Action's Papers on peer-reviewed International Journals

Statistics

	General interest	WG1	WG2	WG3	WG4	Total
All Journal Papers	**5**	**5**	**17**	**28**	**15**	**70**
Authors from 2 Countries	1	0	7	15	2	**25**
Authors from 3 Countries or more	4	0	2	1	0	**7**
Authors from Inclusiveness Target Countries	0	0	2	6	5	**13**
Authors from NNC	0	0	1	0	0	**1**
Authors from IPC	2	0	1	5	0	**8**
STSM outcome	0	2	2	1	2	**7**
Industry involvement	1	1	2	3	1	**8**
Open Access	1	3	4	5	6	**19**

Impact*:						
Citations Citations per paper	1 <0,2>	8 <2>	29 <1,93>	71 <2,958>	75 5	**184** **2,92**
Citation OA papers Citations per OA paper	0 <0>	7 <2,33>	7 <1,75>	7 <1,75>	19 3,12	**40** **2,22**
Intl. cooperation 1-Country	Tot→Avg 1→0,2 0	Tot→Avg 0 8→2	Tot→Avg 19→2,7 10→1,25	Tot→Avg 38→2,53 33→3,67	Tot→Avg 1→0.5 74→5.7	**Tot→Avg** **59→2,03** **125→3,67**

**Citations were updated in April 2017 when papers were 63 – just to have a first idea. Will be updated at the end of September 2017.*

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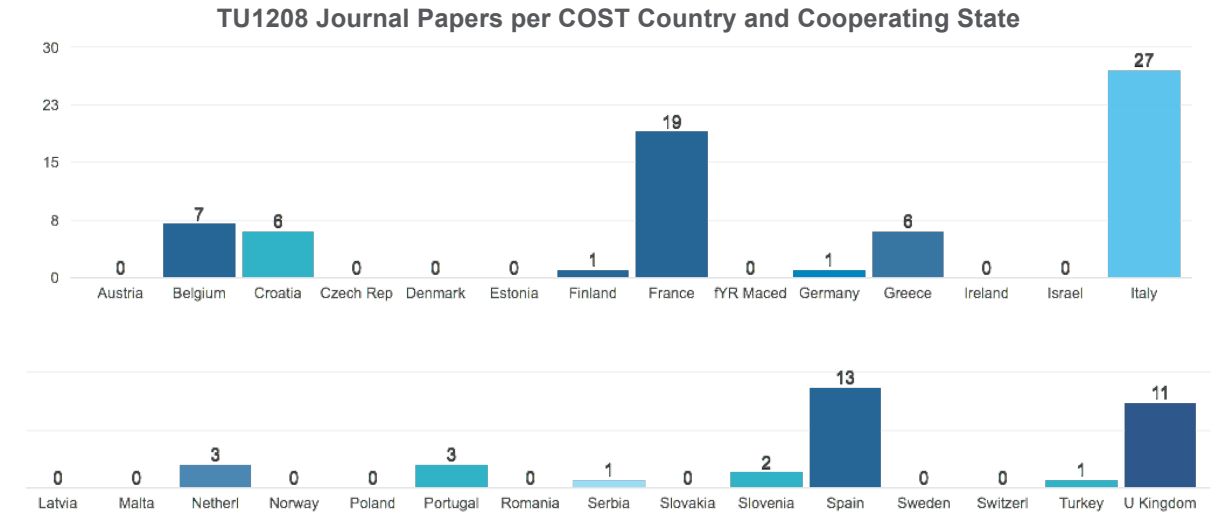

