Modeling the Limitations due to Different Rough Surface Statistics for Landmine Detection and Localization using Direct Ground Contact GPR

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Abstract

In 2008, over 5,000 casualties due to landmines were reported worldwide, necessitating the development of effective detection techniques. Over the last few decades ground penetrating radar (GPR) has developed into a popular tool for subsurface imaging and a promising technique to fulfill this requirement. Landmines, however, are typically buried under rough surfaces where conventional air-coupled GPR data is generally difficult to analyze, as the surface scatters the signal in unpredictable ways. By utilizing a ground-coupled system, signal penetration is dramatically improved and data analysis is simplified.

Previous work demonstrated the feasibility of using three bistatic ground-coupled antennas to triangulate the location of a landmine buried in rough, dispersive, soil using a 3-dimensional finite difference time domain (FDTD) model and an exact background trace. In this poster, background signal is approximated and the limitations of this method are analyzed with regard to the correlation length and height variance of the rough surface. This analysis is intended to characterize the operational range of topographical parameters for this detection algorithm. Though this research currently focuses on localizing landmines, this technology has numerous potential subsurface imaging applications for rough topography.

FDTD

- Discretizes Maxwell's equations which govern the fundamental behavior of electromagnetic fields
- Fast, accurate, easy to implement, and intuitive
- Both non-dispersive materials and dispersive materials, such as soil, can be approximated, however dispersive materials complicate implementation

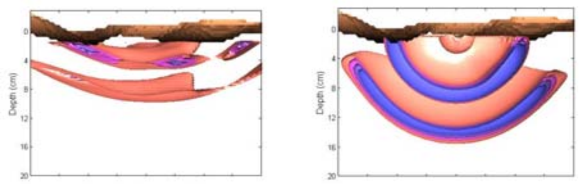
Setup

Soil Properties	
Lossy Bosnian Soil	Dispersive
Electric Permittivity	$\varepsilon_r = 6.15$ for defined frequency
Conductivity	$\sigma = 0.096$ S/m for defined frequency
Landmine Properties	
Height	4cm
Diameter	10cm
Electric Permittivity	$\varepsilon_r = 2.9$
Conductivity	$\sigma = 10^{-4}$ S/m
Simulation Details	
Spatial Resolution:	0.4cm (satisfies 10 points per wavelength in soil for given frequency)
Temporal Resolution:	2 ps (satisfies Courant condition)
GPR Details	
Bi-static Separations	25.98 cm
Excitation Signal:	Gaussian Pulse: 2.0GHz center freq and bandwidth

Air-Coupled vs. Ground-Coupled GPR

- GPR is a non-destructive evaluation technique that transmits microwaves into a medium of interest and records the reflected waves.
- The depth of a subsurface target can be determined by the time of arrival of the reflected waves and the velocity of the wave through the medium
- The waves can either be launched from the air or from direct contact with the medium of interest. Each type has advantages and disadvantages

	Survey Speed	Signal Penetration	Rough Surfaces
Air-Coupled	**Fast:** •T/R mounted on vehicle •Capable of traffic speed	**Weak**: •Considerable portion of signal is reflected at the medium surface	**Weak:** •Surface reflections are unpredictable •Spherical waveform is distorted
Ground-Coupled	**Slow**: •T/R stays in contact with ground •Quick movement can damage antennas	**Strong:** •Majority of signal is transmitted into the medium of interest	**Strong:** •Surface reflection combined with direct signal •Surface has little impact on waveform


Air-Coupled GPR
Ground-Coupled GPR

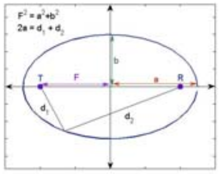
Comparison of the waveform after 7.5ns of an air-launched GPR system and a ground-launched GPR system for the same dispersive soil with a rough surface.

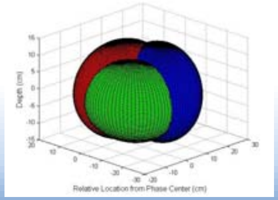
Localization Method

- Moving ground contact antennas can be difficult on a rough surface, as the surface can quickly damage the antennas
- The robot developed by Square One moves by lifting its "legs." Consequently, antennas can be attached to each leg of the robot and provide ground contact while avoiding damage


Image courtesy of Square One

- Three antennas are modeled, each in transmitting and receiving modes. Each pair returns a single trace of the subsurface from which a two-way travel time to the target can be determined
- For each trace, the antennas act as foci of a prolate spheroid (ellipsoid with *a* > *c* = *b*). The parameters of this ellipsoid can be determined by the bistatic separation and the two-way travel time.



