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Buried Target Parameter Characterization for Handheld Ground Penetrating Radar

Suki Dauda Sule[1]

[1]School of Engineering and Computer Science, University of Hull,
Cottingham Road, Hull, HU6 7RX, United Kingdom

Abstract:
Subsurface parameter characterization for ground penetrating radar (GPR) is very challenging given the typically lossy, cluttered soil with varying conditions form one environment to another. An approximation of the velocity of propagation for homogeneous, isotropic, non-magnetic materials is used to aid the evaluation of GPR measurements and subsurface parameter estimation. For landmine detection, parameter estimation introduces increased complexity due to soil heterogeneity and clutter signals. This paper presents the results of a study that investigates the relationship between the velocity of propagation with soil and mine parameters for a landmine detection application using GPR. Most GPR studies for landmine detection focus on vehicular systems or scanned measurements. This study assumes a homogeneous, non-magnetic soil for a handheld impulse GPR system based on A-scan data. Synthetic data is used to undertake empirical experiments, performed in the CST STUDIO SUITE environment for 3D electromagnetic analysis.

Keywords: GPR, handheld, parameter, characterization.

1. Introduction

Landmine detection with ground penetrating radar (GPR) offers one of the most successful techniques for humanitarian demining [1]. Due to the lossy half-space, buried subsurface objects and the mine itself, the system presents multiple unknown parameters that require accurate estimation to enable mine detection. The GPR problem is also generally regarded as an ill-posed problem and therefore very challenging considering the varying nature of soil types and conditions in different environments. Understanding the nature of the behaviour of subsurface parameters is critical to the application of methods of estimating such parameters and hence mine detection. Most studies consider vehicle based GPR systems with scanned measurements or ensemble data. In this paper a handheld GPR system is used to characterise the changes or variation in subsurface parameters for a time domain, A-scan output waveform. The responses to changes in the soil and mine parameter values are investigated to determine how the system output is affected, with reference to the relationship between the velocity of propagation, relative permittivity of the soil and the depth of the target [2] for an isotropic, non-magnetic medium, given by

$$V_p = \frac{c}{\sqrt{\varepsilon_r}} ms^{-1} \qquad (1)$$

and

$$d = V_p \frac{t}{2} m \qquad (2)$$

where V_p is the velocity of propagation, c is the velocity of light in free space, ε_r is the relative permittivity of the soil, d is depth and t is the time to and from the buried object.

The application in this case is for landmine detection. Therefore, the experiments are based on a flat, homogeneous domain. The system model is for a 3D handheld GPR system with bistatic Vivaldi antennas positioned vertically over the ground, which presents a novel setup for investigating these widely studied phenomena. A more detailed description of the model is provided in section two. The five parameters under test include the soil relative permittivity ε_r^s, soil loss tangent $\tan\sigma$, relative permittivity of the mine ε_r^m, depth of the mine d in cm and the radius of the mine R in cm. The initial parameter vector set is given by

$$[\varepsilon_r^s, \tan\sigma, \varepsilon_r^m, \mathrm{d}, \mathrm{R}] = [2.53, 0.0033, 2.8, 1\mathrm{cm}, 3\mathrm{cm}]$$
(3)

Section two presents the 3D system model and simulation setup while the results are provided in section three. A conclusion is presented in section four.

2. Modelling and Simulation

The ground model setup used for the simulations is equivalent to the model described in the work in [3], with sandy soil and a cylindrical, plastic mine with internal components of an air void, tetryl charge and metal pin. A bistatic Vivaldi antenna system is used with the dimensions and structure designed and optimized automatically using the Antenna Magus software for a center frequency of 3.5GHz, which yielded an operating frequency range of 1GHz- 6GHz. The Vivaldi antenna has a planar geometry with dimensions of 440 mm by 0.1 mm by 219 mm. The Vivaldi antennas are placed in a linear (line) configuration. Due to reciprocity, any of the antenna elements is excited as the transmitting element while the time series output is measured at the other element as the receive antenna. This setup enables the GPR system to be analyzed with dimensions suitable for a handheld system. See Figure 1.

