Short-Term Scientific Missions on Electromagnetic Modelling and Inversion Techniques for Ground Penetrating Radar – COST Action TU1208

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Abstract — **This work aims at offering an overview on the scientific results stemming from a selection of Short-Term Scientific Missions (STSMs) funded by the COST (European COoperation in Science and Technology) Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar" and dealing with the development of electromagnetic modelling and inversion techniques for Ground Penetrating Radar applications. STSMs are important means to develop linkages and scientific collaborations between participating institutions involved in a COST Action. Scientists have the possibility to go to an institution abroad, in order to undertake joint research and share experience, techniques, equipment and infrastructures that may not be available in their own institution.**

Index Terms — **Ground-Penetrating Radar, forward electromagnetic scattering, inverse electromagnetic scattering.**

I. INTRODUCTION

Founded in 1971, COST (European COoperation in Science and Technology) is the first and widest European framework for the translational coordination of nationally funded research activities. It is based on an inter-governmental agreement and currently comprises 36 European Countries plus one Cooperating State. COST's mission is to strengthen Europe's scientific and technical research capacity by supporting cooperation and interaction between European researchers, covering from basic to applied and technological research, and including research addressing issues of pre-normative nature or of particular social importance.

COST is funded from the budget of the European Research and Technological Development Framework Programme (Horizon2020) and operates through Actions, science and technology networks with a duration of four years. COST Actions are active through a range of networking tools, such as meetings, conferences, workshops, Short-Term Scientific Missions (STSM), training schools, publications and dissemination activities. COST currently supports over 300 Actions, on topics that embrace all fields of research. It also supports research networks spanning over several scientific domains (trans-domain) with broad, interdisciplinary dimension, as well as targeted networks aiming at strengthening the role that COST plays in a given policy domain, stimulating the strategic development of future-oriented societal challenges, and contributing to European policy goals. More information on COST, as well as a list of completed and running Actions, is available on www.cost.eu.

The COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar" [1] was launched in April 2013 and will end in April 2017. The main objective of this Action is to exchange and increase scientific and technical knowledge and experience on Ground-Penetrating Radar (GPR) techniques in civil engineering, while promoting a wider and more effective use of this safe and non-destructive technique. The Action currently involves almost 300 participants from 28 COST Countries (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, former Yugoslav Republic of Macedonia, Germany, Greece, Ireland, Latvia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom), one Cooperating State (Israel), six Near Neighbour Countries (Albania, Armenia, Egypt, Jordan, Russia, Ukraine), and six COST International Partner Countries (Australia, Colombia, Hong Kong Special Administrative Region of the People's Republic of China, Philippines, Rwanda, United States of America).

The scientific structure of the Action TU1208 includes four Working Groups. Working Group 1 focuses on the design of novel GPR instrumentation. Working Group 2 deals with the development of protocols and guidelines for GPR surveying of transport infrastructures and buildings, as well as for GPR sensing of underground utilities and voids. Working Group 3 studies electromagnetic forward and inverse methods for the solution of near-field scattering problems by GPR scenarios; it also deals with the development of data-processing techniques. Working Group 4 is concerned with applications of GPR outside from the civil engineering field and with integration of GPR with other non-destructive testing techniques. More information on TU1208 is available on the Action's website: www.GPRadar.eu.

STSMs are important means to develop linkages and scientific collaborations between participating institutions involved in a COST Action. Scientists have the possibility to go to an institution abroad, in order to undertake joint research and share experience, techniques, equipment and infrastructures that may not be available in their own institution. STSMs are particularly intended for Early-Career Investigators, i.e., young scientists who obtained their PhD since no more than 8 years when they started to be involved in the Action. Duration of a standard STSM can be from 5 to 90 days and research activities carried out during this short stay shall specifically contribute to the achievement of the scientific objectives of the supporting COST Action.

This paper aims at disseminating the scientific results stemming from a selection of STSMs funded by TU1208. All these STSMs were carried out within Working Group 3 of the Action. Research activities dealt with the development and use of electromagnetic-modelling methods (Section II) or inversion techniques (Section III) for GPR applications [2, 3].

II. STSMs on Electromagnetic Modelling for GPR

The first STSM presented in this Section was carried out by Lara Pajewski (Roma Tre University, Italy), visiting Antonis Giannopoulos at The University of Edinburgh (United Kingdom) [2-4]. The research activities focused on the electromagnetic modelling of GPR responses to complex targets.

A set of test scenarios was defined and proposed to the Members of Working Group 3, to test and compare their electromagnetic forward- and inverse-scattering methods. These scenarios include a series of concrete structures, which were modelled by using the well-known finite-difference time-domain simulator gprMax [5]. The content of the concrete structures varies with growing complexity, from a simple cell with rebar of different diameters embedded in it at increasing depths, to a final cell with a quite complicated pattern, including a layer of tendons between two overlying meshes of rebar. Other cells, of intermediate complexity, contain pvc ducts (air filled or hosting rebars), steel objects commonly used in civil engineering (as a pipe, an angle bar, a box section and an u-channel), void and honeycombing defects. For each cell, a subset of models with growing complexity was defined, starting from a simplified representation of the cell and ending with a more realistic one. In particular, the model's complexity was increased from the geometrical point of view, as well as in terms of how the constitutive parameters of involved media and GPR antennas were described.

