Author's Accepted Manuscript

www.elsevier.com/locate/sigpro

# Editorial of SI: GPR signal processing

Nikos Economou, Francesco Benedetto, Maksim Bano, Andreas Tzanis, Jonathan Nyquist, Karl-Josef Sandmeier, Nigel Cassidy

PII: S0165-1684(16)30183-9
DOI: http://dx.doi.org/10.1016/j.sigpro.2016.07.032
Reference: SIGPRO6224

To appear in: *Signal Processing*

Cite this article as: Nikos Economou, Francesco Benedetto, Maksim Banc Andreas Tzanis, Jonathan Nyquist, Karl-Josef Sandmeier and Nigel Cassidy Editorial of SI: GPR signal processing, *Signal Processing* http://dx.doi.org/10.1016/j.sigpro.2016.07.032

## 1. Introduction

Ground penetrating radar (GPR) is a non-destructive geophysical method that uses electromagnetic waves to image the subsurface. A typical GPR system has three main components: transmitter and receiver, directly connected to the transmitting and receiving antennas, and a control unit. Electromagnetic pulses are transmitted into the subsurface and the earth response is recorded. The GPR method is characterized by the rapidly decaying amplitude of the electromagnetic waves, together with the loss of the relevant higher frequency harmonics. Thus, GPR data are highly non-stationary and processing is inherently a challenge.

GPR technology has seen tremendous progress in its range of applications, as well as in the analysis and processing algorithms, over the past 20 years. GPR applications currently include sedimentology, ground-water contamination, glaciology, archaeology and cultural-heritage management, civil and geotechnical engineering, planetary exploration, demining, and more. Even though there is an undoubted promise for this technique regarding the most of the above-mentioned applications, the most successful results have come from glaciology, archaeology and civil engineering.
GPR signal processing and subsequent display/presentation of the results are of paramount importance to GPR operators and end-users. They should be considered as an integrated part of the methodology, as well as a prerequisite for successful surveying and data interpretation.

In April 2013, the COST (European COoperation in Science and Technology) Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar" officially started. This Action focuses on the exchange of scientific-technical knowledge and experience of GPR techniques in civil engineering. It has established several new active links between universities, research institutes, companies and end users working in the field, fostering and accelerating its long-term development in Europe. It is also having a strong impact in promoting throughout Europe a wider and more effective use of this safe and non-destructive inspection method. The Action is now in progress and the leading Guest Editors of this Special Issues are coordinating the scientific activities of Project 3.4, focused on the development of advanced GPR data-processing algorithms. Such Project is part of Working Group 3 of the Action, which is dealing with the improvement and implementation of accurate and fast electromagnetic-scattering methods for the characterization of GPR scenarios, imaging and inversion techniques, and effective data-processing algorithms for the elaboration of GPR data collected during civil-engineering surveys. We are very honoured to report here a brief comment about the COST programme and the Action TU1208 by the Chair, Dr. Lara Pajewski, and the Editorial Coordinator, Prof. Andrea Benedetto:

*"COST is the longest-running European framework supporting transnational cooperation among researchers, engineers and scholars across Europe and beyond. It is a unique means for them to jointly develop their own ideas and new initiatives across all fields in science and technology. By faithfully following COST's inclusiveness policy and key principles, and by successfully exploiting all COST networking tools, the Action TU1208 has created a wide, pan-European, trans- and multidisciplinary network, where useful knowledge has been generated and shared. A critical mass of people with experience and competences in the GPR field has been built, according to the European Research Area goals: more than 300 experts are actively participating to TU1208, from 147 Institutes in 28 COST Member Countries, a Cooperating State, 6 Near Neighbour Countries and 11 International Partner Countries. The network has also set up fruitful cooperation with renowned European and national associations. Research activities carried out in TU1208 include all aspects of the GPR technology and methodology: design, realisation and testing of radar systems and antennas; development and testing of surveying procedures for the monitoring and inspection of natural and manmade*

*structures, in civil engineering and beyond; integration of GPR with other non-destructive testing methods; and finally, advancement of electromagnetic modelling, imaging, inversion and data-processing techniques, where the latter are the main subject of this Special Issue. Thoughtful processing and proper graphical representation of collected data are essential steps of a GPR survey, in all application areas: if properly carried out, they crucially facilitate radargram analysis and interpretation. Additionally, although in many cases radargrams are still inspected with a qualitative approach (and a number of real problems can be satisfactorily addressed in this way), data-processing techniques are evolving fast and the quantitative analysis of GPR results is increasingly expanding. Apparently, the ability to translate electromagnetic information stored into radar signals into other useful application-specific engineering or scientific quantities is of great importance: it enables a more advanced employment of GPR in its consolidated application fields, besides extending the usability of this technique towards new horizons. In this promising and variegated framework, the Action TU1208 has decided to publish a Special Issue focused on cutting-edge data-processing techniques for GPR, and related topics. We are truly grateful to the Chief Guest Editors and co-Guest Editors for their proactive contribution to COST Action TU1208 and for all the hard work they have done to compose this most interesting collection of excellent papers, as well as to the Authors who decided to publish the outcomes of their best-quality research work in this volume".*

