A new integrated approach for characterizing the soil electromagnetic properties and detecting landmines using a hand-held vector network analyzer

Olga Lopera^{a,b,c}, Sebastien Lambot^d, Evert Slob^e, Marnik Vanclooster^f, Benoit Macq^b and Nada Milisavljevic^a

^aSignal and Image Centre, Royal Military Academy, Av. renaissance 30, 1000 Brussels, Belgium;

^bTelecommunications Laboratory, Catholic University of Louvain, Place du Levant 2, Louvain-la-Neuve, Belgium;

^cDept. of Electrical and Electronic Engineering, University of Los Andes, Kr 1 Este 18A-10 ED W P4, Bogota, Colombia;

^dInstitute of Chemistry and Dynamics of the Geosphere, Forschungszentrum Jülich GmbH, Jülich, Germany;

^eDepartment of Geotechnology, Delft University of Technology, Mijnbouwstraat 120, Delft, The Netherlands;

^fDepartment of Environmental Sciences and Land Use Planning, Catholic University of Louvain, Croix du Sud 2, Louvain-la-Neuve, Belgium

ABSTRACT

The application of ground-penetrating radar (GPR) in humanitarian demining labors presents two major challenges: (1) the development of affordable and practical systems to detect metallic and non-metallic antipersonnel (AP) landmines under different conditions, and (2) the development of accurate soil characterization techniques to evaluate soil properties effects and determine the performance of these GPR-based systems. In this paper, we present a new integrated approach for characterizing electromagnetic (EM) properties of mine-affected soils and detecting landmines using a low cost hand-held vector network analyzer (VNA) connected to a highly directive antenna. Soil characterization is carried out using the radar-antenna-subsurface model of Lambot *et al.*¹ and full-wave inversion of the radar signal focused in the time domain on the surface reflection. This methodology is integrated to background subtraction (BS) and migration to enhance landmine detection. Numerical and laboratory experiments are performed to show the effect of the soil EM properties on the detectability of the landmines and how the proposed approach can ameliorate the GPR performance.

Keywords: ground penetrating radar, soil electromagnetic properties, landmine detection, background subtraction, migration

1. INTRODUCTION

Ground penetrating radar (GPR) is currently the subject of intensive research with respect to humanitarian demining applications as it permits to provide useful information about the shallow subsurface in a non-invasive way.² Hardware development, software processing and soil characterization are the main research topics in the field of GPR dedicated to landmine detection.³ Such research aims to improve GPR performance and efficiency to be applied in real mine-affected fields (*e.g.*, roads, fields, mountains, forests and deserts). GPR operates by detecting electromagnetic (EM) contrasts in the soil, which allows it to locate even non-metallic landmines. However, the GPR signal contains not only the response from a potential target, but also includes undesirable effects from antenna coupling, system ringing and soil reflections, which obscure the target response. These

Further author information:

O.L.: E-mail: olopera@elec.rma.ac.be, Phone: +32 2737 6666

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Figure 1. The GPR system emulated using the hand-held VNA connected to the horn antenna via a 50-Ohm N-type coaxial cable.

effects have to be filtered out from the signal to enhance landmine detection. Additionally, soil EM properties, as dielectric permittivity and electric conductivity, govern EM wave propagation, affecting the GPR performance and therefore the detection of landmines. The EM properties of a soil depend on a number of factors of which the most significant is the volumetric water content, which can vary considerably over time and space. Due to the resulting large spatio-temporal variability of the soil EM properties, it is therefore essential to characterize them at the local scale and during the demining operation. Practical and affordable GPR-based system development, robust signal processing approaches and accurate techniques for soil EM properties characterization are crucial steps for rendering GPR useful for humanitarian demining applications.⁴

A variety of systems and algorithms employing GPR sensors have been applied to the problem of landmine detection. GPR systems operate either in time domain or in frequency domain.⁵ Time-domain systems transmit a single discrete pulse of nanosecond duration or a pulse train frequency modulated waveform. Frequency-domain GPR are continuous wave systems in which the carrier frequency is changed either continuously or with a fixed step. Stepped-frequency continuous-wave (SFCW) radars have some advantages over the others, including wider dynamic range and better signal-to-noise ratio (SNR).⁶ Besides the domain of operation, GPR may detect landmines using either monostatic, bistatic or array configuration of different antenna types. In this particular application, ultra-wide band (UWB) antennas are required to achieve high depth resolution.⁷ Vehicle-based systems generally use array antenna mode⁸ in combination with other sensors such as metal detectors.⁹ Laboratory prototypes of UWB radar systems usually are built in bistatic mode.^{10,11} The same configuration is adopted for hand-held GPR landmine detectors^{12,13} which have the advantage of being practical for different field conditions. For all these configurations, different types of antennas such as horn, loop, spiral, Vivaldi and combinations of them are used. An overview of their characteristics, advantages and drawbacks can be found in [14].

