Development of an Efficient Numerical Set-up to Predict the Performance of Ground-Penetrating-Radar Systems for On-site Earth and Planetary Applications

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Abstract

The aim of this study is to assess the features of a numerical tool able to predict in an efficient and accurate way the performance of a Ground Penetrating Radar (GPR) in many typical on-site Earth and planetary applications. Suitable implementation of a computer-aided-design (CAD) package is carried out by accounting for the most critical aspects of the GPR behavior (e.g., antenna elements, signal waveforms, physical characteristics of host media and scatterers). Representative examples of different application scenarios have been developed and tested. Full validation is achieved also by means of appropriate comparisons derived through ad-hoc experimental set-up.

1. Introduction

In the last years a great amount of interest has been devoted to the development of innovative ground-penetrating-radar (GPR) systems, due to the interest in diverse fields of applications: geophysical and archaeological investigations, environmental and climatic studies, biochemical analyses, energetic resources' localization, mining clearance, planetary explorations, etc. [1],[2]. A reliable estimate of the GPR behavior is fundamental in environments with a great variability of conditions: presence of clutter due to human activities, critical conditions due to soils with high attenuation or rough surfaces, planetary scenarios with partially-known electromagnetic characteristics. In all these cases, the possibility to efficiently perform a great number of parametric analyses, varying the environmental conditions and the parameters of the instrumentation, are of paramount importance in order to get a significant, inexpensive estimate of the GPR performance in terms of its basic elements.

The numerical characterization of a GPR set-up can involve either simplified or full-wave modeling of both the instrument (transmitting/receiving antennas, signal waveforms) and the operational environment (physical and geometrical characteristics of surface and subsoil). In this work, a full-wave time-domain approach based on a commercial high-frequency electromagnetic simulator has been implemented and tested in order to obtain reliable GPR results, which include correct sources, appropriate UWB signal waveforms, and realistic scattering effects. By means of this flexible and widespread tool, reliable investigations can be achieved in various GPR operational contexts.

As a testing example of such a numerical approach, a specific implementation is presented and discussed here considering a GPR application to planetary exploration. Specifically, in the frame of the future ExoMars mission, planned in 2018 [3], a GPR equipment (named "WISDOM") is expected to be mounted on the bottom of a rover performing on-site scanning of the Martian equatorial subsurface [4,5]. One of the aims of this mission is the drilling and collection of sample soil for chemical and biological analyses; the GPR should detect possible rocks buried in the Martian sand and help locating the safest and most interesting places to drill. In the specific simulations presented here, two types of equatorial soils have been considered: a sandy dry soil with no magnetic minerals, and a dry soil with a moderate content of magnetite. Their electromagnetic parameters are chosen from experimental data obtained from real samples, with suitable profiles for frequency-dependent behaviors [5-7]. A bistatic ultra wide-band (UWB) antenna has been designed and used in the scanning of the ground, to correctly simulate a typical GPR wideband waveform. The numerical results have been suitably post-processed under the typical 'radargram' form of the GPR instruments. In this way, it has been possible to directly check the reliability of the proposed approach by considering also experimental comparisons, achieved through measurements performed on an experimental GPR set-up in a synthetic silica layer, simulating nonmagnetic dry sandy soil. A commercial GPR is used to locate basaltic blocks buried in the mixture, thus obtaining measured radargrams in excellent agreement with the simulated results.

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2. A Laboratory Set-up for GPR Measurements

