Advanced Inversion Techniques
for Ground Penetrating Radar

Alessandro Fedeli, Matteo Pastorino, and Andrea Randazzo

Department of Electrical, Electronic, Telecommunications Engineering, and Naval Architecture (DITEN),
University of Genoa, Genova, Italy

Abstract—**Ground Penetrating Radar (GPR) systems are nowadays standard inspection tools in several application areas, such as subsurface prospecting, civil engineering and cultural heritage monitoring. Usually, the raw output of GPR is provided as a B-scan, which has to be further processed in order to extract the needed information about the inspected scene. In this framework, inverse-scattering-based approaches are gaining an ever-increasing interest, thanks to their capabilities of directly providing images of the physical and dielectric properties of the investigated areas. In this paper, some advances in the development of such inversion techniques in the GPR field are revised and discussed.**

Keywords—electromagnetic scattering, Ground Penetrating Radar, inverse problems.

1. Introduction

Ground Penetrating Radar (GPR) imaging has attracted a lot of interest in the last years. Nowadays, GPR systems are used in a great variety of research and application areas, including civil engineering [1]–[3], archaeological and geophysical prospecting [4], and cultural heritage monitoring [5]. Besides these classical areas, novel applications, such as through-wall imaging [6], contaminant detection [7], [8], tunnel and underground facility detection [9], and planet exploration [10], are attracting an ever-increasing attention.

In order to obtain accurate GPR images, it is necessary to carefully design the different parts of the system, ranging from the acquisition hardware to the signal processing algorithms needed to interpret the data. Moreover, there are usually several requirements, such as portability of the imaging systems, ultra-wide-band behavior, and limited coupling between transmitting and receiving antennas, which must be suitably considered in the GPR design and realization.

Concerning the data interpretation, there is also the need for performing some preparatory steps. In fact, usually scattered field extraction procedures must be employed in order to isolate the scattering contribution in the measured electromagnetic field data and to suppress the effects of clutter [11]. Moreover, it is needed to obtain a satisfactory estimate of the dielectric properties of the background medium [12] and to develop appropriate forward scattering

models [13], [14]. Antennas also represent key elements in the development of effective imaging systems. In fact, since they are located in close proximity with the ground (or more generally, with the host medium) accurate antenna characterizations are needed [15], [16].

Although GPR is now a standard inspection tool, there are still open issues that must be faced in order to further enhance the imaging capabilities. In particular, GPRs usually provide the output images in the form of B-scans, i.e. two-dimensional representations of the amplitude of the acquired scattered field data versus position and time. Such images can be quite difficult to interpret, especially when dealing with complex embedding media. Significant improvements can be obtained by reformulating the image formation process as an electromagnetic inverse scattering problem, where the main parameters describing the inspected scene are retrieved by inverting a proper model describing the scattering phenomena.

Several research groups around the world follow this point of view and very interesting numerical and experimental results have been already reported in the scientific literature. In this paper, some recent advances concerning the development of inverse scattering procedures for GPR imaging are revised and discussed.

2. GPR Imaging as an Inverse Problem

Subsurface imaging requires to solve an electromagnetic inverse scattering problem [17], i.e. starting from measurements of the scattered electric field collected in a proper measurement domain (e.g. a line over the air-ground interface), the aim is to retrieve some parameters describing the buried targets. Such parameters can be the full distributions of the dielectric properties or some features able to describe the target (e.g. its shape and position). As it is well known, such kind of problems turns out to be non-linear [18] and ill-posed [19]. Consequently, special care is required in the development of effective solving strategies.

2.1. Quantitative Electromagnetic Inversion

In the scientific literature, several methods have been proposed for tackling this task, not only in the field of subsurface imaging [20]–[24]. When a quantitative reconstruc-

tion is needed, e.g. when the aim is to retrieve the whole dielectric distribution of the inspected region, the full nonlinear problem must be taken into account. In this case, the imaging problem is usually recast as an optimization problem. Newton-like iterative methods [25]–[27] and gradient based solution procedures [28]–[30] are often used in this case. However, such approaches suffer from local minima problems [31], and thus are quite sensitive to the availability of a suitable starting guess. Stochastic minimization schemes have also been largely used [32]–[34]. These methods are in principle able to overcome the problem of local minima, but their numerical complexity is often higher than the one of deterministic approaches.