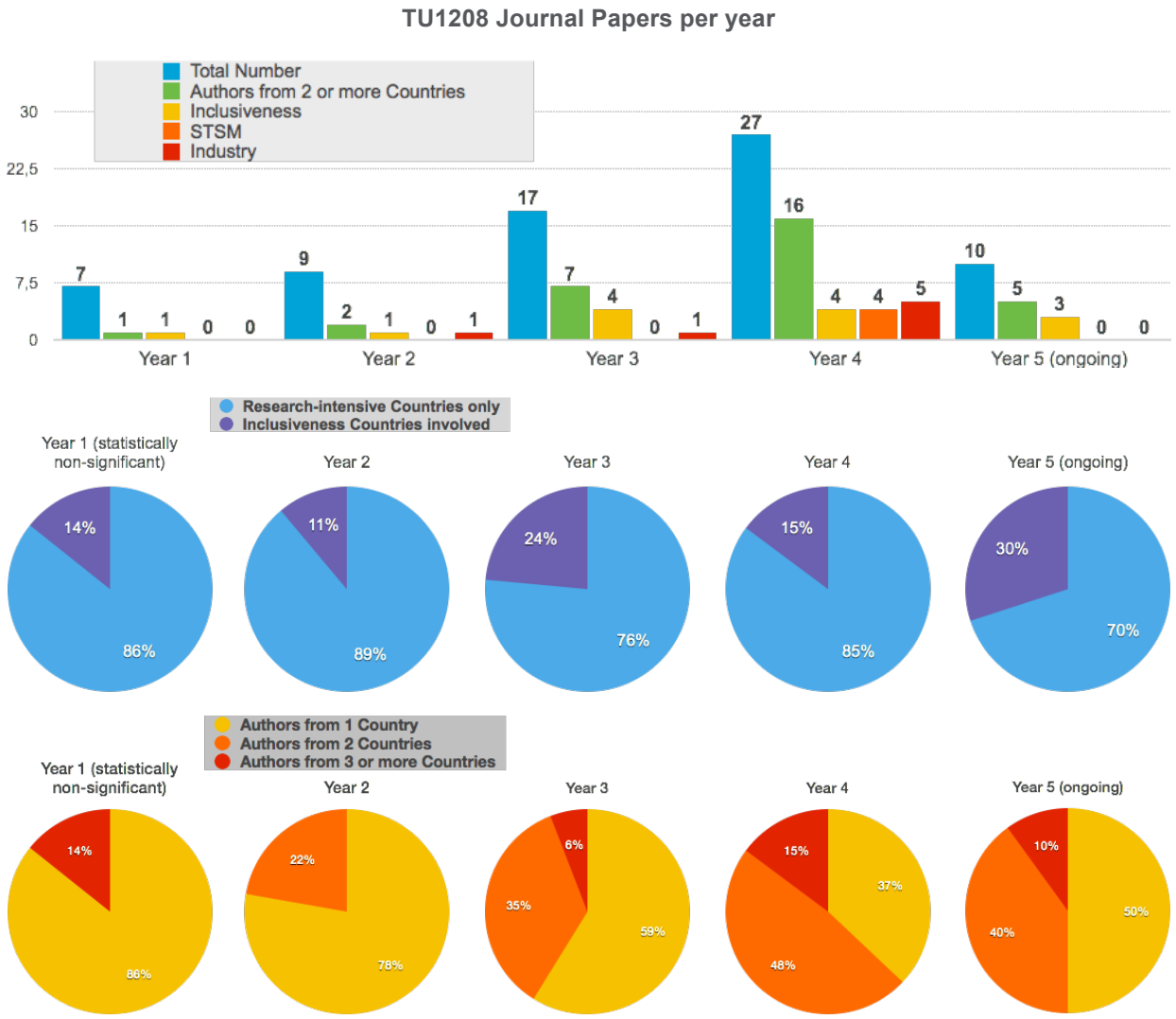

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General interest

[j1] L. Pajewski, A. Benedetto, A. Loizos, E. Slob, "Preface to the Special Issue on "Ground Penetrating Radar for nondestructive evaluation of pavements, bridges and subsurface infrastructures," Elsevier Journal of Applied Geophysics (JAG), vol. 97, pp. 1-2, October 2013; doi: 10.1016/j.jappgeo.2013.07.001 (Greece, Italy, Netherlands)

Impact: Cited by 1

Citing paper:

1) M. Salucci, L. Poli, N. Anselmi and A. Massa, "Multifrequency Particle Swarm Optimization for Enhanced Multiresolution GPR Microwave Imaging," IEEE Transactions on Geoscience and Remote Sensing, vol. 55, no. 3, pp. 1305-1317, March 2017, doi: 10.1109/TGRS.2016.2622061

[j2] S. Lambot, A. Giannopoulos, L. Pajewski, E. Slob, M. Sato, "Foreword to the Special Issue on Advances in Ground-Penetrating Radar Research and Applications," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (IEEE JSTARS), vol. 9(1), pp. 5-8, January 2016; doi: 10.1109/JSTARS.2016.2518518 (Belgium, Japan, Italy, Netherlands, United Kingdom; GPR 2014 Special Issue; OPEN ACCESS; COOPERATION WITH IPC)