In connection with the design of the WISDOM radar, an experimental set-up has been implemented to simulate a typical equatorial Martian soil [5-7]. A dielectric basin of dimensions 1.5×1.0×0.3 m has been built and filled with a synthetic silica mixture of glass beads with average diameter 400−800 μm. Basaltic rocks of different shapes and sizes have been buried in the mixture (see Fig. 1(a), where the rocks are shown before being buried). A commercial bistatic GPR system [8] is placed on the free-space/mixture interface, transmitting a Gaussian-pulse waveform in the frequency band 0.5−1.5 GHz. This frequency band is consistent with the WISDOM system under design. In fact, it complies with the requirements of antenna compactness on the rover; on the other hand, since only the first meters of a dry subsurface should be investigated, soil attenuation is less significant than spatial-resolution issues: a central frequency of 1 GHz is therefore a reasonable choice. A sweep of the antennas is performed along the box in a common-offset mode (with a 15 cm offset between transmitter and receiver). At each position, a received trace is collected and regarded as column of a matrix, visualized through a suitable gray scale in the typical form of 'radargram' as in Fig. 1(b). In the radargram, direct and ground waves are visible at the time t = 1 ns; a similar flat echo refers to the bottom of the box, at around t = 4 ns. Each identifiable object produces an approximately hyperbolic echo, emphasized in blue and red in Fig. 1(b). The two smaller rocks at the left are less clearly identifiable, in particular the smallest is almost not visible. Anyway, due to its reduced dimensions, its presence would not create problems for the on-site drilling operation of the ExoMars rover.

3. The Numerical Modeling: Antenna Optimization

Simulated results can be compared with the realistic radargrams, measured in the experimental set-up, provided that the same signal waveform is implemented in the two approaches. For these reasons, the numerical simulations require a correct modeling of a bistatic antenna system with the mentioned ultra wide-band features. The antennas are here designed on the basis of the radiating element proposed in [9], where a UWB printed compact monopole antenna was shown for the frequency range 3−10 GHz. The antenna dimensions are suitably scaled, with the pair of radiating elements placed on the same substrate at a mutual distance of 15 cm (the same offset used in the experimental set-up). After an optimization of the overall structure (its top view is given in Fig. 2(a)), a good input matching in the desired band is obtained (Fig. 2(b)), and a fairly uniform and regular pattern (not shown here for brevity) is also achieved.

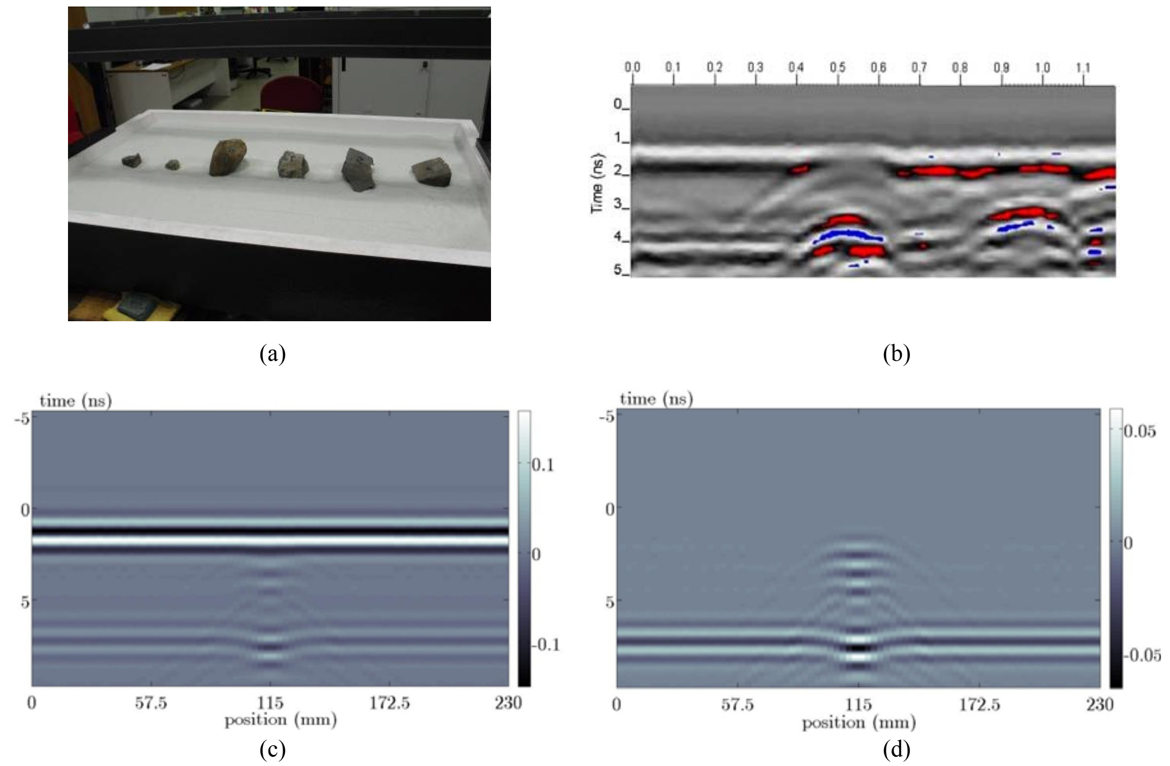
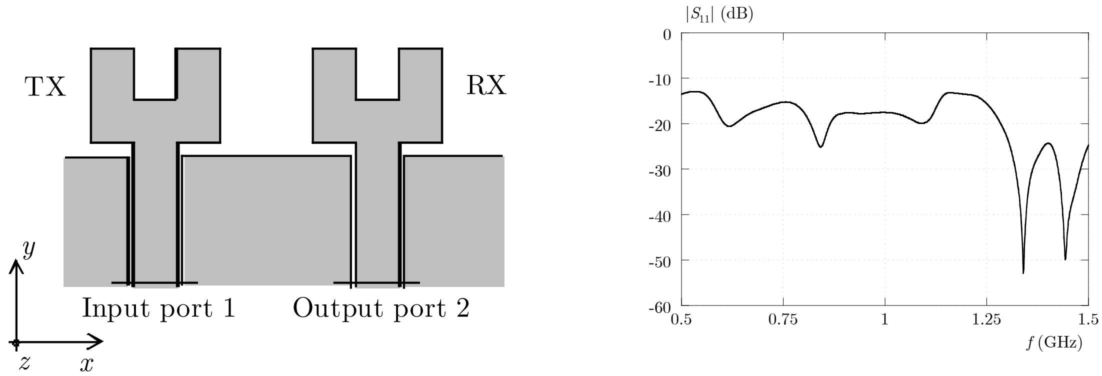