The imaging problem can be simplified by using linearized scattering models, e.g. by exploiting Born or Rytov approximations [17] in the case of penetrable scatterers and the Kirchhoff one for metallic objects. It is worth noting that the class of scatterers for which linear models effectively work is limited, and consequently, they usually do not allow a quantitative reconstruction. Anyway, such approaches are able to detect, localize and provide rough information about the scatterers' shape [35]. Moreover, linear estimations can be used to provide a starting point for non-linear quantitative approaches. In all cases, ill-posedness still remains an issue and consequently there is a need to employ some regularization scheme able to increase the stability versus noise [19].

2.2. Other GPR Imaging Techniques

In the framework of GPR imaging, migration algorithms are still being used for obtaining qualitative reconstructions of the inspected scene. Although such approaches have been initially developed in the framework of seismic imaging starting from qualitative concepts, they can be derived from approximated linear scattering models [36]. Some of the main approaches belonging to such class are back-propagation [37], time-reversal [38], and omega-kappa algorithms [39].

Beside the previous approaches, other qualitative methods, aimed at directly retrieving only a limited set of information about the embedded scatterers (e.g. their positions and external supports), have also been proposed. The linear sampling [40], the factorization, and the MUltiple SIgnal Classification (MUSIC) methods [41] belong to this class of inversion algorithms.

3. Recent Advancements in the Development of Inversion Techniques for GPR Imaging

In the last few years, several research activities have been performed in order to increase the imaging capabilities of GPR systems. In particular, beside the development of

novel inverse-scattering schemes, also methods for background removal and clutter rejection, soil models and medium estimation procedures, and GPR antenna modeling as well as deconvolution techniques have been proposed. Moreover, efficient approaches for solving the forward scattering problem by buried structures have also been developed.

3.1. Nonlinear Inverse Scattering Methods

Concerning the development of novel inverse-scattering schemes, several different approaches that extend and combine various methods previously mentioned have been discussed and evaluated in the scientific literature. Iterative multi-scale strategies have been proposed in [42]–[45], allowing an efficient usage of the limited amount of available information. In such techniques, the inspected area is iteratively reconstructed at different scales and at each scale specific inversion methods are used to obtain a quantitative reconstruction of the dielectric properties. Compressive sensing techniques have also been successfully applied in the field of GPR imaging [46]–[48]. In such approaches, the imaging problem is recast as a minimization in L^1 functional spaces. Consequently, sparse solutions (with respect to a properly selected basis) are obtained. Non-linear inversion algorithms performing a regularization in L^p Banach spaces (with p greater than 1) have also been recently proposed in [49], [50]. Such methods have been found to be very effective in reconstructing small targets and in reducing over smoothing and background artifacts with respect to standard inversion in the Hilbert space ($p = 2$).

3.2. Linear Inverse Scattering Techniques

Linear strategies have been considered, too. For example, in [51] a tomographic approach based on a truncated singular value decomposition (TSVD) inversion procedure has been compared to common procedures creating three-dimensional images by interpolating two-dimensional reconstructions. The problem of imaging buried targets from airborne gathered scattered field data has also been addressed in in [52] by using linear techniques.

3.3. Qualitative Approaches and Sampling Methods

Concerning the use of qualitative techniques, subspace-based approaches [53] and sampling methods [54] have been found to be quite effective. It is worth noting that sampling techniques able to provide quantitative reconstructions have also been recently developed [55], [56]. Approaches devoted to the localization and shaping of targets have also been reported. As an example, a technique belonging to this class has been presented in [57]–[59]. The positions of buried targets are detected by estimating the scattered field directions of arrival through subarrays processing followed by a statistical filtering and a triangularization technique.

Real-time detection of multiple buried scatterers has also been attained by using learning based techniques such as Support Vector Machines (SVM) [60].

3.4. Preprocessing Methods

Several novel algorithmic solutions have also been proposed for the preprocessing stage needed to successfully apply inverse scattering methods. Concerning the background removal and surface clutter mitigation problem, several strategies have been proposed in the past. Although average trace subtraction is often used for its simplicity, more effective approaches could enhance the reconstruction quality. As an example, in [61] a time-gating entropy based method is presented, which is able to provide better reconstructions than standard methods.

3.5. Soil Properties Estimation

The development of soil models and medium estimation procedures is also of great interest. In fact, such information is always required for correctly defining the electromagnetic models used in the inversion procedures. For example, in [62] an efficient algorithm for the computation of the time domain reflection coefficient in the transverse magnetic (TM) case has been developed in order to better characterize the surface reflections. In [63], [64] subspace methods and learning-based strategies have been used for the estimation of time delays, permittivity and roughness parameters within pavement structures. Estimation of specific soil parameters (e.g., moisture and clay content) have also been addressed in [65]. Moreover, in [12], [66], [67] inversion approaches have been employed for determining ground water contents in hydrological applications.