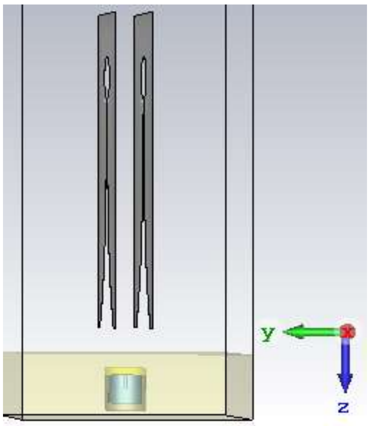

Figure 1: Bistatic Vivaldi handheld GPR system model

Given the initial parameter vector in (3), the relative permittivity of the mine is with reference to a fixed value of soil relative permittivity. This also enables an investigation of the impulse response to changes in the soil-mine contrast, as the value of the relative permittivity of the mine increases further away from the value of the soil relative permittivity. For each parameter under test, the value in the initial parameter vector set is changed in ascending order while the other four parameters in the parameter set are kept constant. Ten different values of each parameter are simulated and for each simulation, the objective is calculated, which is given by the sum squared difference of the A-scan output of the simulation and a reference A-scan impulse output without a mine. The parameter set for the GPR system without a mine comprises only the soil relative permittivity and the loss tangent, due to the absence of a mine. The values of these parameters are equivalent to the corresponding parameters in the initial parameter set given in (3). The objective is plotted against each parameter under test, separately.

3. Results and Discussion

The results of the simulations are presented in Figures 2, 3, 4, 5 and 6 for the relative permittivity of the soil, loss tangent, relative permittivity of the mine (soil-mine contrast), depth of the mine and radius of the mine respectively.

3.1 Characterization of parameter changes

The changes in the soil relative permittivity and the loss tangent are generally consistent and in agreement with (1) as a plot of the inversely proportional relationship between a fraction of the velocity of propagation and the relative permittivity, neglecting c, shown in Figure 7, confirms. Therefore, the relative permittivity of the soil and the loss tangent generally decrease with the velocity of propagation for homogenous, isotropic media, based on (1). The objective also demonstrates the increasing uncertainty and deviation from the original values of the soil relative permittivity and loss tangent of 2.53 and 0.0033 respectively. This is not the case for the other plots, which indicate the variation of the soil-mine contrast, depth and dimensions of the mine. The results show that depth does not vary in direct proportion with the velocity of propagation as expected, based on (2). The soil-mine contrast yields the largest uncertainty in parameter estimation as shown by the maximum value of the L2 norm in Figure 4. Furthermore, the soil-mine contrast is also the most dominant parameter based on the objective values despite the incremental steps of only 0.2 for the mine relative permittivity parameter variation.

While the soil parameters decrease with increasing velocity of propagation based on (1), the parameters linked directly with the mine do not. This is attributed partly to the consideration that materials where the complex permittivity varies with frequency i.e. dispersive, the value of propagation velocity will be different from that of simple materials. Additionally, is also the consideration the non-isotropic nature of the mine, i.e. the plastic cylindrical container and the tetryl charge internal component. These results confirm that equations (1) and (2) enforce only in the presence of both homogeneity and isotropy. The steep rise between the first and second depth parameters in Figure 5 is attributed to the change in impedance from the air to the ground as the first depth value has the top of the mine just above the ground surface, positioned in free space, and is the first part of the mine that the incident radiation from the transmitting antenna encounters [4]. This underlines the role of clutter as a key limiting factor in mine detection using GPR.

Therefore, in practical terms, the GPR environment is heterogeneous, cluttered and contains other subsurface materials that are anisotropic. This introduces greater complexity and uncertainty in the characterisation of the behaviour of the individual parameters and distorts the relationships provided in (1) and (2) for a real landmine detection scenario.

