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Foreword to the Special Issue

We are very pleased to present the Special Issue “Recent Progress in Electromagnetic Theory and its Applications”, an outcome of the COST (European Cooperation in Science and Technology) Action TU1208 “Civil engineering applications of Ground Penetrating Radar”. The Special Issue comprises two parts: Part I includes eight papers on Ground Penetrating Radar (GPR) technology, methodology and applications; Part II contains six papers dealing with other applications of electromagnetic fields. Overall, the papers are authored by scientists from nineteen institutes in nine countries (Armenia, France, Germany, India, Ireland, Italy, Poland, Russia, and United Kingdom).

Part I

GPR overview

GPR is a non-destructive testing technique that uses low-power electromagnetic waves to produce high-resolution images of the subsurface and structures. A GPR instrument emits a wide-band electromagnetic signal and detects echoes coming from the environment, caused by discontinuities of electric and magnetic properties. By exploiting signal processing and imaging methods, the echoes recorded by the radar can be transformed into three-dimensional images, which enable seeing into structures that are opaque to the human eye.

GPR started being used in the 1970s for ice surveys in Antarctica and, through the decades, has gained broad acceptance internationally. Nowadays, it is successfully employed for a great variety of tasks. In civil engineering, GPR is used for the inspection of transport infrastructures (roads, highways, airport runways, railways, bridges, tunnels), to detect and locate voids, cavities and buried services (pipes, cables), for the monitoring of retaining walls, embankments and dams, for the investigation of buildings and foundations, to map soil layers, measure bedrock depth, and identify faults and fracture zones in rock (for geotechnical and geological studies, or foundation design) and more. In archaeology and cultural-heritage management, GPR is employed to discover and map buried archaeological artefacts, to inspect ancient buildings, bridges, columns and statues, to investigate frescoes, mosaics and decorations, and to study the internal conditions of several other objects of historical value. GPR is also used for the inspection of natural structures of historical, geological, biological

or landscape conservation value, such as trunks and roots of veteran trees, glaciers, caverns, fossil beds, sand dunes, and more. Furthermore, GPR is extensively applied in agriculture, for the investigation of the bottom of lakes and coastal regions, for planetary explorations, as an auxiliary tool in autonomous transport systems, and more.

At present, GPR systems typically operate in the 10 MHz – 10 GHz range. Generally, there is a direct relationship between the frequency of the electromagnetic waves emitted by the radar and the resolution that can be obtained. Conversely, there is an inverse relationship between frequency and penetration depth. Hence, high frequencies are used to detect small, shallow targets and low frequencies are used to detect larger, deeper targets. The antennas have dimensions comparable to the wavelengths of the signals. Therefore, the size of a GPR instrument is basically defined by the frequency range of operation. Some systems use two or more antennas operating simultaneously over different frequency ranges. To couple the electromagnetic energy into the investigated structure, the antennas can operate in close proximity (ground-coupled antennas), else at a limited distance above the structure (air-coupled antennas).

A GPR can be monostatic, bistatic, or multistatic – as all radar systems. In monostatic systems, a single antenna is used for transmitting and receiving electromagnetic signals (currently, this type of GPR can be considered as obsolete and is seldom used). A bistatic system uses two separate antennas for transmitting and receiving, which are often housed in a single module. Antennas in independent modules represent an interesting technological solution that allows placing the transmitter and receiver on the two opposite sides of the investigated structure, thus halving propagation and attenuation losses. Multistatic systems are composed by multiple spatially diverse monostatic or bistatic radar components, usually with a shared area of coverage. At the present time, commercial multistatic GPR systems are implemented as multiple bistatic systems and their main advantage is that they enable faster data collection by increasing the extension of the investigated area per time unit. Furthermore, they make it easier for the operator to produce three-dimensional images.