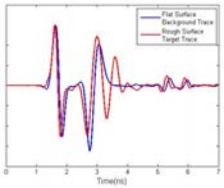


- For each bistatic pair the target is located somewhere on the corresponding ellipsoid
- Using three pairs of antennas, the target can be triangulated given that the three ellipsoids meet at one and only one point (below ground)

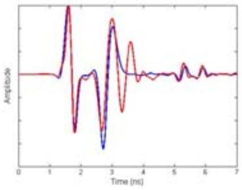
Approximating the Background Signal

- Previous work demonstrated that with a known background signal the subsurface target can be both detected and localized
- In a real scenario, the background signal of the rough surface will not be known
- An FDTD code can approximate the signal for a flat surface with the same electrical properties which can then be manipulated to produce an approximate background signal for the rough terrain

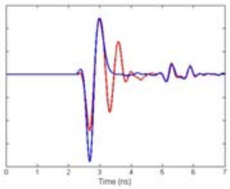
Given – Receiver data for a target buried under a rough surface and background data for a flat surface



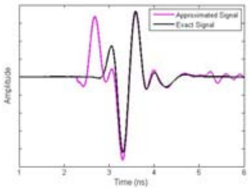
Step 1 – Align and remove first arrival from both signals



Step 2 – Correlate and scale remaining background signal to the target signal



Result – Approximate background accurately captures target signal with some additional noise



Comparing the results using the approximated background signal with the results from the exact background signal, it can be seen that the major peaks created from the target reflection are maintained allowing for detection and localization

Surface Variations

- In order to test this method for robustness, 16 rough surfaces with varying surface statistics were created

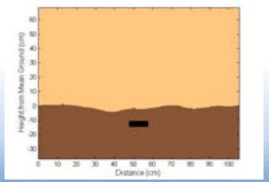
l_c = correlation length – how quickly the surface varies across a distance

σ_h = standard deviation – how much the height varies

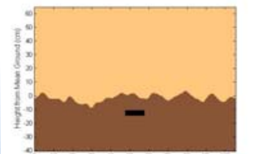
Both statistics are based on a Gaussian distribution

Surface	l_c (cm)	σ_h (cm)	Surface	l_c (cm)	σ_h (cm)
1	10	2	9	10	3
2	9	2	10	9	3
3	8	2	11	8	3
4	7	2	12	7	3
5	6	2	13	6	3
6	5	2	14	5	3
7	4	2	15	4	3
8	3	2	16	3	3

Surface 1



Surface 16

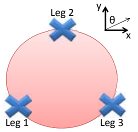


Simulation Results

Case 1 – Transmit on Leg 1
Receive on Leg 2, θ = 120°

Case 2 – Transmit on Leg 1
Receive on Leg 3, θ = 30°

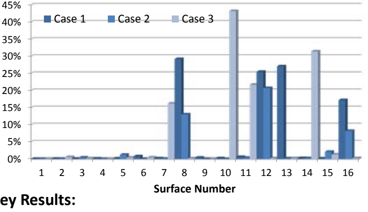
Case 3 – Transmit on Leg 2
Receive on Leg 3, θ = 210°



The receiver data was created by combining the Ex and Ey receiver components for both an x-directed and a y-directed dipole excitation, such that:

$$R = \left(E_{y_y} cos\theta + E_{x_y} \sin\theta\right) cos\theta + \left(E_{y_x} cos\theta + E_{x_x} \sin\theta\right) sin\theta$$

Percent Error in Two-Way Travel Time Using Approximated Background Signal



Key Results:

- 78% of two-way travel times accurately determined with approximate background
- 88% accuracy for surfaces with $l_c = 2$, "less rough"
- 88% of target signals obtained – errors occurred from noise dominating target signal

Conclusions and Future Work

Utilizing ground-coupled GPR shows remarkable advantages to conventional air-coupled GPR when the terrain is rough. Inversion techniques and localization are simplified since the predictive waveform is maintained.

The technique presented for approximating the background signal is computational simple and intuitive. It was observed that this technique is robust for small roughness, however as roughness increases, other methods may need to be taken into consideration. However, since the error in two-way travel time was not a result of poorly recreating the target signal, but rather a result of the noise being greater than the target signal, it is expected that with further data processing and potentially signal filtering, these results can be improved.

References

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