Our intent was to collect into this Special Issue relevant research contributions from academics and industry professionals in the GPR signal processing area, as well as from practitioners and engineers working in the field of GPR. This Special Issue will also serve these scientific communities by presenting the state of the art in GPR signal processing methodologies, and fostering future research in this area. We collected papers related to the most recent advanced GPR signal processing techniques used in the principal application fields (e.g. civil and environmental engineering). In particular, submissions came from an open call for papers and finally 12 papers (out of 17 submissions, with an acceptance rate of 70%) were selected after rigorous reviews.

These papers cover topics of signal processing such as increase of GPR data temporal resolution by deconvolution, denoising and improving the interpretation of GPR sections by the simulation of GPR data, detection and classification of subsurface targets, assessment of calibration procedures, and interferometric imaging approach. Below is a brief presentation of the articles included in this special issue.



## 2. Overview of the articles

*2.1 Review articles*

*A. Benedetto et al.* in [1] provide a review article on the main signal processing techniques employed in road engineering using GPR. Starting with the theoretical basis of GPR, they provide the main GPR data processing techniques utilized in road monitoring they present a number of significant and relevant GPR applications. They conclude that, the proper performance of a GPR survey on the site is the fundamental and most important factor to pursue, in order to emphasize the effectiveness of the data processing.

*E. Forte and M. Pipan* in [2] focus on the multi – offset data acquisition methods and Multi Fold (MF) data processing techniques similarities and differences through examples taken from different subsurface and target conditions in order to provide a comprehensive and critical review. MF GPR, even though laborious at both acquisition and processing stages, allows obtaining enhanced subsurface images and quantitative information about physical properties of the materials if compared with the usual

Common-offset techniques. The EM velocity field represents the most important information that can be extracted from field data as several other properties can be derived or correlated thanks to the existing theoretical physical laws as well as empirical or semi-empirical equations. Multi-channel acquisition, full wave-form inversion, pre-stack depth migration, azimuthal and polarimetric analysis, are among the many topics in current and future research that are briefly reviewed to provide some highlights of the forthcoming developments in GPR methods.

*2.2 Simulation of GPR data*

*C. Warren and A. Giannopoulos* in [3] present an investigation of the radiation characteristics of a high-frequency ground coupled GPR antenna in lossless homogeneous and, for the first time, in lossy heterogeneous environments using detailed FDTD models. They compare the results of different values of dielectric constant, and different types and distributions of realistic soil properties, and observe significant variations in the magnitude and pattern shape of the radiated energy of the antenna for the case of lossy heterogeneous environments. They also conclude that the simulations that included only an infinitesimal dipole model produced a very similar radiated energy distribution to those that used the full antenna model.

*2.3 GPR data directional filtering*

*X. Wang and S. Liu* in [4] discuss a new application of Shearlet transform (ShT) for ground penetrating radar (GPR) to remove the direct wave arrivals and suppress random noise by utilizing multi-scale and multi-direction properties of ShT. Furthermore, Curvelet transform, whose characteristics are similar to ShT, is also discussed for suppressing random noise, and it is demonstrated that the latter outperforms the former. ShT also proves to produce better performance in removing the direct arrivals of the GPR signal than the moving average and mean filter methods usually implemented for this application.

*A. Tzanis* in [5] introduces the *curveletiform* directional filter and its application to edge detection in general images and fracture detection in GPR data. The filter is essentially a curvelet with adjustable anisotropy that can be tuned on any given wavenumber: while retaining the properties of curvelets, it is not bound to the scaling rules of the Curvelet Frame. The curveletiform can efficiently recover information of specific scale and geometry from straight or curved edges in general images. In geotechnical GPR data it may distinguish reflections from small and large fractures, discriminate between groups of fractures, resolve fracture density and aid the assessment of damage in rocks and structures.



