an accurate geometry with disparate material properties and excellent representation of the original simulated environment. The COMSOL Multiphysics triangular meshing algorithm was set on every subdomain. Environment subdomains and PMLs were meshed to a resolution of just under the set wavelength used in the smallest iteration of the study's parametric sweep, while the landmine subdomain was meshed to a significantly finer resolution, with the max element size of 0.05 meters, as to maintain maximum scattering interaction surfaces akin to those a wave would encounter in the real world.

In order to attribute correct electromagnetic characteristics to each domain different microphysical parameters were set in regard to the real world properties shared by their respective material. The optical properties of the soil and the other materials were characterized by the absorption and scattering coefficients. The scattering of the electromagnetic radio waves from the transmitter is completely dependent on the microphysical parameters and properties of each material in a real world land mine environment. Since both the ground and the landmine in any situation can vary drastically, therefore significantly varying in microphysical properties, different transmitted and reflected signals for each situation will be returned to the receiver. Such differences in scattering patterns from the electromagnetic waves sent into the model geometry or any real world GPR sensing environment allow the identification of the chemical composition of detected anomalies underground as well as the structure and other characteristics of subsurface objects. The microphysical properties that scatter waves include relative permittivity, relative permeability, and conductivity. The properties of air, TNT, and the variables of dry soil and wet soil that were implemented are listed in Table 1.

| Material | Relative permittivity | Relative permeability | Conductivity |
|---|---|---|---|
| **Air** | 439.2 | 1 | 0 |
| **Dry Soil** | 1273+31i | 2.9 | 0.004 |
| **Wet Soil** | 1756+395i | 4 | 0.049 |
| **TNT** | 2.9 | 1 | 4.8e-4 |

**Table 1**. The microphysical parameters of all used materials [23,37]

After establishing the basic computational geometry with accurate dimensions as illustrated in Figure 1 and setting basic boundary conditions and microphysical properties, the position and size of the target landmine object was parametrically adjusted to account for real world variations applicable to predicted mine type disparities. Microphysical parameters of different environmental domains were also adjusted to test the variable of soil moisture content in various layers. Different combinations of various moisture layers were also tested.

The Electromagnetic Waves, Frequency Domain (emw) module in COMSOL was used as the computational physics present in the simulation with the Frequency-Domain Model study. A parametric sweep stepping every 0.5 GHz starting at 0.5 GHz and stopping at 3.0GHz was preset in the Frequency Domain Model study to run with every environmental adjustment test. This would allow educated selection of the optimal frequency for detection in every situation.

Thus, the key independent variables of this work were variations in the sensing scenario around the landmine. These variations included details regarding differences in ground moisture content, geometry specifications, such as depth and size of the landmine targets, and frequency of incident GPR waves, all which were modeled or parametrically set, simulated and analyzed to receive final scattering results.

### 2.3 Wave Physics and Governing Equations

Waves were introduced into the computational domain non-invasively, as to not cause unnecessary uncertainty with the scattering results. A transverse electric (TE) wave applied in the physics propagated in the z direction, while various frequencies, ranging from 0.5-3.0 GHz were tested in a parametric sweep. The physics of a plane wave were set in COMSOL in accordance with the Plane Wave Equation (1).

$$E_o = \left(0, 0, e^{ik_0 y}\right) \quad (1)$$

In order to study the scattering results based on microphysical parameters, the partial differential equation known as the Helmholtz equation (2) was coded in MATLAB syntax and imported into the COMSOL Radio Frequency Module. COMSOL's Eigenvalue Frequency Study, using this equation derived from Maxwell's Equations, produces a Radar Cross Section (RCS) which quantifies the scattering effects of the various objects in the simulation. The RCS is a product of five main factors, all preset in the COMSOL Multiphysics simulation, including projected cross section, reflectivity, directivity, contrast between the target and the background, materials, and the shapes of the landmine and the ground surface.

$$\nabla^2 \vec{E} + \mu_r \mu_0 \varepsilon_c \omega^2 \vec{E} = 0 \quad (2)$$

For the 2D case, the Scattering Parametric Equation (3) which solves for the Scattering Width (SW), or alternatively, the RCS per unit length, was implemented in COMSOL through the use of MATLAB syntax.

$$\sigma_{2D} = \lim_{\rho \to \infty} \left[ \frac{\left|E_s\right|^2}{\left|E_i\right|^2} \right] \quad (3)$$



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## 3. Experimental Results

The received amplitude of scattered wave field graph surfaces from the Scattering Width Equation show that, as expected, when the target's depth increases, the scattering effects become increasingly negligible. The depth-to-scattering ratio shows a clear correlation to the soil's interference with the wave.