Later on, the idea to define test scenarios was extended and Working Group 3 of the Action decided to gather a wider set of both numerical and experimental GPR responses from natural and manmade structures. Descriptions of the structures, along with synthetic and measured data, are available to interested researchers. The aim of this initiative is to realise a reference database, openly available to the scientific community through the Action's website, that researchers can use in order to test and validate, against reliable data, their electromagnetic forward- and inverse-scattering techniques, imaging methods and data-processing algorithms. Similar initiatives were successfully carried out in the past, in different areas, as the Ipswich [6] and Fresnel [7] databases in the field of free-space electromagnetic scattering (collections of experimental data measured on metallic and dielectric scatterers, in anechoic chamber) or the Marmousi dataset [8] in seismic science (a set of complex marine data, synthetically generated by using a two-dimensional acoustic finite-difference modelling simulator, which require advanced processing techniques to obtain a correct earth image).

Still during the STSM in The University of Edinburgh, Matlab procedures to facilitate the processing and visualisation of gprMax output data were developed. These procedures can be used to plot A-scans, B-scans, field maps in given time instants, to display geometries of two- and three-dimensional models, and to produce movies of the electric/magnetic field, showing how the field map changes with time in a certain region of the model. All procedures are available in [2].

The second STSM presented in this Section was carried out by Iraklis Giannakis (The University of Edinburgh, United Kingdom) who visited Lara Pajewski at Roma Tre University (Italy) [2, 9]. The study was concerned with the numerical modelling of horn antennas for GPR.

Air-coupled horn antennas with different parameters, as well as ridged horn antennas, were implemented in gprMax and tested in realistic modelled situations. Moreover, they were compared with previously-implemented ground-coupled bow-tie antennas. Accurate models of road pavement, soils and concrete were used to test and compare the antennas. In particular, stochastic methods were employed to realistically simulate the geometrical features of the involved media, whereas Debye approximations were adopted to model the dielectric properties of the media on the frequency range of interest.

Air-coupled antennas have been extensively used in GPR systems for pavement evaluation, as they are capable to detect thin layers, can operate safely in highway speeds because they don't need to be close to the ground, and are relatively easy to manufacture. The obtained results indicated that air-coupled antennas receive clear reflections from distinct layers within the pavement but they are not very effective to detect air cracks. On the other hand, by using ground-coupled antennas it is much easier to interpret hyperbolic responses from sub-superficial cracks.

The developed modelling framework is a powerful tool in evaluating the performance of high-frequency GPR transmitting and receiving antennas in realistic scenarios. This approach can therefore be used to effectively evaluate and improve antenna designs.

The present Section is concluded by shortly mentioning two further STSMs carried out in Working Group 3, on electromagnetic-modelling topics.

Hovik Baghdasaryan (State Engineering University of Armenia, Armenia) visited Marian Marciniak at the National Institute of Telecommunications (Poland) [4]: their research activities were concerned with investigating whether and how the Method of Single Expression [10] and Beam-Propagation Method [11], previously developed by the two Members to study the propagation of optical waves, could be applied in the GPR field.

Subsequently, Igor Prokopovich (Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences, Moscow, Russia) visited Marian Marciniak [4]: their joint work aimed at deriving an analytical solution to the two-dimensional forward-scattering problem of a pulsed field emitted by a dipole and impinging on a multilayered medium. The solution was obtained by extending the Bremmer-Brekhovskikh [12] approximation to the time domain; the theory was implemented and preliminary numerical results were obtained.

III. STSMs on Inversion Techniques for GPR

The first STSM presented in this Section was carried out by Mehdi Sbartai (Université Bordeaux, France) who visited Jan van der Kruk at Forschungszentrum Jülich (Germany) [3]. Their research activities dealt with the full waveform inversion (FWI) [13] of civil-engineering objects, with a particular focus on the inversion of GPR data collected on concrete structures.

Rebar buried in concrete represent easy targets for GPR, indeed their detection and location can be assigned to fully automatic algorithms. Nevertheless, rebar diameter is difficult to be estimated through a geometrical analysis of radar images. Migrated images tend to show rebar with overestimated diameters. Empirical procedures have been proposed in the literature, to estimate the rebar size, but results are always limited to a specific range of diameters and geometrical configurations. The main goal of the STSM was to use an original approach based on FWI to evaluate the size of circular-section objects embedded in concrete. FWI is based on the inversion of the full wave of radar signals and, until now, it was successfully used for soil permittivity and conductivity evaluation, whereas it has seen limited application to reinforced concrete, such as rebar/pipes recognition, evaluation of permittivity and conductivity of concrete, chlorides and moisture assessment [14, 15].