There are two main types of GPR: impulse and step-frequency systems. Impulse systems are the most widely used, they operate in the time domain and emit a series of short electromagnetic pulses (normally, of 1–10 ns duration). Step-frequency systems are less common, although they are less expensive. They operate in the frequency domain and emit a series of harmonic waves, which frequency is progressively incremented across a broad spectrum in a step-wise fashion. By exploiting the inverse Fourier transform (from frequency to time-domain), a step-frequency GPR provides results equivalent to those measured by an impulse GPR. The step frequency approach is possible because the investigated scenario is regarded as a time-invariant system and the received signal is a linear function of the transmitted one. Impulse systems are typically more sensitive to radio frequency interference and may require an averaging of measurements to improve the signal-to-noise ratio. Step-frequency systems can process a higher energy without increasing the maximum level of the signal. The thermal noise at their receiver is lower, therefore the signal to noise ratio is higher. Another advantage of step-frequency systems is the ability to skip frequencies that could interfere with broadcast stations. A drawback of step-frequency systems is that attention must be paid to the aliasing problem, due to the sampling of the harmonic answer. This is resolved by using a frequency step small enough, which slows down the collection of data.

Data interpretation and visualization

To enable analysis and interpretation of results, GPR data are normally plotted as a two-dimensional map, showing the amplitude of the field measured by the receiver as a function of time and position (B-scan or profile). Time can be replaced by depth when the propagation velocity in the subsurface or structure is known. Looking at single traces (A-scan, amplitude of the field measured by the receiver as a function of time in a specific position) is also useful, in most applications. When several parallel profiles are acquired, a three-dimensional matrix of field amplitudes is available (C-scan) and three-dimensional images of the investigated scenario can be produced. From a C-scan it is possible and straightforward to obtain horizontal slices of data, i.e. plan views of field amplitudes at designated depths, which are very useful in most applications.

In some cases, raw GPR data are examined and interpreted. More often, signal processing algorithms are applied to the data, as required by the specific application and situation. The steps and algorithms may vary according to each survey, and normally involve filtering to remove unwanted noise, gain adjustment to balance signal strengths, migration to remove diffraction effects, corrections for variations in surface topographic elevation, and improvement of graphic display by using suitable color palettes. For complex scenarios and/or for analyzing and interpreting reflections coming from deep layers, more advanced procedures are used.

After the processing, GPR results are interpreted by recognizing reflection and diffraction patterns on the radargrams and by determining their position. Discrete buried objects with circular cross-section typically appear as hyperbolic reflections in the raw data, with hyperbola prongs projected downwards like an inverted V shape. Subsurface layers appear as continuous reflectors on the radargrams. More in general, reflection and diffraction patterns in the raw GPR profiles may have different shapes, which do not resemble the true shape or orientation of the scatterers. Various factors, including the innate design of the survey equipment and the complexity of electromagnetic propagation in the scenario, can disguise complex structures recorded on GPR profiles. For simple scenarios, such as regular structures hosting widely spaced targets, reflection patterns can be adequately interpreted by trained operators. For complex scenarios, such as natural subsoil with stones and rocks, ancient bridges, or any structures hosting closely spaced targets, it may be convenient to aid the interpretation by using an electromagnetic simulator or by applying to the radargrams suitable imaging and inversion algorithms.

The COST scientific programme

A significant contribution to the GPR technique has been given by the COST Action TU1208 “Civil engineering applications of Ground Penetrating Radar”.

COST is the longest-running European framework supporting cooperation among scientists and researchers across Europe and beyond. Founded in 1971, it is currently integrated in the Horizon 2020 programme. It contributes to reducing fragmentation in European research investment, building the European Research Area (ERA) and opening it to worldwide cooperation. It also aims at constituting a “bridge” towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of excellence in key scientific domains. Gender balance, support to early-career investigators and inclusiveness are strategic priorities of the COST programme.

COST does not fund research itself, but provides support for activities carried out within Actions: these are bottom-up science and technology networks, centered around nationally funded research projects, with a four-year (or, exceptionally, slightly longer) duration and a minimum participation of five countries. The Actions are active through a range of networking tools, such as meetings, workshops, conferences, training schools, short-term scientific missions and dissemination activities. They are open to researchers and experts from universities, public and private research institutions, nongovernmental organizations, industry and small and medium-sized enterprises. By creating open spaces where people and ideas can grow, COST fosters the birth of new ideas and unlocks the full potential of science.

