Remote Sensing of Subsurface Electromagnetically Penetrable Objects: Landmine and Improvised Explosive Device Detection

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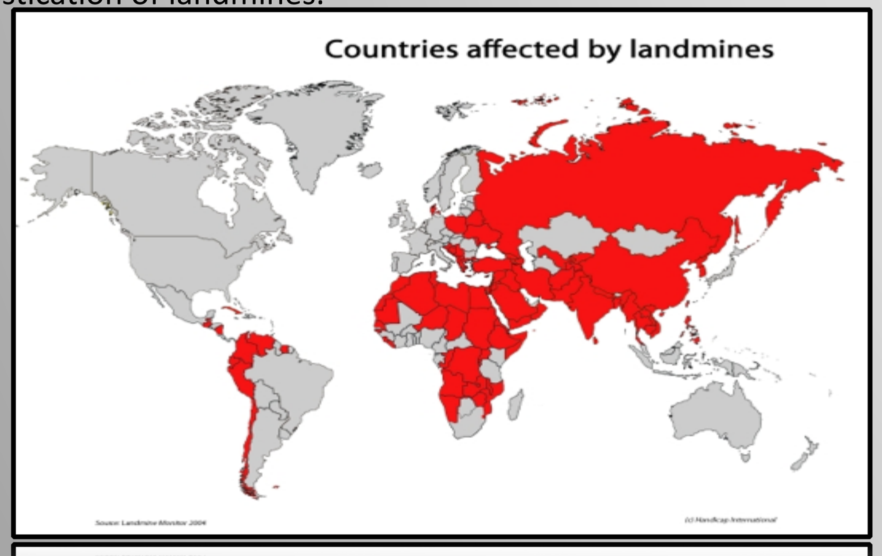
Abstract

The detection, analysis, and characterization of subsurface objects have been an active area of research of the scientific community in recent years. Current subsurface detection technology and methods are invasive, expensive, and inaccurate as a result of sophistication in manufacturing and cloaking technology. Through various advances in technology, efficient and safer techniques of detecting objects underground are being implemented. One such imaging technique based on Finite Element Modeling analyzes the scattering of electromagnetic waves based on the microphysical parameters of different materials.
The objective of this project is to apply the Finite Element Modeling technique in COMSOL Multiphysics to create computational simulations that mimic real-world environmental situations. This study examines numerous simulations of many real-world scenarios. Parametric modeling and testing of hypothetical situations using the following properties; frequency, depth of landmines, shape of objects, profile of subsurface, soil composition, and boundary conditions were conducted in COMSOL Multiphysics. Comparing the different scattering effects of each material with all its variations, at 1GHz wavelength, comparative amplitude feedback signals were developed.

Introduction

Detection of subsurface landmines and other potentially destructive objects that pose a lethal threat to innocent civilians and infrastructure is an international concern and an imminent necessity. Current landmine detection techniques and technologies are becoming obsolete and inaccurate as landmine creation technology and materials improve. Significant recent advancements in this competing technological field, especially the creation of non-metallic mines and the utilization of casing materials with similar microphysical parameters to soil, have drastically improved mine cloaking. Such landmine technological improvements are thus impeding the successful sensing rates of classical Ground Penetrating Radar (GPR) techniques. A new means of detecting and identifying subsurface hazards through variations in the current electromagnetic wave scattering models is paramount to keep up with the increasing sophistication of landmines.



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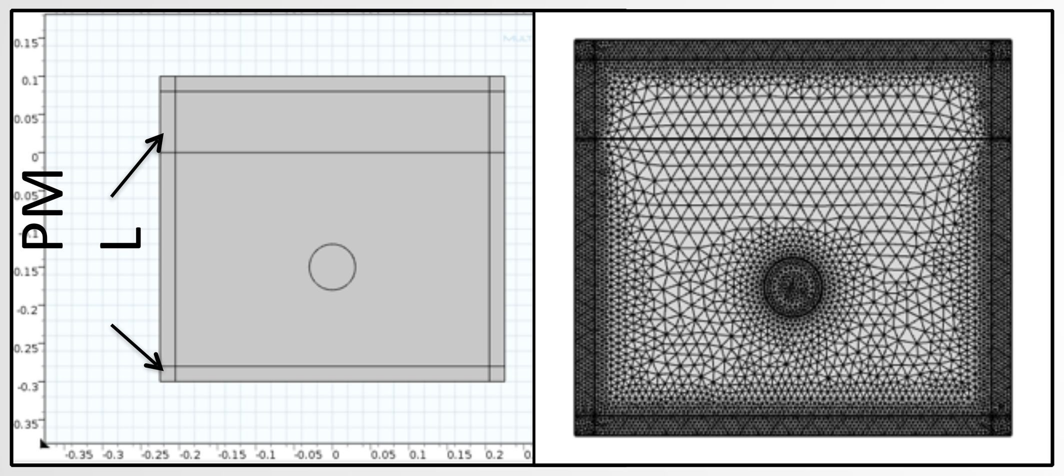
Objective

The purpose of this research is to apply the Finite Element Method of radio frequency modeling to create an accurate computational simulation template for the detection and classification of various objects buried underneath the Earth that are a potential threat to human life.