*2.4 Resolution enhancement*

*S. Zhao and I.L. Al-Qadi* in [6] exploit both synthetic and real GPR data in order to apply several types of regularized deconvolution methods (i.e., zeroth-, first-, and second-order Tikhonov; and total variation regularization) for the separation of thin asphalt layers' boundaries reflections. By demonstrating that the “L-curve” criterion can be applied to both zeroth-order Tikhonov and total variation regularization methods in order to find the appropriate regularization parameter, they conclude that these two methods can effectively increase the GPR signal range resolution even when the second pulse from asphalt pavement overlay is small. Accurate impulse distance can be obtained when the impulse distance is larger than 0.51ns and when the layer thickness is not thinner than 25.5mm, the absolute layer thickness estimation error is less than 1mm, which is well below the construction tolerance.

*M. Sun et al.* in [7] study time delays and interface roughness estimation with coherent backscattered echoes. After applying the interpolated spatial smoothing technique to decorrelate the received echoes, they proposed a modified MUSIC algorithm, which is able to estimate the time delays without knowing the frequency behaviour from roughness. The influence of the interface roughness was also estimated by Maximum Likelihood (MLE) method. These algorithms are applied for the evaluation of the pavement. The performance of the proposed algorithms, tested on data from Method of Moments (MoM), showed good performance for time delays and interface roughness estimation.

*2.5 Subsurface target detection*

*X. Feng et al.* in [8] apply the model-based Freeman decomposition to full polarimetric GPR data to improve the subsurface target classification and to overcome the ambiguity in interpreting migrated GPR sections which contain similar reconstructed imaging shapes from different geometrical features. They conclude that it is better to use both the geometrical feature and polarimetric information to classify targets. Consequently, the classification ability of GPR can be improved, depending on the geometrical feature obtained by migration imaging technique and the polarimetric information obtained by model-based Freeman decomposition technique.

*Q. Hoarau et al.* in [9] develop an algorithm in order to detect and locate pipes buried between 1 and 3 meters underground by taking into account the estimation of the dielectric constant. The proposed detector, based on an Adaptive Normalized Matched Filter (ANMF) depends on a signal of interest, this being the theoretical response of a buried pipe. They investigate the impact of the regularisation parameters on both Probability of False Alarm (PFA) and Probability Detection (PD) values. Application on real data and performance comparison with standard migration processes showed the interest of the approach in particular to detect buried pipes having very weak responses.

*M. Salucci et al.* in [10] performed quantitative imaging of the dielectric characteristics of unknown targets buried in a lossy half-space by suitably processing wide-band ground penetrating radar (GPR) measurements. They propose an innovative multi-frequency (MF) fully non-linear inverse scattering (IS) technique exploiting the integration of a conjugate-gradient (CG) solver within the iterative multi-scaling approach (IMSA). A set of representative synthetic experiments has been presented and discussed to assess the effectiveness of the introduced methodology as well as to compare it to a state-of-the-art FH-based technique. They conclude that the FH technique is more reliable and accurate than the MF one in several situations such as different shapes, dimensions, and contrasts of the unknown targets, while on the other hand, the MF strategy is faster thanks to the execution of a single multi-resolution minimization.

*2.6 Interferometric imaging approach*

*L. Liu* in [11] reports the application of an interferometric imaging approach to cross-hole multi-offset transmission (CHMOT) borehole radar data to generate a virtual single-hole, multi-offset reflection (SHMOR) profile with the validation of a real SHMOR data set. The results of the present study expanded the validation to the SHMOR case implemented in previous work. The potential of the Wave Interferometric Virtual Source (WIVS) approach for improving the resolution of bedrock fracture imaging for some needed applications was demonstrated. It will provide more useful information when it applies to situations where multiple borehole transmission surveys are routinely conducted, such as in the fields of mining industry and geothermal explorations for imaging water transport or other fluid bearing fractures in the target formations.

*2.7 Performance assessment of GPR test methods*

*F: Benedetto and F. Tosti* in [12] propose a GPR signal processing methodology, calibrated and validated on the basis of a consistent amount of data collected by means of laboratory-scale tests, to assess the performance of the American Society for Testing and Materials (ASTM) standards for GPR systems. This paper is the first study that focuses on the ASTM SNR test, thereby aiming at providing a detailed analysis of the bias and variance of the testing variable under consideration (i.e. the SNR). The study is performed with several GPR systems (i.e. exploiting antennas tuned to several frequencies), analyzing the specific relationship between the frequency of investigation and the optimal thresholds for the ASTM test methods.

## 3. Acknowledgment

We would like to thank Prof. B. Ottersten for providing the opportunity to organize this special issue and the Elsevier staff for their support. Special thanks also to the Chair and Editorial Coordinator of COST Action TU1208 for their great support towards this initiative. We are also very grateful to all the reviewers who have provided timely and constructive reviews and contributed to the high quality of this issue. Finally, we would like to thank all the authors who have contributed to this special issue, by sharing their latest research results.