3.6. Inclusion of Advanced Antenna Models

Because of the complexity of the inverse problem which has to be solved in GPR imaging, reconstruction procedures can be significantly improved including detailed models of the involved antennas [68], [69]. These models can in principle allow to avoid the introduction of strong simplifying approximations, which clearly degrade the inversion results. The combination of far-field antenna models with a tomographic linear inverse scattering method (under the Born approximation) has been proposed in [70]. More recently, near-field models have been developed and included in inversion techniques [16], [71], [72].

3.7. Validation of GPR Inversion Approaches

In the development of inverse scattering methods, the validation of results is crucial. Frequently, inversion techniques are tested using synthetic data, and sometimes with experimental measurements (where experimental facilities are available). However, it is difficult to compare different approaches without a common benchmark. In this respect, it is worth noting that in the framework of the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar" an open database of radargrams is available [73]. This database, which contains both synthetic and experimental data (e.g., radargrams of concrete cells, roads, trees, columns, bridges, and so on) can be exploited by researchers for testing and comparing the performance of GPR inversion techniques. A contribution to this initiative has also been represented by the GPR imaging challenge organized within the IWAGPR 2017 conference [74], where a simulated three-dimensional realistic landmine detection environment has been proposed.

4. Conclusions

In this paper, a brief overview about advanced inversion techniques for GPR has been presented. GPR imaging can be seen as an inverse scattering problem, in which the dielectric properties of the buried targets have to be estimated starting from measurements of the electromagnetic field. With respect to free space configurations, the problem is more challenging. Therefore, the estimation of the soil properties and the use of advanced antenna models act important roles. Of course, several kinds of solution techniques can be adopted. In particular, both quantitative (linear and nonlinear) and qualitative approaches have been considered, discussing some of the recent research trends.

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Alessandro Fedeli received the B.Sc. and the M.Sc. in Electronic Engineering from the University of Genoa (Italy) in 2011 and 2013, respectively. In 2017 he received the Ph.D. degree in Science and Technology for Electronic and Telecommunications Engineering from the same University. His research activity is mainly focused on microwave imaging and computational methods for the solution of forward and inverse electromagnetic scattering problems. He is interested in biomedical imaging applications and advanced processing techniques for Ground Penetrating Radar (GPR) systems. He is WG Member of the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar", and Member of the IEEE Antennas and Propagation Society.

Alessandro Fedeli, Matteo Pastorino, and Andrea Randazzo

E-mail: alessandro.fedeli@edu.unige.it
Department of Electrical, Electronic, Telecommunications
Engineering, and Naval Architecture
University of Genoa
Via Opera Pia, 11A
I-16145 Genova, Italy

E-mail: matteo.pastorino@unige.it
Department of Electrical, Electronic, Telecommunications
Engineering, and Naval Architecture
University of Genoa
Via Opera Pia, 11A
I-16145 Genova, Italy

Matteo Pastorino is a Full Professor of electromagnetic fields at the Polytechnic School of the University of Genoa, where he has been the past Director of the Department of Biophysical and Electronic Engineering (DIBE, 2008–2011) and the past Director of the Department of Electrical, Electronic, Telecommunications Engineering and Naval Architecture (DITEN, 2011–2013). At present, he is a Fellow of the IEEE, the Chair of the National URSI Commission B (Fields and Waves), the responsible for the local section of the National Society of Electromagnetics (SIEM), and the chair of the local section of the Interuniversity Center for the Interaction between Electromagnetic Fields and Biosystems (ICEmB). He has coauthored about 450 papers in international journals and conference proceedings in the field of applied electromagnetics. Prof. Pastorino is an Associate Editor of the *IEEE Antennas and Propagation Magazine* and of the *IEEE Transactions on Instrumentation and Measurement*.

Andrea Randazzo received the laurea degree in Telecommunication Engineering from the University of Genoa, Genoa, Italy, in 2001 and the Ph.D. degree in Information and Communication Technologies from the same university in 2006. Currently, he is an Associate Professor at the Department of Electrical, Electronic, Telecommunications Engineering, and Naval Architecture of the University of Genoa. His primary research interests are in the field of electromagnetic scattering (both direct and inverse), smart antennas, and numerical methods for microwave nondestructive evaluations and imaging.

E-mail: andrea.randazzo@unige.it
Department of Electrical, Electronic, Telecommunications
Engineering, and Naval Architecture
University of Genoa
Via Opera Pia, 11A
I-16145 Genova, Italy