Together with the progress in hardware development, the acquired data can be enhanced by means of signal processing techniques. These techniques aim to reduce the clutter of the background and to identify the buried object signal. By far the most applied clutter reduction techniques are average and moving average background subtraction (BS).⁵ Other BS approaches include wavelet transform¹⁵ and system identification.¹⁶ Once these techniques partially reduce the clutter, the next logical step is to detect the target. Among processing methods for the identification of the target signal, advanced algorithms for hyperbola detection,^{17,18} convolutional models¹⁹ and migration techniques²⁰ are applied.

Despite the considerable and growing efforts in hardware and software development, landmine detection using

Figure 2. Representation of the attenuation of the target signal simulated using a FDTD modeling program. Results are for a M14 AP landmine buried at 5 cm in a loamy sand soil which is subject to three different water contents.

GPR is still limited by the effects of the soil EM properties on EM wave propagation. Different techniques have been developed to characterize such properties and can be used to determine the applicability and limitations of GPR-based systems. Among the non-invasive approaches, in [1, 21] a new EM model for identifying the relative dielectric permittivity (ϵ_r) and conductivity (σ) using a SFCW UWB monostatic radar is proposed. The model is based on linear system response functions and the exact solution of the three-dimensional (3-D) Maxwell's equations. Subsurface dielectric properties are calculated by model inversion using a robust global optimization technique. In this paper, this approach is applied for soil EM properties characterization and is integrated with background subtraction and migration for landmine detection.

2. GROUND PENETRATING RADAR SYSTEM

Besides being practical and affordable, GPR-based systems for humanitarian demining demand specific requirements such as a minimal antenna elevation above the ground, large linear dynamic range, time and amplitude stability and high down-range resolution.²² The radar system used in this study covers several of these requirements. It consists of a low-cost hand-held vector network analyzer (VNA) connected to a high-directive monostatic horn antenna, thereby emulating a SFCW radar. The antenna we use for the measurements is a linear polarized double ridged broadband horn antenna of which dimensions are 22 cm length and 14×24 cm² aperture area. This antenna is highly directive (3-dB beam width of 45° in the E-plane and 30° in the H-plane at 1 GHz and 27° in the E-plane and 22° in the H-plane at 2 GHz) and covers an ultra-wide frequency band from 0.8-5.0 GHz on 3 dB level. The complete system can be seen in Fig. 1. In this study, the measurements were performed in the range 0.8-2.6 GHz which optimally combines penetration and resolution abilities. The radar has the linear dynamic range of 60 dB, which allows to detect weak scatterers. Antenna ringing is accurately determined and taken in to account in the underlying EM model. Therefore, it does not affect negatively the signal-to-noise ratio of the system. The effect of amplitude drift is limited by a simple and accurate calibration procedure using a standard Open-Short-Match calibration kit.

3. SFCW GPR-MULTILAYERED MEDIUM MODEL

In [1, 21], an EM model describing the radar-antenna-subsurface system for enabling accurate mapping of ϵ_r and σ using a SFCW UWB monostatic radar is proposed. The model is based on linear system transfer functions and on the exact solution of the 3-D Maxwell's equations for wave propagation in a horizontally multilayered medium representing the subsurface. This model of complex scalar and linear transfer functions assumes that

Figure 3. Laboratory measurements representing the attenuation of the target signal for a non-metallic standard test target (SIM12) buried at 10 cm in a sandy soil which is subject to four different water contents.

the shape of the electromagnetic field received by the antenna is independent of the target (soil), *i.e.*, only the phase and amplitude of the field are function of the target. This has been proven to be a valid assumption when the antenna is sufficiently far above a multilayered medium ($> \sim 10 - 15$ cm in the frequency range 0.8-2.6 GHz).²³ The corresponding transfer function, expressed in the frequency domain, is given by:

$$S_{11}(\omega) = H_i(\omega) + \frac{H(\omega)G_{xx}^\dagger(\omega)}{1 - H_f(\omega)G_{xx}^\dagger(\omega)}, \quad (1)$$

where $S_{11}(\omega)$ is the quantity measured by the VNA, ω being the angular frequency, $H_i(\omega)$ the return loss, $H(\omega) = H_t(\omega)H_r(\omega)$ the transmitting-receiving transfer function, $H_f(\omega)$ the feedback loss, and $G_{xx}^\dagger(\omega)$ the transfer Green's function of the air-subsurface system modeled as a 3-D multilayered medium.

