Analysis of the effect of watering on landmine detection: experimental and in-field results

Olga Lopera*, Jan Rhebergen†, Evert Slob‡, Nada Milisavljevic§ and Sébastien Lambot§

*Signal and Image Centre, Royal Military Academy, Brussels, Belgium
email: olopera@elec.rma.ac.be, nada@elec.rma.ac.be
†TNO Physics and Electronics Laboratory, The Hague, The Netherlands
email: jan.rhebergen@tno.nl
‡Dept. of Geotechnology, Delft University of Technology, Delft, The Netherlands
email: e.c.slob@tudelft.nl
§Dept. of Environmental Sciences and Land Use Planning, Université catholique de Louvain, Louvain-la-neuve, Belgium
email: sebastien.lambot@uclouvain.be

Abstract—In this study, we analyze the effect of watering on the GPR landmine detection performance in both laboratory and field conditions. In previous work, a parametric study was carried out on the influence of soil properties on signatures extracted from GPR data. In this paper, synthetic data are replaced by real measurements under different scenarios. Firstly, full-waveform inversion of the radar signal focused in the time domain on the surface reflection is applied for characterizing the soil electromagnetic properties. Secondly, target response is extracted using a new integrated filtering approach for enhancing buried targets detection. The GPR detection performance is then analyzed and a comparison between the computed and the measured results is carried out. Results demonstrate the applicability and show the limitations (attenuation, low dielectric contrast) of GPR for detecting antipersonnel landmines and improvised explosive devices in field conditions.

I. INTRODUCTION

Ground penetrating radar (GPR) is currently the subject of intensive research with respect to humanitarian demining applications as it permits to detect both metallic and non-metallic antipersonnel (AP) landmines by imaging rapidly and in a non-invasive way the shallow subsurface. An essential factor determining the detectability of buried landmines using GPR is the soil dielectric permittivity and its spatial distribution which governs GPR wave propagation. The dielectric permittivity of a soil depends on a number of factors including mainly the volumetric water content, which can vary considerably over time and space. Due to the resulting large spatio-temporal variability of the soil water content, it is therefore essential to characterize this property at the local scale and during the demining application.

Several authors have focused their research on the analysis of the effects of dielectric properties of the soil surrounding AP landmines on the performance of GPR for landmine detection [1]–[3]. In some of these studies, electromagnetic (EM) models have been coupled to pedotransfer functions to simulate EM wave propagation in soil-mine mediums considering different types of landmines and changes on soil water content. In [4], a finite-difference time-domain (FDTD) modeling program [5] is used to estimate two of the major effects of soil properties on GPR performance: attenuation and contrast. The authors have focused their study on two Colombian mine-affected soils and on typical Colombian AP landmines and improvised explosive devices (IEDs). From the simulated values of attenuation and contrast, GPR performance could be predicted. However, in real conditions, there are other parameters that adversely affect GPR performance, such as soil inhomogeneity and surface roughness, which are not considered in the simulations.

In this paper, the effects of attenuation and dielectric contrast on the GPR performance are illustrated through laboratory and field measurements, the latter applied to two Colombian mine-affected soils. Firstly, a stepped-frequency continuous-wave (SFCW) radar combined with an off-ground horn antenna in monostatic mode is used to acquire data. Measurements in laboratory conditions are carried out using a sand box and different landmines. Outdoor measurements are performed in two Colombian mine-affected soils where low- and non-metallic improvised explosive devices (IEDs) are buried. Soils in both experimental and in field conditions are subject to artificial watering and measurements are carried out considering different water content levels. Secondly, radar data are pre-processed to enhance landmine reflection detection by filtering out antenna and soil effects following the procedure proposed in [6], [7]. Finally, effects of attenuation and dielectric contrast are analyzed and interesting results are observed.

II. MATERIALS AND METHODS

A. Ground-penetrating radar

The GPR system used for the measurements is presented in Fig. 1. It consists of a SFCW radar that we emulate using a low-cost hand-held vector network analyzer (VNA) connected to a monostatic horn antenna via a 50 Ω N-type coaxial cable [8], [9]. The VNA is composed of a spectrum analyzer
Table 1. Characteristics of the three landmines buried in the sand and the two IEDs buried in the mine-affected soils. The AT landmine is a surrogate of the 72MT, the PMN2 is a Russian AP landmine and the M14 is an American AP landmine. ($\varepsilon_r$ is an approximative value.)