## 4. References

[1] A. Benedetto, F. Tosti, L. Bianchini Ciampoli, F. D'Amico. An overview of ground-penetrating radar signal processing techniques for road inspections, Signal Processing, this issue, 2016.

[2] E. Forte, M. Pipan. Review of multi-offset GPR applications: data acquisition, processing and analysis, Signal Processing, this issue, 2016.

[3] C. Warren, A. Giannopoulos. Characterisation of a Ground Penetrating Radar Antenna in Lossless Homogeneous and Lossy Heterogeneous Environments, Signal Processing, this issue, 2016.

[4] X. Wang, S. Liu. Noise suppressing and direct wave arrivals removal in GPR data based on Shearlet transform, Signal Processing, this issue, 2016.

[5] A. Tzanis. A versatile tuneable curvelet-like directional filter, with application to fracture detection in two-dimensional GPR data. Signal Processing, this issue.

[6] S. Zhao, I.L. Al-Qadi. Development of Regularization Methods on Simulated Ground-Penetrating Radar Signals to Predict Thin Asphalt Overlay Thickness, Signal Processing, this issue, 2016.

[7] M. Sun, C. Le Bastard, N. Pinel, Y. Wang, J. Li, J. Pan, Z. Yu. Estimation of time delay and interface roughness by GPR using modified MUSIC, Signal Processing, this issue, 2016.

[8] X. Feng, E. Nilot, C. Liu. Application of Freeman decomposition to full polarimetric GPR for improving subsurface target classification, Signal Processing, this issue, 2016.

[9] Q. Hoarau, G. Ginolhac, A. M. Atto, J.M. Nicolas. Robust Adaptive Detection of Buried Pipes using GPR, Signal Processing, this issue, 2016.

[10] M. Salucci, L. Poli, A. Massa. Advanced Multi-Frequency GPR Data Processing for Non-Linear Deterministic Imaging, Signal Processing, this issue, 2016.

[11] L. Liu. Virtual multi-offset reflection profiling with interferometric imaging for borehole radar, Signal Processing, this issue, 2016.

[12] F. Benedetto, F. Tosti. A signal processing methodology for assessing the performance of ASTM standard test methods for GPR systems, Signal Processing, this issue.

Chief-guest-Editors
Dr. Nikos Economou, Ph.D.
Applied Geophysics Lab
School of Mineral Resources Engineering
Technical University of Crete
Polytechnioupolis, Kounoupidiana, Chania, Crete, Greece
e-mail: neconom@mred.tuc.gr
web:http://www.mred.tuc.gr/fileadmin/users_data/mred/cv_staff/economou_uk.pdf

Dr. Francesco Benedetto, Ph.D.
SP4TE - Signal Processing for Telecommunications and Economics Laboratory,
University of ROMA TRE
Via Vito Volterra 62, 00146 Rome, Italy.
e-mail: francesco.benedetto@uniroma3.it
web: http://host.uniroma3.it/laboratori/sp4te/staff/benedetto.html

Co-guest-Editors
Dr. Maksim Bano
Institut de Physique du Globe de Strasbourg
Ecole et Observatoire des Sciences de la Terre
University of Strasbourg
5 rue René Descartes, 67084 Strasbourg Cedex, France
email: maksim.bano@unistra.fr
web: http://eost.unistra.fr/recherche/ipgs/ge/ge-perso/maksim-bano/

Dr. Andreas Tzanis, Ph.D.
Department of Geophysics,
National and Kapodistrian University of Athens
Panepistimiopoli, Zografou 15784, Greece
e-mail: atzanis@geol.uoa.gr
web: http://users.uoa.gr/~atzanis

Dr. Jonathan Nyquist
Weeks Chair of Environmental Geology
Department of Earth & Environmental Science
Temple University
Philadelphia, PA, 19122, USA
e-mail: nyq@temple.edu
web: http://sites.temple.edu/geophysics

Dr. Karl-Josef Sandmeier
Geophysical Research
Zipser Strasse 1
76227 Karlsruhe
Germany
e-mail: info@sandmeier-geo.de
web: http://www.sandmeier-geo.de

Dr. Nigel Cassidy
Applied and Environmental Geophysics Group
School of Physical and Geographical Sciences
Keele University
Staffordshire, UK.
e-mail: n.j.cassidy@keele.ac.uk
web: http://www.keele.ac.uk/gge/people/nigelcassidy