Fig 1: (a) A laboratory experimental setup; (b) A measured radargram (blue and red lines highlight the most visible rocks); (c) A simulated radargram of a box filled with nonmagnetic sand having height 50 cm, a conducting plane at the bottom, and a 20×20×10 cm basaltic rock 15 cm deep; (d) A regularized radargram of the environment in Fig. 1(c).



(a) (b)

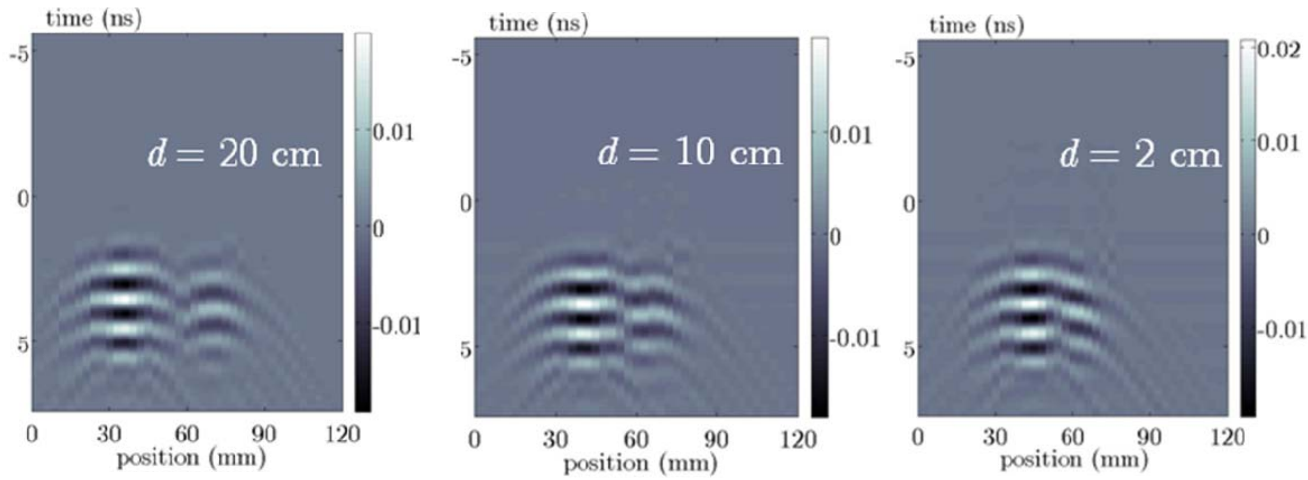
Fig 2: (a) Top view of the bistatic printed antennas implemented in the numerical approach (the metalizations are shown, printed on a substrate with ε_r = 3.66 and thickness 5.37 mm); (b) Magnitude of the reflection coefficient in dB (return loss) at the input port 1 of the transmitting antenna.