The antenna characteristic transfer functions $H_i(\omega)$, $H(\omega)$ and $H_f(\omega)$ can be determined by solving a system of equations as (1), pertaining to different and well known model configurations (*i.e.*, with the antenna situated at different heights above a metal sheet playing the role of an infinite perfect electric conductor (PEC)¹). For estimating soil EM properties, subsurface parameter identification by inverse modeling is applied. Inversion of the Green's function is focused on the surface wave reflection in the time domain. In this particular case, only the surface dielectric permittivity is identified.²⁴ Finding a parameter vector $\mathbf{b} = [\varepsilon, h]$ (h being the height of the antenna phase center), so that an objective function $\phi(\mathbf{b})$ is minimized, is a nonlinear optimization problem formulated here in the least-squares sense. The objective function to be minimized is defined as

$$\phi(\mathbf{b}) = \left| \mathbf{G}_{xx}^{\dagger*} - \mathbf{G}_{xx}^\dagger \right|^T \mathbf{C}^{-1} \left| \mathbf{G}_{xx}^{\dagger*} - \mathbf{G}_{xx}^\dagger \right|, \quad (2)$$

where $\mathbf{G}_{xx}^{\dagger*} = G_{xx}^{\dagger*}(\omega)$ and $\mathbf{G}_{xx}^\dagger = G_{xx}^\dagger(\omega, \mathbf{b})$ are the vectors containing, respectively, the observed and simulated response functions, and $\mathbf{C}$ is the error covariance matrix. We use the global multilevel coordinate search algorithm combined sequentially with the classical Nelder-Mead simplex algorithm for the optimization problem.²¹ The overall approach has been validated in laboratory and field conditions.^{1, 24-26}

4. EFFECT OF THE SOIL EM PROPERTIES

Electromagnetic models can be used to predict the response from a landmine buried in a particular soil and to study the effects of the soil EM properties on landmine detection.^{27, 28} In this paper, a finite-difference time-domain (FDTD) modeling program²⁹ is used and laboratory experiments are performed to show two of the major effects of the soil EM properties in buried target detection: attenuation and contrast.

Figure 4. Laboratory measurements representing the low contrast in the dielectric properties of a non-metallic standard test target (SIM12) and the sandy soil surrounding it. The sandy soil is subject to two different water contents.

The FDTD program is used to simulate the response of buried landmines for an UWB radar in monostatic mode and to show how the radar signal can be attenuated due to an increment of ε_r . This EM property depends on different soil characteristics, mainly the soil water content (WC). In Fig. 2, the simulated responses of a low-metallic AP landmine (the American M14) buried at 5 cm in a loamy sand soil (72% sand, 27% silt 1% clay) subject to three different WCs are shown. The x-axis represents the normalized amplitude of the radar signal and the y-axis represents the two-way traveling time. Note that the reflection of the soil surface is subtracted and only the response of the buried target is presented. For this simulation, we consider three different relative dielectric permittivities $\varepsilon_{r,1} = 7.7$, $\varepsilon_{r,2} = 14.1$ and $\varepsilon_{r,3} = 21.4$, related to each WC ($0.1 \text{ m}^3 \cdot \text{m}^{-3}$, $0.2 \text{ m}^3 \cdot \text{m}^{-3}$ and $0.3 \text{ m}^3 \cdot \text{m}^{-3}$, respectively). The response of the landmine is pointed out by the dotted line and the attenuation effect is clearly represented.