<table>
<thead>
<tr>
<th>Type</th>
<th>Case material</th>
<th>Metal content</th>
<th>Diameter (cm)</th>
<th>Width (cm)</th>
<th>$\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antitank (AT)</td>
<td>Plastic</td>
<td>high</td>
<td>30</td>
<td>8</td>
<td>13.6</td>
</tr>
<tr>
<td>PMN2 (AP)</td>
<td>Plastic</td>
<td>low</td>
<td>12.5</td>
<td>5.2</td>
<td>2.8</td>
</tr>
<tr>
<td>M14 (AP)</td>
<td>Plastic</td>
<td>low</td>
<td>5.6</td>
<td>4.2</td>
<td>2.8</td>
</tr>
<tr>
<td>IED1</td>
<td>PVC</td>
<td>no</td>
<td>6.3</td>
<td>13</td>
<td>3.6</td>
</tr>
<tr>
<td>IED2</td>
<td>PVC</td>
<td>low</td>
<td>6.3</td>
<td>13</td>
<td>3.6</td>
</tr>
</tbody>
</table>

(FSH6, Rohde&Schwarz, Munich, Germany) equipped with a bridge and power divider (VSWR, Rohde&Schwarz, Munich, Germany) to enable vector measurements. The antenna we use for the measurements is a linear polarized double ridged broadband horn antenna (BBHA 9120A, Schwarzbeck Mess-Elektronik, Schönau, Germany), of which dimensions are 22 cm of length and $14 \times 24$ cm$^2$ of aperture area. This antenna is highly directive (3-dB beam width of $45^\circ$ in the E-plane and $30^\circ$ in the H-plane at 1 GHz and $27^\circ$ in the E-plane and $22^\circ$ in the H-plane at 2 GHz) and operates in the 0.8-5.0 GHz frequency range. In this study, the measurements ($S_{11}$) were performed in the range 0.8-2.6 GHz with a frequency step of 6 MHz.

B. Measurement Setup

1) Preliminary experiment in laboratory conditions: A preliminary experiment in laboratory conditions was carried out at the test facilities of the TNO, The Hague, The Netherlands, on a sand box of 3 m depth and $1.5 \times 2.8$ m of surface area (see Fig. 1(a)). Radar measurements were performed over three different cylindrical landmines (one antitank (AT) and two AP), whose characteristics are described in Table 1. They were placed horizontally, longest side up. The relative dielectric permittivity of the sand varied from 2.7 to 7.5, corresponding to dry (initial) conditions and irrigation (time zero for the hydrodynamic event), respectively. The water content was modified by artificial irrigation and it was continuously measured with TDR. Collected data from TDR are compared with the estimated dielectric permittivity values calculated by full-wave inversion of the radar signal focused in the time domain on the surface reflection [10], showing quite good agreement.

To acquire 2-D data, the radar system was moved along the horizontal $x$-axis, crossing the center of the buried objects, using a scanning frame. Radar traces ($\mathbf{S}_{11}$) were recorded with a constant space step. The height of the antenna aperture above the sand was 12 cm (antenna phase center at 19 cm).

2) Outdoor measurements: Outdoor measurements were performed on silt loam and loamy sand soils from mine-affected areas in Colombia (see Fig. 1(b)). Their textural compositions and other characteristics were used in [4] for the simulations. Due to the impossibility of recreating all the scenarios considered in [4], radar measurements were carried out using to two different IEDs (IED1 and IED2, described in Table 1) buried at different depths (1 cm, 5 cm). Both soils were subject to three different water contents. The water content was modified by artificial irrigation and it was measured before each data gathering with TDR. Collected data from TDR are compared with the estimated dielectric permittivity values calculated by full-wave inversion of the radar signal focused in the time domain on the surface reflection [10], showing quite good agreement. For the loamy soil, the relative dielectric permittivity of the sand varied from 4.1 to 10.7. For the silt loam soil, it varied from 6.2 to 14.6. The antenna was placed over the center of the target, using a support frame. Radar traces ($\mathbf{S}_{11}$) were recorded with a constant space step. The height of the antenna aperture above the sand was about 18 cm (antenna phase center at about 25 cm).

