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Estimation of subsurface dielectric target depth for GPR planetary exploration: Laboratory measurements and modeling

Sebastian Emanuel Lauro [a,*], Elisabetta Mattei [b], Pier Matteo Barone [a], Elena Pettinelli [a], Giuliano Vannaroni [a], Guido Valerio [c], Davide Comite [d], Alessandro Galli [d]

[a] Department of Mathematics and Physics, "Roma Tre" University – Via della Vasca Navale 84, 00146 Rome, Italy
[b] DEIM-Industrial Engineering, University of Tuscia, Largo dell'università snc, 01100 Viterbo, Italy
[c] Institut d'Electronique et de Télécommunications de Rennes (IETR), Université de Rennes – Campus Beaulieu, Avenue du Général Leclerc, 35042, Rennes, France
[d] Department of Information Engineering, Electronics and Telecommunications, Sapienza University of Rome – Via Eudossiana 18, 00184 Rome, Italy

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ABSTRACT

In order to test the accuracy of Ground Penetrating Radar (GPR) in the detection of subsurface targets for planetary exploration, a laboratory scale experiment is performed based on a 'sand box' setup using two different bistatic GPR commercial instruments. Specific attention is paid to the challenging case of buried dielectric scatterers whose location and dimensions are of the same order of magnitude of the GPR antenna separation and signal wavelengths. The target depth is evaluated by using the wave propagation velocity measured with Time Domain Reflectometry (TDR). By means of a proper modeling of the different wave-propagation contributions to the gathered signal, the position of buried targets is correctly estimated with both GPRs even for rather shallow and small-size scatterers in near-field conditions. In this frame, relevant results for a basalt block buried in a silica soil are discussed. The experimental configuration is also simulated with an ad-hoc numerical code, whose synthetic radar sections fully confirm the measured results. The acquired information is of paramount importance for the analysis of various scenarios involving GPR on-site application in future space missions.

1. Introduction

Ground penetrating radar (GPR) is one of the most eligible geophysical system for space missions devoted to shallow-soil planetary exploration (Ciarletti et al., 2011; Grant et al., 2010; Leuschen et al., 2003; Vannaroni et al., 2004). This technique has several advantages with respect to other methods, such as: *i)* it does not need a strong contact between the instrument and the soil; *ii)* it performs quite well in dry and icy environments; *iii)* it is capable to generate a real image of the subsurface; *iv)* it ensures a good compromise between penetration depth and spatial resolution (Daniels, 2004; Jol, 2009).

As is well known, the capability to successfully detect a dielectric target with GPR mainly depends on the target/background electromagnetic contrast and on the overall attenuation within the subsurface. On the Earth, GPR signals are usually strongly attenuated by the presence of water in the soil, even though the difference in water content between the background material and the buried targets can increase the dielectric contrast and thus the detectability of the objects. Conversely, in a planetary environment (Mars, the Moon, etc.), the absence of water strongly improves the signal penetration depth, but potentially reduces the dielectric contrast between the background material and usual targets (Grant et al., 2004; Pettinelli et al., 2007). In this condition, the detection is still possible although it is not clear how accurate can be the estimation of the location of a dielectric target.

Laboratory and field experiments devoted to evaluate the GPR capability of detection and depth estimation of targets in extra-terrestrial terrains are quite challenging, especially when relatively large test sites are requested. Specifically, one of the critical aspects in this type of experiments is the choice of the soil analogue, which can simulate a dry (magnetic or nonmagnetic) soil or an icy terrain. A practical solution to this problem is the use of synthetic granular materials, having dielectric properties similar to a dry low-magnetic regolith or to the water ice (Pettinelli et al., 2003, 2005; Robinson and Friedman, 2002; Sen et al., 1981).

At laboratory scale, this problem has partly been addressed in order to define the detectability limits of basalt scatterers in different Martian-like scenarios: comparisons have specifically been performed between measured radar sections, collected on a dielectric box filled with a synthetic silica sand, and 'simulated' radar sections, derived by a suitable implementation of a numerical code (Valerio et al., 2012).