Laboratory measurements were performed to represent this effect. In Fig. 3, the radar signal of a non-metallic ITOP (the SIM12 standard test target) buried at 10 cm in a sandy soil subject to four different WC is shown. For the different water contents $\text{WC1} \cong 0.07 \text{ m}^3 \cdot \text{m}^{-3}$, $\text{WC2} \cong 0.12 \text{ m}^3 \cdot \text{m}^{-3}$, $\text{WC3} \cong 0.15 \text{ m}^3 \cdot \text{m}^{-3}$ and $\text{WC4} \cong 0.21 \text{ m}^3 \cdot \text{m}^{-3}$, different relative dielectric permittivities were measured: $\varepsilon_{r,1} = 3.4$, $\varepsilon_{r,2} = 5.4$, $\varepsilon_{r,3} = 7.6$ and $\varepsilon_{r,4} = 10.1$, respectively. The surface reflection is clearly identified between $t=2.5 \text{ ns}$ and $t=3 \text{ ns}$. A metallic sheet is located at 25 cm of depth to control the boundary conditions, and its reflection can be seen beneath 6 ns. The response of the landmine is pointed out by the dotted line and the attenuation effect is clearly represented. We could then conclude that very wet conditions will affect negatively the detection of the landmine. However, dry soils could have a ε_r very close to that of the landmine yielding to low dielectric contrast conditions, which also could worsen the detection of the landmine. Laboratory measurements were performed to represent such effect. In Fig. 4, the radar signal of SIM12 buried at 4 cm in a sand layer subject to two different WC is shown. The layer width is 14 cm and at the bottom there is concrete and subsoil. Here, for the lower water content $\text{WC1} \cong 0.0 \text{ m}^3 \cdot \text{m}^{-3}$ a $\varepsilon_{r,1} = 2.7$ were measured, which is really close to the ε_r of the target ($\varepsilon_{tg} \cong 2.8$). The water content is increased to $\text{WC2} \cong 0.07 \text{ m}^3 \cdot \text{m}^{-3}$ ($\varepsilon_{r,2} = 3.5$) with the aim of increasing the dielectric contrast. The target response is pointed out by the dotted line, and the dielectric contrast is increased indeed. As the result is not clearly noticeable without subtracting the background, signal processing approaches as background subtraction (BS) and migration are applied to isolate the target signal and emphasize such effect.

Figure 5. Time domain representation of radar measurements performed in the sand layer with WC2 for the SIM12 buried at 4 cm: (a) raw data, (b) $h_i(t)$, $h_f(t)$, $h(t)$ filtered from signal $s_{11}(t)$ using Equation (1), (c) $g_{xx}^\dagger(t)$ filtered from signal $s^*(t)$ using Equation (1), and (d) phase-shift migration applied on $r_{obj}(t)$.

5. ENHANCING THE TARGET RESPONSE BY BS AND MIGRATION

All the reflections that do not originate from the target (*i.e.*, originate from the background) are called clutter. A BS approach is applied here considering the model described in Section 3 to data acquired using the GPR system proposed in Section 2. As stated in Section 3, the antenna effects H_i , H and H_f are determined for the frequency range concerning this study (0.8-2.8 GHz) by a simple set of measurements over a metallic sheet, and a single radar acquisition (*i.e.*, A-scan) is performed in a local mine-free area to determine the Green's function of the soil by signal inversion. These values are subtracted from the radar signal S_{11} using Equation (1). The effects of the antenna and soil surface are partially removed and then the response of the buried target is isolated. In the remainder of this paper the latter will be called R_{obj} . In some cases, for differentiating this response of the residual noise, more target characteristics need to be determined. Additional information as the target shape can be extracted using a focusing algorithm on several A-scan acquired consecutively (*i.e.*, B-scan). As is presented in [30], phase-shift migration is applied to the pre-processed B-scan (see Appendix A for details). Raw, preprocessed and migrated data (S_{11} , R_{obj} and $\hat{R}_{obj}$, respectively) are shown in the time domain in Fig. 5 for the SIM12 buried at 4 cm in the sand layer with WC2. As can be seen in Figs. 5 (c) and (d), the surface reflection is partially filtered. It is due to a difference in the soil moisture (*i.e.*, different ε_r) between the first half part of the sand layer and the last one. This shows how soil inhomogeneities (naturally present in real conditions) could affect the performance of GPR for landmine detection, as these changes could obscure a shallow target reflection. Other BS methods use statistically-based models to take into account soil inhomogeneities. The advantage of the model used here is that different A-scans can be collected in the local mine-free area and physical values, instead of statistical, are used to reduce such residual clutter. For this procedure, a second Green's function is

Figure 6. Second BS applied to the noisy sub-area of Fig 5. No object is identified.

estimated using one A-scan from the noisy area. BS is then applied in this region and results can be seen in Fig. 6. Note that the A-scan used to perform the inverse modeling is shown without filtering, to emphasize the effectiveness of the BS.

The effect of the increment on the dielectric contrast by increasing the soil water content can be now clearly seen in Fig. 7 for the filtered target response. Target reflection is pointed out by a dotted line. On both cases, the signal to noise ratio is ameliorated. However, a bigger target reflection appears after increasing the dielectric permittivity of the soil. The knowledge of this soil EM property can thus help to improve the GPR performance.