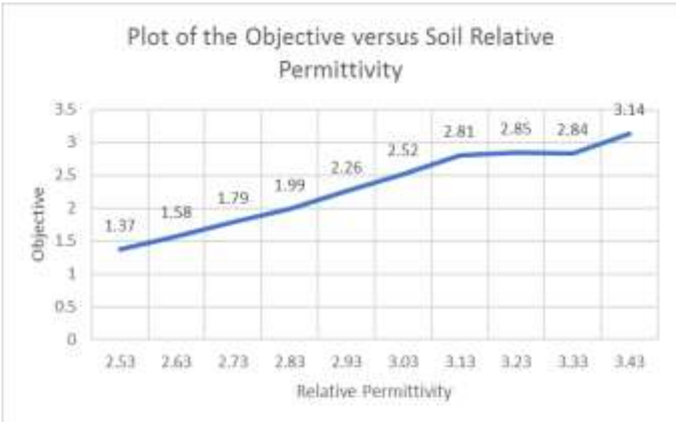

Figure 2: Plot of the objective with changing soil relative permittivity

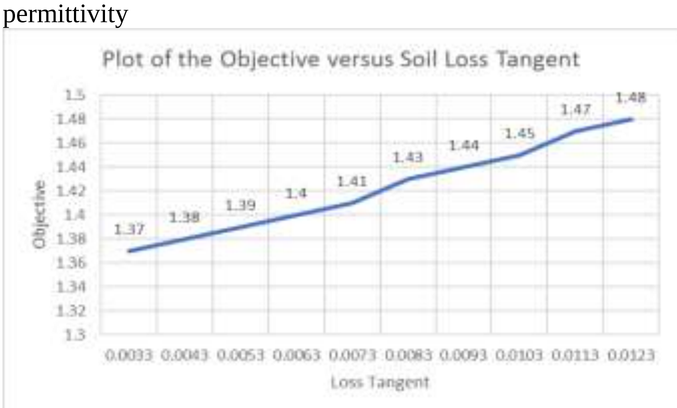

Figure 3: Plot of the objective with changing soil loss tangent

Figure 4: Plot of the objective with changing mine relative permittivity (soil-mine contrast)

Figure 5: Plot of the objective with changing depth of mine

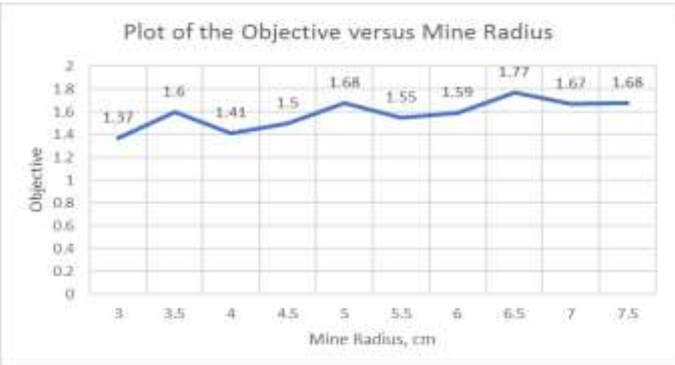

Figure 6: Plot of the objective with changing mine radius (horizontal dimension)

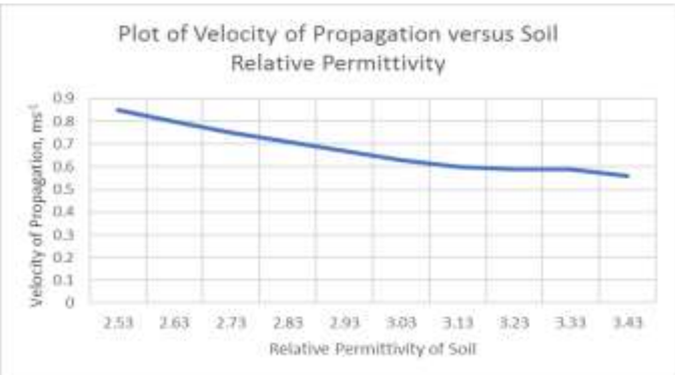

Figure 7: Plot of velocity of propagation (fractional) against soil relative permittivity

4. Conclusion

Changes in soil and landmine parameters were characterised with reference to the velocity of propagation for a flat, homogeneous, isotropic sandy soil. Expectedly, soil relative permittivity and loss tangent were found to vary inversely with the velocity of propagation. However, the relative permittivity, depth and radius of a plastic, cylindrical mine surrogate were found to vary irregularly with the velocity of propagation. This is caused by factors such as the dispersive and anisotropic properties of the mine. Hence, depth was found to yield a nonlinear relationship with the velocity of propagation, contrary to the approximations for a homogeneous, isotropic medium. Additionally, uncertainty in parameter estimation is significantly increased when the mine is completely buried in the ground as shown in Figure 5. This underlines the impact of the dominant air-ground reflections which typically mask target backscattered signals [5]. Overall, this study demonstrates the complexity of parameter estimation and characterisation for landmine detection using handheld GPR. Future work is expected to consider parameter sensitivity for a more realistic, heterogeneous, cluttered domain.

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Author Profile

Suki Dauda Sule received the B.Eng. degree from the Abubakar Tafawa Balewa University in Electrical/Electronics Engineering in 2006 and MSc in Radio Systems Engineering from the University of Hull in 2010. In the same year he was employed with the National Space Research and Development Agency (NASRDA) in Abuja, Nigeria as an Engineer in mission planning and ICT. He is currently a final year PhD student at the University of Hull, researching on multi-static handheld ground penetrating radar (GPR) for humanitarian demining.