Methodology

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 landmine environment. Since both the ground and the landmine in any situation can vary drastically, therefore significantly varying in microphysical properties, different imaging signals for each situation will be returned to the receiver. These differences in scattering patterns when the electromagnetic waves are sent into the model geometry or any real world simulation, allow the identification of the material and structure of subsurface objects. These microphysical properties that scatter waves include relative permittivity, relative permeability, and conductivity.
Thus, the key aspects of our simulation were microphysical property variations, especially regarding differences in ground moisture content, and geometry specifications, such as depth and size of the landmine targets, which were both simulated and analyzed to receive final scattering results.



In the COMSOL Multiphysics simulation, after establishing the basic 2D geometry with accurate dimensions as illustrated above, the position of the target landmine object was adjusted to account for depth variations. Different microphysical parameters were set in regard to the real world properties shared by their respective material. The properties of air, TNT, and the variables of dry soil and wet soil that were implemented into COMOSL are listed below.

Material	Relative permittivity	Relative permeability	Conductivity
Air	1	1	0
Dry Soil	2.9	1273+31i	0.004
Wet Soil	4	1756+395i	0.049
TNT	2.86	1256+2.25i	4.8e-4

The Helmholtz equation was coded in Matlab and imported into the COMSOL Radio Frequency Module to study the scattering results based on the microphysical parameters.

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

In order to simulate real world settings, in which the waves would not be affected by an enclosed boundary as modeled in our COMSOL simulation, Perfectly Matched Layers (PMLs) were implemented on all sides of the simulation. By absolutely reabsorbing all incident waves, the domains allowed the simulation of infinite boundaries as expected in a real world situation, completely removing all traces of reflection that would otherwise interfere with the scattering pattern results.
The wave applied in the physics propagated in the z direction, incident at a 45 degree angle to the x-y plane, while various frequencies, ranging from 0.5-3.0 GHz were tested. The wave physics were set in COMSOL using the equation below in MATLAB syntax.

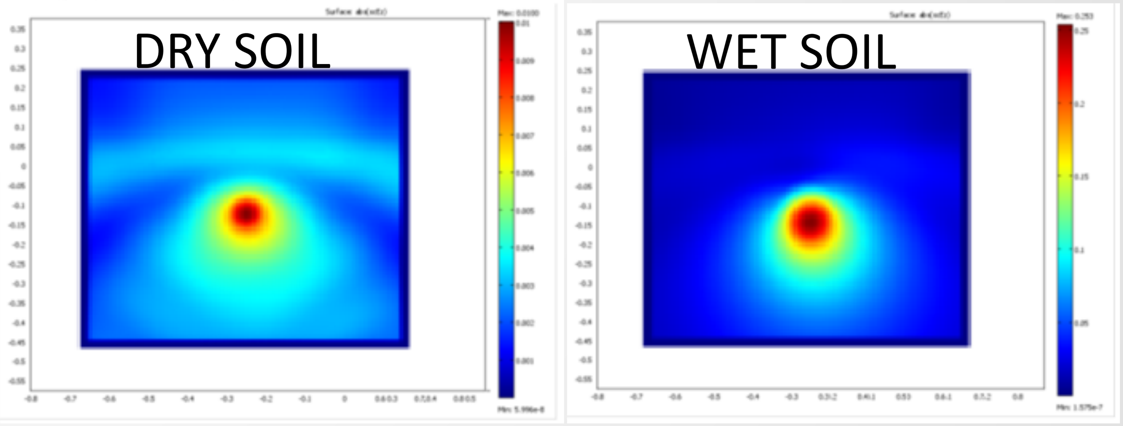
$$E = E_0 e^{\pm i \vec{k} \vec{r}}$$

Results

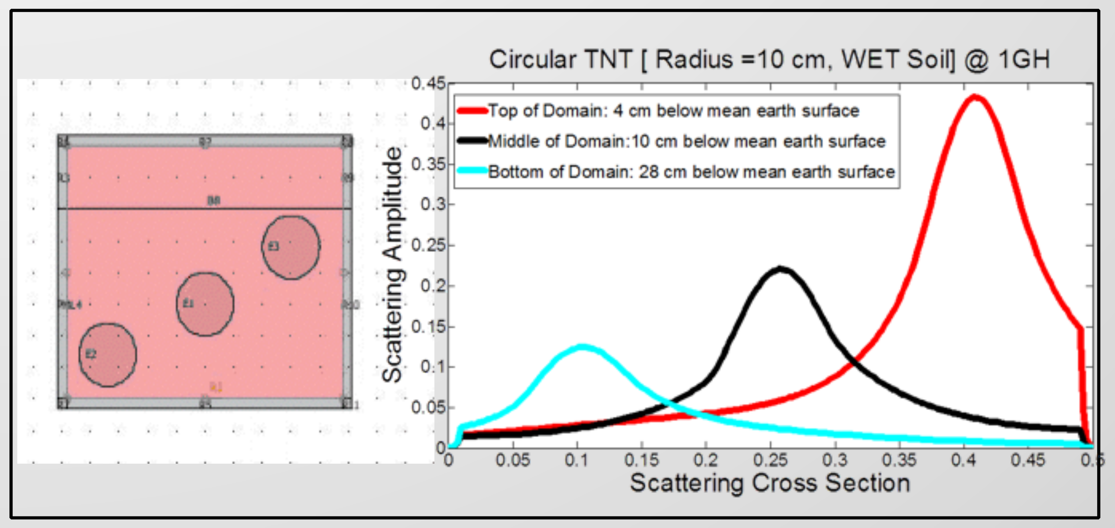
In order to quantify the scattering effects of the various objects in the simulation, the Radar Cross Section (RCS) of the simulation was computed to get the results. The Radar Cross Section represents the electromagnetic wave scattering by a target and is defined as the "area intercepting the amount of power that, when scattered isotropically, produces at the receiver a density that is equal to the density scattered by the actual target" (Balamis, 1989). 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. All these variables are taken into account in the Scattering Parametric Equation for 2D models which solves for the Scattering Width (SW), or alternatively, the radar cross section per unit length, which produced the surfaces and graphs in the lists below.