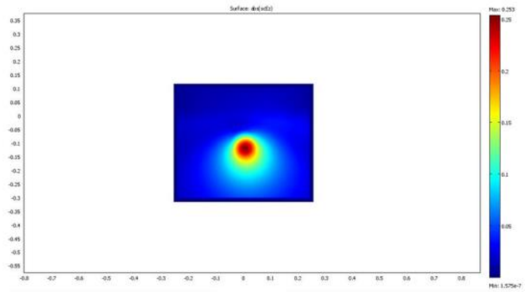

**Figure 2:** Wet Soil (1GHz, TNT Radius 5 cm)

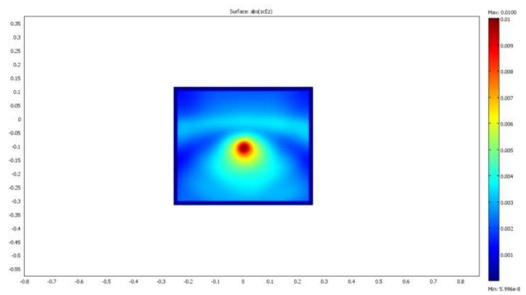

**Figure 3:** Dry Soil (1GHz, TNT Radius 5 cm)

As shown by comparison between Figures 1 and 2, dry soil has more interference with the Radio Frequencies (RF) than wet soil because wet soil is more conducive to scattering due to its higher conductivity, a product of its higher water concentration. The higher conductivity allows the Radio Wave's energy to stay in the medium and waves to interfere more with the target object than the medium itself.

Additionally, size of landmine directly correlates to the amount of scattering. When doubling the radius of the landmine, as shown in the graph above, the scattering results of the central target area increased, showing a much higher scattering sensitivity.

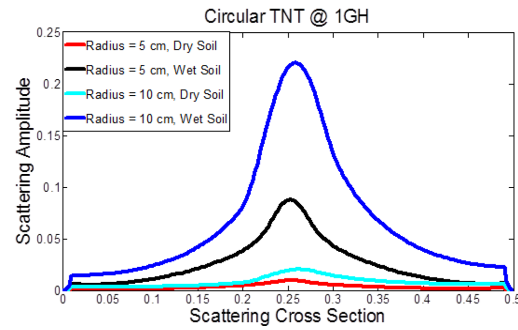


**Figure 4:** This graph quantifies the result surfaces shown above (including the additional variable of landmine diameter) on a linear scale for better comparison.

In addition to two main independent variables studied, including the size of landmines and the soil types involved, the depth of the landmine directly correlated to the amplitude of scattered wave reabsorbed. As expected, TNT from higher up in the domain produces the highest amplitude of scattered waves and is most easily detected.

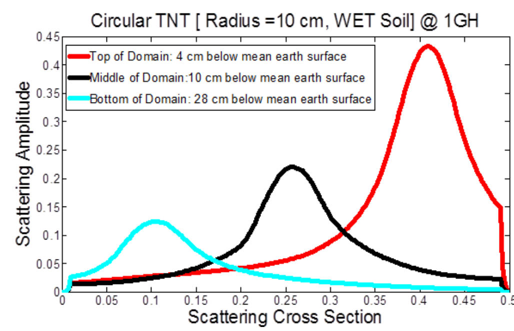


**Figure 5:** Another linear scaled cross section of scattering amplitude based on various depth of landmines

The parametric sweeps run with each simulation to test the various efficacies of different potential GPR frequencies, produced notable results, especially regarding tests with simulated environments of varying ground layers of different moisture content. As seen in Figures 6 through 12, Air/Wet Soil/ Dry Soil model layering produced the most scattering and notable diffraction and interference patterns. Additionally, for most models, the 2GHz incident frequency was significantly superior in regards to the accurate and maximum sensitivity of the scattering amplitude signature from