In this paper, we have performed a new different 'sand-box' experiment by employing separately two bistatic GPR systems equipped with similar ground-coupled dipole antennas that operate around the

* Corresponding author. Tel.: +39 0657337021.
E-mail addresses: lauro@fis.uniroma3.it (S.E. Lauro), elisabetta.mattei@unitus.it (E. Mattei), pmbarone@fis.uniroma3.it (P.M. Barone), pettinelli@fis.uniroma3.it (E. Pettinelli), vannaroni@fis.uniroma3.it (G. Vannaroni), guido.valerio@univ-rennes1.fr (G. Valerio), comite@die.uniroma1.it (D. Comite), galli@die.uniroma1.it (A. Galli).

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central frequency of 1 GHz: one system has the transmitting/receiving (Tx/Rx) antennas housed in a single case and the other system in two separated cases (with a different distance between the antennas). The main scope of the measurements has been to test independently the capability for such instruments of correctly estimating the depth of a shallow buried rock in a simple and smooth nonmagnetic environment simulating the Martian regolith. To this goal, a basaltic rock has been buried at different depths from the surface and, for each configuration, the depth of the top of the rock has been estimated evaluating the time delay of the scattered radar signals by means of both GPR systems. These values have then been compared with reference data estimated combining information on the physical location of the rock and on the electromagnetic velocity of the background material, measured independently with the time domain reflectometry (TDR) technique (Topp et al., 1980). The results of this study have thus been analyzed and discussed into the relevant theoretical frame. To this aim, the experimental results have been checked also with data derived by a suitable extension of the above-mentioned numerical setup simulating our experimental environment, as detailed next.

2. Materials and methods

2.1. Laboratory sand box

Our laboratory setup consists of a dielectric box equipped with GPR instrumentation, as illustrated in the picture of Fig. 1(a). This box (placed on two 80-cm high wooden tables, as shown also in Fig. 1(b)) is made of fiberglass (relative permittivity $\varepsilon_r \cong 3$) and is about 150-cm long, 100-cm wide, and 30-cm high (the walls are approximately 1-cm thick). Its lateral dimensions were chosen to prevent superposition between the signals scattered by targets buried in a low-permittivity material and those reflected by the side walls; as a consequence, any target located in the central part of the box can be detected with no significant interference.

The precise position and orientation of the GPR antennas is performed using a structure built on the top of the dielectric box (see again Fig. 1(a)). Guides running along the major axis of the box can support two mobile antenna holders. Each holder consists of a plexiglass plate, with wheels that can be moved along the guides, and of a central graduated pole with brackets holding the antenna that can be moved vertically (with an uncertainty of 0.5 cm) and also rotated up to 360° to change the dipole orientation. The system was specifically designed for a commercial bistatic GPR, having the two Tx/Rx antennas housed in two separated cases. (The structure can easily be modified to accommodate other types of antennas, even if, as discussed later, this is not directly available for the measurements performed with the radar having the pair of antennas housed in a single case).

In the experiment presented here, the box was filled with silica glass beads having a diameter range 400–800 μm, to simulate a planetary soil with electromagnetic properties similar to dry low-magnetic sand, regolith or water ice (Fa et al., 2011; Fujita et al., 2000; Pettinelli et al., 2005, 2007). A basaltic rock was used as dielectric target; this rock was chosen from a set of basaltic blocks collected in a quarry located near Rome, Italy, for its quasi-regular shape and its size comparable to the radar wavelengths in the material (see further for additional details).