$$\sigma_{2D} = \lim_{\rho \to \infty} \frac{|E_s|^2}{|E_i|^2}$$

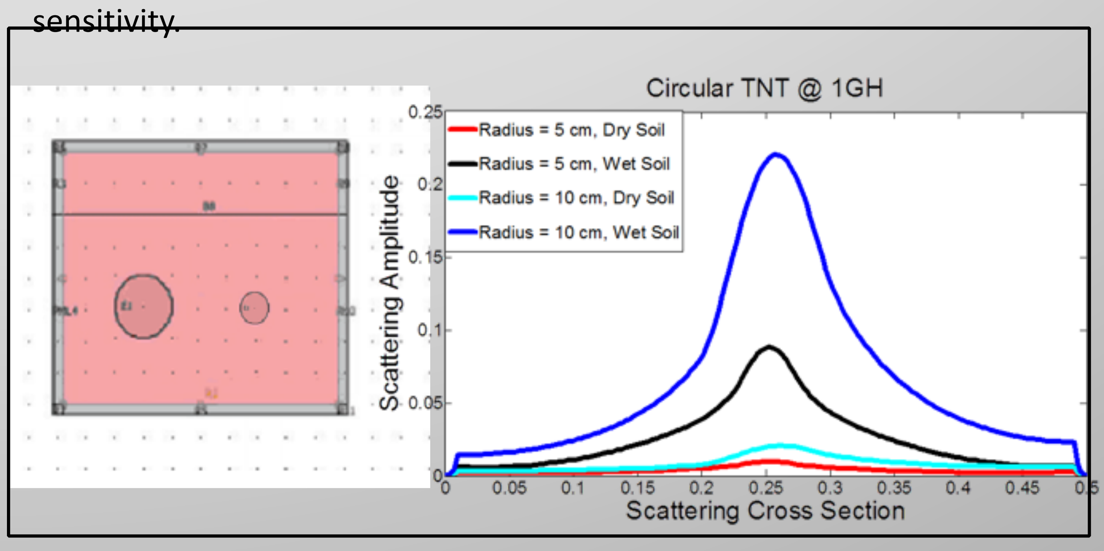
As shown below, wet soil has less scattering interference with the Radio Frequencies (RF) than dry soil because of increased conductivity due to higher water content.



The graph below of the amplitude of scattered wave received from the depth results illustrates that, as expected, when the target's depth increases, the scattering effects become increasingly negligible. The depth-scattering ratio shows a clear correlation to the soil's interference with the wave.



Additionally, when doubling the radius of the landmine, the scattering results of the central target area increased, showing a much higher sensitivity.



Conclusion

Through our 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, future studies can be more prepared for real life application in which the template can be applied. This would reduce unknown influences and unaccounted for variables so that the detection of these harmful objects would be inevitable. By simulating such models with all variables accounted for in TNT and landmine type real world applications, the template accounts for most variables that would be present in numerous other subsurface imaging applications -- from 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 to that, the knowledge of frequencies compatible with certain soil types is another important extrapolation from the research that adds additional value to the subsurface sensing template that was generated. For example, in the radar cross section fields in the column to the left, the interference between electromagnetic waves of 1GHz and various moisture types of soil can be clearly distinguished. In order to reassure that the waves travel in air and soil without interference, the correct wavelength must be applied to the situation so that the true scattering pattern of the target object can be observed. If the frequencies applied cannot intercede according to the specifications and microphysical properties of the specific mine and soil, the scattering of the target can be observed by subtracting the soil's interference of electromagnetic waves in one simulation from the total interference of electromagnetic waves in a simulation containing the mine.
For future research, potential goals will include changing the microphysical properties of the soil to account for different compositions (e.g. clay, sand, silt, etc.), as well as simulating different explosives in COMSOL (e.g. RDX, Composition B, C4, Tetryl, etc.). We could also further investigate the surface type of the soil, regarding the angles of incidence on a slope, bumpy surfaces, and levels of ground roughness.

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