For more information about COST, please visit www.cost.eu.

The Action TU1208

The Action TU1208 started in April 2013 and is coming to an end in October 2017. It involves more than 300 experts from 150 partner institutes in 28 COST countries (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, former Yugoslav Republic of Macedonia, Germany, Greece, Ireland, Italy, Latvia, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, and the United Kingdom), a COST cooperating state (Israel), 6 COST near neighbor countries (Albania, Armenia, Egypt, Jordan, Russia, Ukraine) and 6 COST international partner countries (Australia, Colombia, Hong Kong, The Philippines, Rwanda, the United States). University researchers, software developers, civil and electronic engineers, archaeologists, geophysics experts, non-destructive testing equipment designers and manufacturers, end-users from private companies and public agencies have participated in the Action.

The scientific structure of Action TU1208 includes four Working Groups (WGs), which research activities cover all areas of the GPR technology, methodology, and applications.

- WG 1 focuses on the development of novel GPR instrumentation. Within this WG, novel equipment has been designed, realized and tested. Moreover, new tests have been proposed for checking the performance and stability of GPR systems.
- WG2 focuses on the use of GPR in civil engineering. This WG has developed guidelines for GPR inspection of flexible pavements, utility detection in urban areas, and evaluation of concrete structures. Recommendations for a safe use of GPR have been produced. Among the most interesting outcomes of WG2, it is worth mentioning a catalogue of European test sites where GPR equipment and procedures can be verified and tested. Additionally, WG2 has developed a wide series of investigations and case studies where GPR has been successfully used in a plethora of different civil-engineering works.
- WG3 studies electromagnetic forward and inverse methods for the solution of near-field scattering problems by buried structures, imaging techniques and data processing algorithms. This WG has released free software for the electromagnetic modeling of GPR scenarios and for the processing of GPR data. A database of radargrams has been composed and organized, openly available for researchers who can use the proposed datasets to test and validate their electromagnetic forward- and inverse-scattering techniques, imaging and signal-processing methods.
- WG4 deals with the applications of GPR outside from the civil engineering area and with the combined use of GPR and complementary non-destructive testing methods. The most interesting output of this WG is a wide series of case studies showing how GPR can be applied in different fields, both in well-established and emerging applications. Special attention has been paid to the use of GPR for the management of our cultural heritage.

It is worth reporting that all WGs have been active in training activities (16 Training Schools were organized in four years) and produced an open-access educational package for teaching GPR in the university.

For more information about TU1208, please visit www.GPRadar.eu.

The issue contents

In the opening paper of the Special Issue, entitled *Improving the GPR Detectability Using a Novel Loop Bowtie Antenna*, the Authors K. K. Ajith and Amitabha Bhattacharya compare the performance of a traditional resistive-capacitive (RC) loaded bowtie against a novel loop loaded bowtie. The bandwidth, gain and radiation patterns of both antennas are measured in the free-space and results are compared with simulations performed by using commercial software implementing the finite-integration technique. GPR profiles are acquired in various scenarios, with brass and iron pipes buried in the soil, or dry bamboo, and over reinforced concrete. GPR images produced by the loop-loaded antenna are better than those of the RC loaded bowtie, for all the considered targets. The Authors indicate that the loop loading technique may be employed in existing antennas also, to enhance their radiation properties.

The Authors of the paper entitled *Analytical Investigation on a New Approach for Achieving Deep Penetration in a Lossy Medium: The Lossy Prism*, Fabrizio Frezza, Patrizio Simeoni, and Nicola Tedeschi, investigate an innovative use of a lossy prism to generate an inhomogeneous wave. The proposed prism allows achieving a deeper microwave penetration in a lossy medium than a leaky-wave antenna.

In *Multiple-ring Circular Array for Ground-Penetrating Radar Applications: Basic Ideas and Preliminary Results*, Roberto Vescovo and Lara Pajewski study the possibility of using a multiple-ring circular array as a GPR antenna array. The theory behind the idea is described and preliminary results are presented. The proposed configuration allows achieving a wide frequency band with a low dynamic range ratio. Moreover, the synthesis of the array can be easily performed at a single frequency within the range of interest.