4. Results of Numerical Set-up: Detection of Scatterers

The environment described in Sec. 2 is here simulated with the software CST Microwave Studio [10]. The bistatic antennas have been modeled according to the analysis in Sec. 3. The electromagnetic parameters of the materials are chosen according to time-domain-reflectometry (TDR) measurements [11] performed on samples of suitable mixtures having a composition similar to Martian surface, according to last explorative missions [5-7]. Here two kinds of sandy dry soils are considered: the glass-bead mixture used in Sec. 2 and a similar mixture with the addition of a moderate content of magnetic minerals. In both cases, the frequency behavior of the relative permittivity is modeled through the 'universal law,' valid in frequency ranges far from resonances

$$\varepsilon_r = \varepsilon_1 + \frac{A}{(j\omega)^{1-n}} \tag{1}$$

and the parameters ε_1, A and n are estimated by interpolating the measured data at different frequencies; magnetic parameters are assumed constant [6],[7]. The estimation of such parameters allows for the evaluation of the attenuation per unit length α [6]; in the nonmagnetic sand, it is $\alpha \approx 0.07$ dB/m, and in the magnetic sand, where also magnetic losses are present, $\alpha \approx 0.5$ dB/m. These low values confirm that the soil attenuation is not a central problem in investigating the first meters of subsoil in connection to the WISDOM design.



(a) (b) (c)

Fig 3: Regularized radargrams of a simulated box with absorbing boundary conditions at its bottom, in the presence of two basaltic rocks, one 20×20×10 cm and the other 10×10×5 cm, buried 15 cm deep in a magnetic sand, at a variable distance *d* apart. (a) *d* = 20 cm; (b) *d* = 10 cm; (c) *d* = 2 cm.

A time-domain numerical simulation is performed for each position of the antennas along the ground, and the relative received signal is collected. After the whole sweep is simulated, since every simulation uses a different time discretization, all these signals need to be interpolated on the same temporal grid and regarded as a column of a matrix; such a matrix is visualized with a gray scale to yield a 'simulated radagram,' as in Figs. 1(c) and 1(d). In Fig. 1(c), a full radargram is shown (direct wave, reflecting bottom of the box, scattering basalt). In Fig. 1(d), the direct wave has been subtracted from every trace, as done, e.g., in [12]: in this new 'regularized' radargram the scattering effect of the basalt is not covered by the direct wave and is more easily recognizable. In Fig. 3, the regularized radargrams are shown for two rocks buried in a sandy magnetic soil at different planar distances, in order to verify the planar resolution Δx of the system in this environment. The results confirm the approximate estimation Δx = 15 cm obtainable from [1]. Other results, not shown here for brevity, allow interesting comparisons between GPR numerical model and measurements.

5. Conclusions

In this work, a numerical set-up based on a CAD tool has been implemented in order to conveniently predict the GPR performance in the investigation of earth and planetary subsoils. Realistic modeling has been considered for the bistatic antenna system, the signal waveform, and the types of grounds and rocks considered, including their dispersive and lossy features. In connection with the planned ExoMars expedition, particular interest has been devoted to realize Martian-like heterogeneous subsoil scenarios, analyzed through the numerical modeling and compared with a proper experimental set-up based on a commercial GPR instrument. Parametric analyses have been performed in order to assess the detectability of buried basaltic scatterers in a dry sandy soils, as requested in such explorative mission.

6. Acknowledgment

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7. References

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