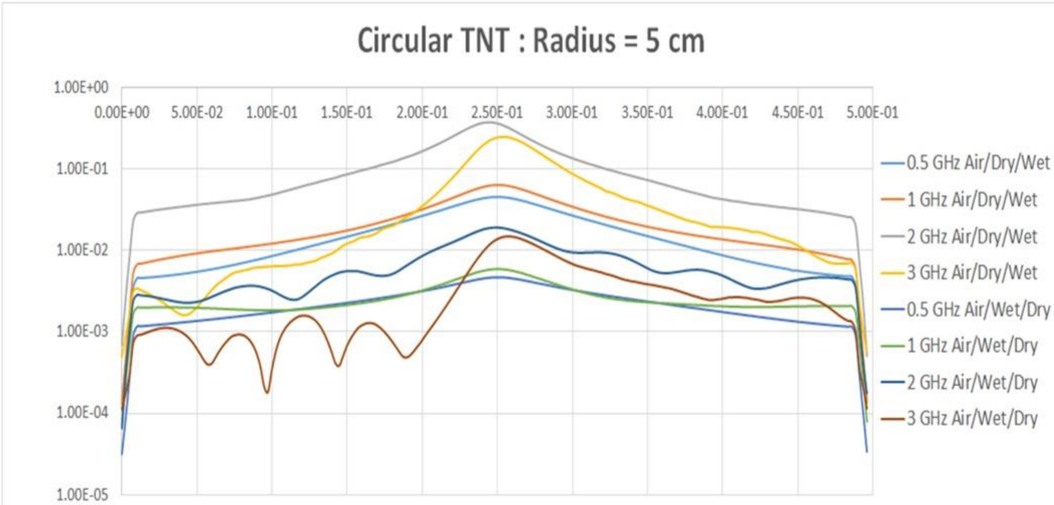


**Figure 6:** Comparison of scattering profiles for the Air/Wet/Dry model and the Air/Dry/Wet model at different frequencies.

landmines. A 2GHz incident wave that produces a 15cm wavelength would be understandably apt to pick up on anomalies, considering the similar dimensions of a landmine and its depth underground (a distance the wave would have to travel through).

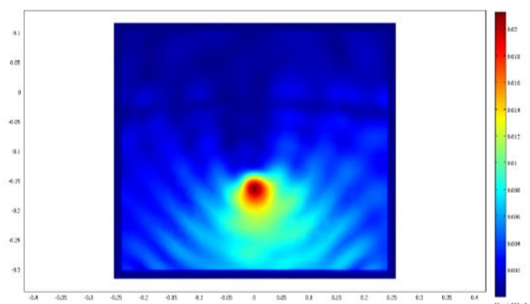

**Figure 7:** Air/Wet Soil/Dry Soil model's absolute scattering map from the results of a 2GHz wave directed towards a 5cm circular target mine.

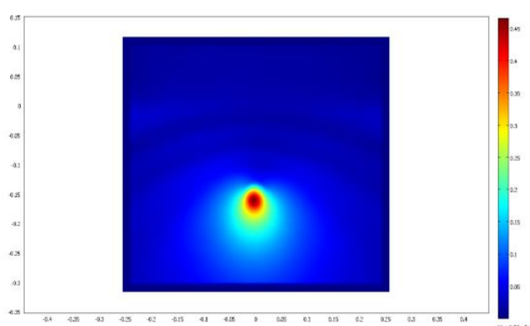

**Figure 8:** Air/Dry Soil/Wet Soil model's absolute scattering map from the results of a 2GHz wave directed towards the same 5cm target mine for comparison.

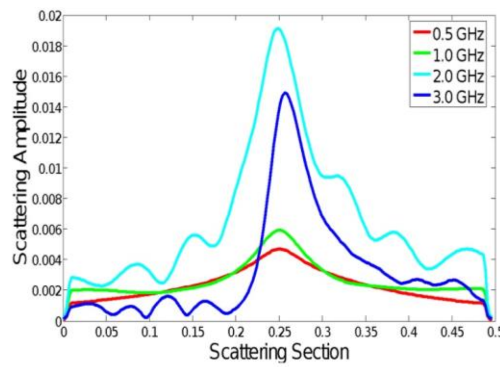


**Figure 9:** Scattering amplitude cross section from the results of our parametric study at different frequencies for the Air/Wet Soil/Dry soil model in Figure 7.