III. RESULTS AND DISCUSSION

A. Laboratory conditions

In Fig. 2, the time-domain radar signal of the AT landmine buried at 35 cm in the sandy soil subject to different water contents is shown. These data have been pre-processed, i.e., antenna effects are filtered out using the methodology pro-
posed in [6]. The surface reflection is clearly identified at about 1 ns. For the first column, the target reflection can be also clearly seen at about 4.5 ns. The second column represents data collected after irrigation (time zero of the experiment). The response of the soil increases drastically and obscures the target reflection. In the third column, the water has infiltrated the soil after some hours and allows us to identify a weak target response at about 5 ns due to a high attenuation. The fourth column shows results after some days of infiltration. Interestingly, the target reflection is stronger than at the initial (dry) conditions. This could be caused by an accumulation of water on the top (surface) of the target, creating a larger dielectric contrast. This effect can be seen also for the other two targets (AP landmines) and it is described next.

In Fig. 3, the time-domain radar signal of the PMN2 landmine buried at 10 cm in the sandy soil subject to different water contents is shown. In Fig. 3(a), antenna effects have been removed from the raw data. The surface reflection is clearly identified at about 1 ns. However, the target signal is still invisible, and therefore, the methodology proposed in [7] for filtering out soil effects and enhancing target detection is applied. Results are shown in Fig. 3(b). In the first column, the target reflection is identified at about 2 ns. After the irrigation process (time zero, second column), a strong reflection can be seen at about 1.7 ns, which could correspond to an accumulation of water on the top (surface) of the target. This effect occurs in an earlier time than the same effect observed for the AT landmine, because this AP landmine is buried in the shallow subsurface. Multiple reflections can be also identified between 2.5 ns and 5.5 ns. The third column shows results after some hours. Here, a reflection appears at about 1.9 ns, which could correspond to the target reflection or can be due to the water accumulation on the top of the target. Note that, if it corresponds to the target reflection, its amplitude is larger than in dry conditions. The last column shows results after some days. The target reflection appears at about 2.1 ns. Due to a high dielectric contrast, its amplitude is larger than at the dry conditions.

The same effects are observed for the M14 landmine, buried at 12 cm. Results are shown in Fig. 4 (a) (data filtered from antenna effects) and (b) (data filtered from antenna and soil effects). In Fig. 4(a), the surface reflection is clearly identified at about 1 ns but the target reflection is completely obscured. In the first column of Fig. 4(b), the target signal is identified at about 1.5 ns. After watering (time zero), a larger reflection appears at about 1.4 ns, which could correspond to an accumulation of water on the top (surface) of the target. As for the PMN2, multiple reflections can be also identified between 2.5 ns and 5.5 ns. After some hours (third column) a strong reflection appears at about 2.2 ns, which could correspond to the target reflection (its amplitude is larger than in dry conditions) or can be due to the water accumulation on the top of the target. After some days (last column), the target reflection appears at about 2.4 ns and its amplitude is larger than in dry conditions, due to a higher dielectric contrast.
Fig. 4. a) Time domain representation of the radar signal (filtered from antenna effects) of the M14 landmine buried at 5 cm depth in the sand box. Radar signal is shown at four different times (water contents) during the infiltration process. (b) Same radar signals after filtering soil effects.

B. Outdoor conditions

In Figs. 5 (a) and (b), time domain representations of the IED1 signal show the effects of increasing the soil water content for the silt loam soil and the loamy sand soil, respectively. For these data, target has been buried at 5 cm depth. Here, signal is presented after applying the filtering algorithm proposed in [6], [7]. Results closely follow the predictions of the simulations presented in [4]. In the loamy sand soil, as the water content increases, the target signal is attenuated. And in the silt loam soil, the target signal is enhanced when the water content increases up to 0.20 m$^3$·m$^{-3}$, but already decreases for a water content > 0.20 m$^3$·m$^{-3}$. In [4], simulations have shown an enhancement on the target reflection even at a water content = 0.30 m$^3$·m$^{-3}$. This difference could be due to the effect of the soil inhomogeneity and surface roughness which adversely affect the GPR performance in real conditions. This factor is not taken into account in the simulations and can have an important effect on outdoor measurements.

IV. CONCLUSIONS

In this paper, some experiments are carried out and results are analyzed for illustrating the effects of watering on the detection performance of GPR. It is shown how a change on the dielectric contrast or the accumulation of water on the top of the target by watering could lead to an enhancement of target detection, improving the detection performance of GPR. However, attenuation due to changes on the water content can negatively affect the GPR detection performance for deeply buried objects. Modeling could help to determine optimal conditions for applying GPR to detect landmines. Nevertheless, soil roughness and soil heterogeneity have to be considered in the simulations to estimate accurately the performance of a GPR in a given scenario.

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