The Special Issue continues with the paper *Enhancement of Air-ground Matching by Means of a Chirped Multilayer Structure: Electromagnetic Modeling with the Method of Single Expression*, by Hovik Baghdasaryan, Tamara Knyazyan, Tamara Hovhannisyan, Marian Marciniak, and Lara Pajewski. In this contribution, a non-uniform multilayer structure contacted with the ground is designed, which reduces the back-reflection of electromagnetic waves towards the transmitting antenna and allows a deeper penetration into the ground. The structure is modeled by using the method of single expression, an analytical-numerical technique ideated and developed by Hovik Baghdasaryan.

The Authors of the paper *Advanced Inversion Techniques for Ground Penetrating Radar*, Alessandro Fedeli, Matteo Pastorino, and Andrea Randazzo, provide a short and useful overview of advanced inversion techniques for GPR. They address nonlinear and linear inverse scattering methods, qualitative approaches and sampling, and pre-processing methods. The need for initiatives dedicated to the validation of GPR inversion approaches is pointed out by the Authors, as well.

SPOT-GPR: A Freeware Tool for Target Detection and Localization in GPR Data Developed within the COST Action TU1208, is authored by Simone Meschino and Lara Pajewski. This paper presents and describes SPOT-GPR (release 1.0), free software implementing an innovative Sub-Array Processing method for the analysis of GPR data with the main purposes of detecting and localizing targets. The approach implemented in SPOT-GPR exploits the matched-filter technique, which has never been used before in the GPR field. The software is written in Matlab and it comes with a graphical user interface. Two examples of applications are provided in the paper, where SPOT-GPR is successfully employed for detecting and locating reinforcing elements in concrete cells. The obtained results are compared with those of a standard hyperbola-fitting approach, which is commonly used for the processing of GPR data when circular-section cylindrical targets are present, and SPOT-GPR demonstrates a good functioning.

The Author of the paper *Development of Data Processing Tools for the Analysis of Radargrams in Utility Detection Using Ground Penetrating Radar*, Florence Sagnard, reports on advanced processing techniques that can be used to extract quantitative information from radargrams recorded over pipes and strips with lateral dimension less than around ten centimeters, in a noisy background, in case of a low image quality, and with overlapping between signatures. The Author proposes a procedure suitable for small object detection and he enriches the model by exploiting the polarization diversity. The Author recommends including further advanced algorithms in the procedure, such as space-frequency time-reversal matrices and wavelet transform, to account for hyperbola misshapeness.

Part I of the Special Issue is concluded with the paper entitled *Search for Chelyabinsk Meteorite Fragments in Chebarkul Lake Bottom (GPR and Magnetic Data)*, authored by Vladimir Buzin, Dmitry Edemsky, Sergey Gudoshnikov, Vladimir Kopeikin, Pavel Morozov, Alexey Popov, Igor Prokopovich, Vladimir Skomarovsky, Nikolay Melnik, Andrey Berkut, Sergey Merkulov, Pavel Vorovsky, and Leonid Bogolyubov. The Authors have employed GPR in their search in Chelabinsk. They provide a detailed description of GPR use in lake water conditions and discuss the limits of its applicability in such an environment. An impressive technical and photographic documentation enclosed in the paper makes you feel as you are actually participating in the Chelabinsk surveys.

Part II

Other applications of electromagnetic fields

Part II of the Special Issue is opened with two papers on antenna arrays for free-space applications. The first contribution is entitled *Multi-Objective Evolutionary Optimization of Aperiodic Symmetrical Linear Arrays*, authored by Francesco Napoli, Lara Pajewski, Roberto Vescovo, and Marian Marciniak. In this paper, a multi-objective approach is used for the design of aperiodic linear arrays of antennas. The adopted procedure is based on a standard Matlab implementation of the Controlled Elitist Non-Dominated Sorting Genetic Algorithm-II and broadside symmetrical arrays of isotropic radiators are considered, with both uniform and non-uniform excitations. The work focuses on whether, and in which design conditions, aperiodic solutions obtained by the adopted standard multi-objective evolutionary procedure

can approximate, or outperform, the Pareto-optimal front for the uniform-spacing case computable by the Dolph-Chebyshev method.