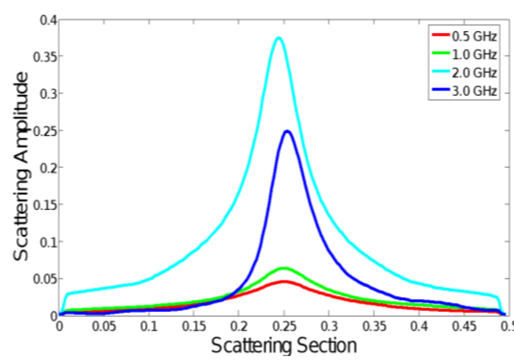


**Figure 10:** Scattering amplitude cross section from the results of our parametric study at different frequencies for the Air/Wet Soil/Dry soil model in Figure 8 for comparison.

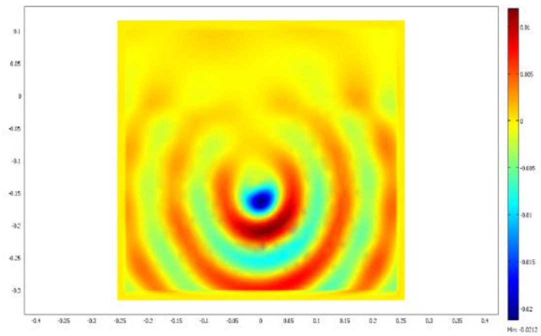

**Figure 11:** Air/Wet Soil/Dry soil model in Figure 7's scattering amplitude model map.

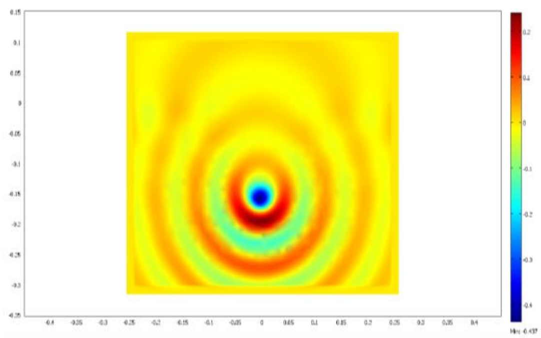

**Figure 12:** Air/Dry Soil/Wet soil model in Figure 7's scattering amplitude model map for comparison.

## 4. Discussion

Through this study's simulation in COMSOL Multiphysics, the observation of any desirable portion of the earth feeds a remarkable amount of insight into creating a template that can be used to sense hazardous objects for real life applications. Although the specifications of landmines can be different, by predicting the probable results of all other variables in real world situations we can be more prepared for real life application where we can apply this study's template, reducing unknown influences and unaccounted for variables so the detection of these harmful objects is inevitable. By simulating such models with all variables accounted for in TNT and landmine type real world applications, this present template accounts for most variables that would be present in numerous other subsurface imaging applications. Examples abound and include: searching for organic archaeological artifacts with close microphysical properties to soil, (a similarly decomposed organic material), to finding pipes made with all different materials and filled with various fluids in construction technology.

In addition, the data of frequencies more compatible with certain soil types is another important extrapolation from the research that adds additional value to the subsurface imaging template that was generated. For instance, in the Radar Cross Section fields shown in Figure 4, the interference between electromagnetic waves of 1GHz and various moisture types of homogenous soil can be clearly distinguished. In order to assure incident waves propagate through air and soil with minimal interference, the correct wavelength must be applied to the situation so the true scattering pattern of the target object can be observed.

For future research, potential goals will include changing the microphysical properties of the soil to account for different compositions (e.g. clay, sand, silt), as well as simulating different explosives in COMSOL (e.g. RDX, Composition B, C4, Tetryl, etc.). The surface type of the soil, regarding angle of incidence on a slope, bumpy surface, and levels of ground roughness, could also be further investigated.

## 5. Conclusion

The objective of this project was to create a comprehensive template for the remote subsurface detection of Landmines and IEDs to negate the detrimental impacts of buried explosives on the international community. The present parametric study resulted in a successful creation of a template to study the effects of various environmental conditions and situations to compare real world GPR data to. By developing this template and understanding more about how landmines interact with radio waves, the goal of this study is to further knowledge about GPR sensing for explosives, and add to the worldwide effort to demine hazardous civilian environments across the globe.

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