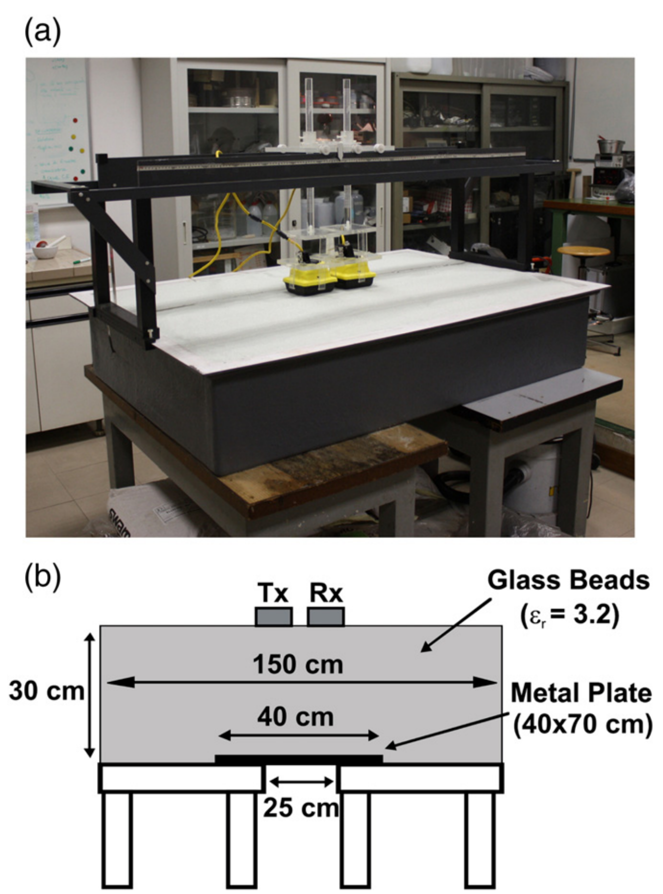

Fig. 1. The laboratory setup used in this work for the analysis of 'small' dielectric scatterers buried in a host medium. (a) Picture of the 'sand box' equipped with a bistatic GPR instrument; (b) Side view of the setup positioned on a pair of wooden tables.

2.2. Measurements of the dielectric properties of the materials

The wave velocities of both target and background materials were first measured using a TDR in order to derive independently their dielectric properties (Pettinelli et al., 2002; Topp et al., 1980). The data were acquired using a three-pronged probe (an open-ended transmission line formed by three stainless-steel parallel rods with a diameter of 0.4 cm, a separating distance of 3.2 cm, and a length of 10 cm). The probe was connected through a 50-Ω coaxial line to a *Tektronix 1502C* cable tester, which applies a step function wave front and measures the signal reflected by the impedance discontinuities. The wave velocity v is calculated as usual through:

$$v = 2L/t \tag{1}$$

where L is the length of the probe inserted in the material and t is the two-way travel time of the signal in the probe.

The wave velocity in the glass beads was measured by simply inserting the TDR probe in the material filling the box. In contrast, the velocity in the basaltic material was measured by drilling three parallel deep holes and pounding the TDR rods into a rock (the biggest of the set), previously cut in a regular shape (pseudo-cubic). Care was used to minimize void spaces and gaps around the TDR rods, which would have caused an overestimation of the velocity in the basalt (Annan, 1977).

For the glass beads a velocity value $v_{gb} = 0.168 \pm 0.003$ m/ns was found, and for the basaltic block a value $v_{bb} = 0.116 \pm 0.002$ m/ns. Note that the uncertainties were determined by the TDR step rise-time and the geometric features of the line, and were estimated by applying the error linear propagation formula (Taylor, 1997) to Eq. (1).

In both cases, the magnetic and lossy features of the materials can be neglected, so that, from the velocity measurement, the evaluation of the relevant dielectric permittivity is directly achieved. From the reported measured values of v, it was found a relative permittivity: $\varepsilon_{gb} = 3.2 \pm 0.2$ for the glass beads and $\varepsilon_{bb} = 6.7 \pm 0.2$ for the basalt block. The rather sharp dielectric contrast between the two materials gives a plane-wave reflection coefficient $r = -0.35$ (for vertical incidence),