In the paper *Reconfigurable Antenna Arrays with Phase-only Control in the Presence of Near-field Nulls*, by Giulia Buttazzoni and Roberto Vescovo, the Authors present a novel effective iterative algorithm for the power synthesis of reconfigurable antenna arrays. This approach allows designing antenna arrays of arbitrary geometry with phase-only control, simultaneously reducing the near-field amplitude in a region close to the antenna. The near-field reduction is obtained by imposing that the field vanishes at a prescribed number of suitably located points. Strong field reductions are obtained without increasing the dimensions of the problem, thus keeping low the required computational time.

Part II of the Special Issue continues with two contributions on grating structures.

The paper entitled *The Optimum-efficiency Beam Multiplier for an Arbitrary Number of Output Beams and Power Distribution*, by Fabrizio Frezza, Marian Marciniak, and Lara Pajewski, focuses on the problem of splitting a beam into a set of equi-intense output beams, or in beams that respect a given power distribution. The diffraction efficiency of a beam multiplier is the fraction of the incident beam power that is converted into the power of the desired output beams: the maximization of this parameter is a fundamental target in designing beam multipliers. The Authors consider beam splitters constituted by periodic diffractive elements and prove that an optimum-efficiency beam multiplier with an arbitrary number of diffraction orders exists. They derive its phase transmittance in an analytic form, by exploiting methods from the calculus of variation. Numerical examples are presented and commented on.

In the paper *Influence of Chirped DBR Reflector on the Absorption Efficiency of Multinanolayer Photovoltaic Structures: Wavelength-scale Analysis by the Method of Single Expression*, by Hovik Baghdasaryan, Tamara Knyazyan, Tamara Hovhannisyan, Gurgen Mardoyan, Marian Marciniak, and Trevor Benson, a novel solution to the topical problem of enhancing the efficiency of photovoltaic elements is proposed. In particular, the Authors investigate the use of a non-uniform multilayer reflector placed under the p-i-n semiconductor junction. The electromagnetic modeling of light interaction with the photovoltaic structure is performed by using the method of single expression, where no division on counter-propagating waves is exploited.

The following two papers of Part II are concerned with photonic and electromagnetic band-gap materials.

In *A Photonic-Crystal Selective Filter*, authored by Lara Pajewski and Giuseppe Schettini, a highly selective filter is designed, working at $1.55\ \mu\text{m}$ and having a 3-dB bandwidth smaller than 0.4 nm, as is required in Dense Wavelength Division Multiplexed systems. Different solutions are proposed, where photonic crystals made of rectangular- or circular-section dielectric rods are used, or else photonic crystals with holes drilled in a dielectric bulk. The required polarization and frequency selective properties are achieved by introducing a defect in the periodic structure. The device is studied by means of the Fourier Modal Method. Practical guidelines about advantages and limits of the investigated solutions are given.

In *Experimental Analysis of a Directive Antenna with a 3D-EBG Superstrate*, by Lara Pajewski, Fabrizio Frezza, Marian Marciniak, Emanuele Piuze, and Giorgia V. Rossi, electromagnetic band-gap (EBG) resonator antennas are studied. A woodpile is used to enhance the gain of a patch antenna. The compound radiating system is thoroughly characterized in the 8–12 GHz frequency range, in a shielded anechoic chamber, by using a vector network analyzer. The return loss, gain, and radiation patterns in the E- and H-planes are measured, for the patch antenna covered with the woodpile. The EBG superstrate is positioned at different suitable distances from the antenna and its orientation is varied. A gain enhancement of about 10 dB is achieved. The paper is concluded with a series of promising ideas for future work.

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Lara Pajewski
Hovik Baghdasaryan
Marian Marciniak
The Guest Editors