First, a ray-based approach [16] was used to estimate the diameter of reinforcing cylindrical elements from rebar hyperbola of synthetic GPR traces: the effectiveness of the approach was tested and results were subsequently used as starting parameters for FWI. Indeed, a good starting model is needed by FWI to limit the search range in the global search. On the other hand, the ray-based method is affordable to identify the hyperbola apex and propagation velocity, whereas for a reliable rebar-diameter estimation a better method is needed. Rebar of different diameters were considered and all synthetic traces were calculated by using gprMax.

A second step consisted in inverting the synthetic GPR traces with FWI. Data were inverted by using a combined global-local search, where the FWI was used to minimize the misfit between the true data and the inverted data. Results are very promising and the rebar diameter could be evaluated with high accuracy.

Nicolas Pinel (Alyotech Technologies, France) visited twice Sébastien Lambot at the Université catholique de Louvain (UCL), in Belgium [3]. This couple of STSMs was devoted to investigating how to model the effect of soil roughness in the inversion of ultra wide-band off-ground monostatic GPR signals. The final aim of the research was the accurate and noninvasive quantification of soil properties through the use of GPR.

During the first STSM, research activities focused on incorporating the asymptotic forward electromagnetic model developed by Pinel et al. [17] in the multilayer Green function code developed at UCL [18]. Numerical tests were made and compared with former measurements lead at UCL [19] to validate the implementation: a case of three layers (two interfaces) was considered, in which only the upper interface is rough. A further numerical validation by comparison with gprMax [5] was decided in order to validate the model and establish its validity domain.

During the second STSM, a measurement campaign was carried out, in order to validate the developed improved and extended theoretical model with real data. In particular, it was possible to perform measurements of the nadir backscattering from a multilayered medium made up of sand over stabilised cement on a perfectly flat copper plate, in order to evaluate the influence of the interface roughness of the sand and/or cement surface(s) on the radar response. The obtained preliminary results confirm that, as expected, the sand interface roughness damps the oscillations of the backscattered field amplitude. More thorough studies are ongoing to quantitatively analyse the measured data.

Finally, Simone Meschino (Airbus Gmbh, Germany) visited Lara Pajewski at Roma Tre University (Italy) [3, 4]. Aim of the STSM was to apply a method based on Sub-Array Processing (SAP) and on the use of Direction of Arrival (DoA) algorithms to GPR data, for the location of reinforcing elements in concrete.

The SAP-DoA method was originally developed to detect targets lying in the near field of an antenna array [21-24]. In such method, an array of receivers is partitioned in sub-arrays; for each of them, the number of incoming signals and their directions are predicted by using Direction-of-Arrival algorithms.

During the STSM, the technique was revised and extended to the case of ultra wideband signals, in order to investigate its applicability to Ground-Penetrating Radar (GPR) data processing. Tests were performed on reference synthetic data included in the database of COST Action TU1208. In particular, three concrete cells were considered: the first cell hosts five circular-section steel rods, with different radii and positions, in the second cell four metallic and dielectric rods are embedded, in the third cell an angle bar, a box section and a u-channel are present. The first and second tests aimed at demonstrating the capability of the procedure to correctly locate multiple objects in concrete. The third more ambitious test aimed at verifying whether the procedure could distinguish between different shapes of typical reinforced concrete elements.

The SAP-DoA procedure revealed to be quite robust for the first two cells: the targets could be detected and correctly located, apart from a bar with 3-cm diameter. At this stage, the procedure is not yet able to recognise different shapes. Concerning target location, the procedure is accurate in estimating the horisontal position and overestimates the burial depth. Globally, the results obtained for the three cells suggested that the limits of the technique lie in the density of reinforcing elements rather than on their geometrical shape. much work is still needed, in order to improve the procedure, define the accuracy of the approach and its limits.

IV. CONCLUSIONS

The paper offers an overview on the scientific results obtained during a selection of Short-Term Scientific Missions (STSM) funded by the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar" and dealing with the development of electromagnetic modelling and inversion techniques for Ground Penetrating Radar (GPR) applications. Topics range from the electromagnetic modelling of radar responses to complex concrete structures, to the numerical modelling of horn antennas for GPR. Further missions focused on the full waveform inversion of civil-engineering objects, the study of the effect of soil roughness in the inversion of ultra wide-band off-ground monostatic GPR signals, and the application of a method based on Sub-Array Processing and on Direction of Arrival algorithms to GPR data, for the location of reinforcing elements in concrete.

STSMs are one of the best instruments COST has. Most exchange visits yield impressive results in a short period of time, and lead to the publication of international journal or conference papers. Thanks to the flexible and bottom-up approach of this tool, researchers across Europe are encouraged and supported to work together – new international cooperations start and existing ones are strenghtened.

ACKNOWLEDGMENT

The Authors are grateful to COST (European COoperation in Science and Technology) for funding the Action TU1208 "Civil engineering applications of Ground Penetrating Radar," supporting the Short-Term Scientific Missions presented in this paper.

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