6. CONCLUSION

Soil EM properties affect the propagation of EM waves and, therefore, they have an impact on landmine detection using GPR. In this paper, a new non-invasive approach integrating soil characterization and landmine detection by a hand-held GPR system is proposed. Soil characterization is done by full-wave inversion of the GPR signal. Landmine detection is done by the application of the radar model presented in [1] for BS and by migration. We show how the knowledge of the EM properties in conjunction with signal processing can ameliorate the detection performance of GPR. Negative effects from signal attenuation, dielectric contrast, strong surface reflection and antenna ringing can be overcome by the proposed approach. Results in laboratory conditions show the appropriateness of this methodology to enhance landmine detection. Under real field conditions, soil characterization is thus of fundamental importance to deal with inhomogeneities in soil EM properties and to ameliorate the GPR performance. Further measurements using the antenna specially developed for landmine detection by Scheers in [14] and in real field conditions are considered.

APPENDIX A. PHASE-SHIFT MIGRATION ALGORITHM

Consider the effect of the object R_{obj} as a 2-D data set $R(x, z, \omega)$, x being the distance along the scanning axis, z the depth, and ω the angular frequency. Applying the Fourier transform with respect to the spatial distance x to spatial frequency k_x , we get as a result an unfocused wavenumber data set

$$R(k_x, z, \omega) = \int R(x, z, \omega) e^{ik_x x} dx. \quad (3)$$

The Fourier transformation along the x coordinate makes sense only if the propagation velocity does not vary in this direction. The method allows variations of the propagation velocity in the z direction. Defining

Figure 7. Time domain representation of the processed radar signal of Fig. 4. The response of the target is enhanced for both water contents WC1 and WC2 using BS by the proposed methodology and by applying phase-shift migration. Due to a high dielectric contrast, results are better for WC2.

the wavenumber vector k ($k = 2\pi/\lambda$, being λ the wavelength in the ground) as the vector sum of k_x and k_z for one-way propagation, we have:

$$k = |\mathbf{k}| = \sqrt{k_x^2 + k_z^2} = \frac{\omega}{v}, \quad (4)$$

where v is the propagation velocity of the ground ($v = c_0/\sqrt{\epsilon_r}$, being $c_0 = 299792458 \text{ ms}^{-1}$ the speed of light in vacuum). The direction of the $\mathbf{k}$ -vector is identical to the traveling direction of a plane wave propagating from the target to the antenna. Assuming only upward coming waves, and introducing k_z from Equation 4 in Equation 3, the Fourier transform of the wavefront at depth z is done by

$$R(k_x, z, \omega) = R(k_x, 0, \omega)e^{-ik_z z}. \quad (5)$$

The migrated data will be the inverse Fourier transform of Equation 5 at time $t=0$:

$$\hat{r}(x, z) = r(x, z, 0) = \int \int R(k_x, 0, \omega)e^{-i(k_x x + k_z z)} dk_x d\omega. \quad (6)$$

Equation 6 is the general representation of the phase-shift migration. The implementation of this method is computationally intensive, because of the number of floating point operations needed for migration.²⁰ For the reduction of the calculation time, a variant of the phase-shift migration for a constant propagation velocity is used. This variant was developed in [31]. In the special case where $v(z)$ is constant, Equation 6 can be further developed by changing the variable $d\omega$ to dk_z . By replacing $d\omega$ from Equation 4, the data must be scaled by the Jacobian of the transformation from ω to k_z , $\frac{k_z v^2}{\omega}$. Hence, for the Stolt migration, Equation 6 becomes

$$\hat{r}(x, z) = v^2 \int \int \frac{k_z}{\omega} R(k_x, 0, \omega)e^{-i(k_x x + k_z z)} dk_x dk_z. \quad (7)$$

Equation 7 is valid only for a constant propagation velocity case. However, there is a discontinuity at the air-ground interface because of the antenna elevation which is essential for landmine detection. Migration is applied considering the antenna at $\hat{h}=0$ cm above the surface. This can be done by calculating the diffraction

point x_d for all measurement points along the x -axis. Starting from Snell's law of refraction and assuming the air-ground interface flat and in the far-field of the antenna, a system of three equations is obtained which can be solved iteratively: (i) $x_d = z_0 \tan(\theta')$, (ii) $\theta' = \sin^{-1}(\sin(\theta)/\sqrt{\epsilon_r})$, (iii) $\theta = \tan^{-1}((x - x_d)/h_0)$, where θ is the inference angle, θ' is the refraction angle for the subsurface and z_0 is the depth of the buried target (extracted from g_{obj}). The real position of the antenna x is thus considered at the diffraction point x_d , for $\hat{h}_0 = 0$ cm and the migration algorithm is performed.

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