Impact: Cited by 0

[j3] F. Tosti, L. Pajewski, A. Benedetto, A. Loizos, "Foreword to the Special Issue on Civil and Environmental Engineering Applications of Ground Penetrating Radar," EAGE Near Surface Geophysics (NSG), vol. 14(2), pp. 103-104, April 2016; doi: 10.3997/1873-0604.2016016 (Greece, Italy, United Kingdom; TU1208 NSG Special Issue)

Impact: Cited by 0

[j4] A. Benedetto, F. Tosti, L. Bianchini Ciampoli, F. D'Amico, "GPR Applications Across Engineering and Geosciences Disciplines in Italy: A Review," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS), vol. 9, pp. 2952-2965, July 2016; doi: 10.1109/JSTARS.2016.2554106 (Italy, United Kingdom)

Abstract: In this paper, a review of the main ground-penetrating radar (GPR) applications, technologies, and methodologies used in Italy is given. The discussion has been organized in accordance with the field of application, and the use of this technology has been contextualized with cultural and territorial peculiarities, as well as with social, economic, and infrastructure requirements, which make the Italian territory a comprehensive large-scale study case to analyze. First, an overview on the use of GPR worldwide compared to its usage in Italy over the history is provided. Subsequently, the state of the art about the main GPR activities in Italy is deepened and divided according to the field of application. Notwithstanding a slight delay in delivering recognized literature studies with respect to other forefront countries, it has been shown how the Italian contribution is now aligned with the highest world standards of research and innovation in the field of GPR. Finally, possible research perspectives on the usage of GPR in Italy are briefly discussed.

Impact: Cited by 0

[j5] N. Economou, F. Benedetto, M. Bano, A. Tzanis, J. Nyquist, K.-J. Sandmeier, N. Cassidy, "Advanced Ground Penetrating Radar Signal Processing Techniques – Editorial," Signal Processing (Elsevier), vol. 132, pp. 197-200, March 2017; doi: 10.1016/j.sigpro.2016.07.032 (Germany, Greece, France, Italy, United Kingdom, United States; TU1208 SP Special Issue; INDUSTRY INVOLVEMENT; COOPERATION WITH IPC)

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Working Group 1

Project 1.1 – Design of novel GPR systems

[wg1-p1-j1] E. Huuskonen-Snicker, P. Eskelinen, T. Pellinen, M.-K. Olkkonen, "A New Microwave Asphalt Radar Rover for Thin Surface Civil Engineering Applications," Frequenz – Journal of RF-Engineering and Telecommunications, vol. 69(7-8), pp. 377-381, January 2015; doi: 10.1515/freq-2015-0034 (Finland; OPEN ACCESS)

Abstract: This paper presents a beyond state-of-the-art, sweeping microwave asphalt radar mounted on a small radio controlled four-wheel-drive rover. The quasi-monostatic, remote-controllable radar operates at Ku-band and has an output power of +10 dBm. Detection follows the zero intermediate frequency principle. The sweep width allows for a depth resolution better than 10 mm. With its four microprocessors and laptop computer processing, the radar system can provide pavement permittivity data with an uncertainty close to 0.1. This is a considerable advancement when applying electromagnetic measurement techniques for applications where near surface or thin surface layer measurements are needed.

Impact: Cited by 2

Citing papers:

1) P. Eskelinen, "A Simple Permittivity Calibration Method for GPR-Based Road Pavement Measurements," Frequenz – Journal of RF-Engineering and Telecommunications, vol. 70(9-10), pp. 429-432, 2016.

2) Z. Wang, H. Wang, D. An, T. Ai, and P. Zhao, "Laboratory investigation on deicing characteristics of asphalt mixtures using magnetite aggregate as microwave-absorbing materials," Construction and Building Materials, vol. 124, pp. 589-597, 2016.

[wg1-p1-j2] R. Persico, D. Dei, F. Parrini, L. Matera, "Mitigation of narrowband interferences by means of a reconfigurable stepped frequency GPR system," Radio Science, vol. 51(8), pp. 1322–1331, August 2016; doi: 10.1002/2016RS005986 (Italy; INDUSTRY INVOLVEMENT; STSM OUTCOME)

Abstract: This paper proposes a new technique for the mitigation of narrowband interferences by making use of an innovative stepped frequency Ground Penetrating Radar (GPR) system, based on the modulation of the integration time of the harmonic components of the signal. This can allow a good rejection of the interference signal without filtering out part of the band of the useful signal (which would involve a loss of information) and without increasing the power of the transmitted signal (which might saturate the receiver and make illegal the level of transmitted power). The price paid for this is an extension of the time needed in order to perform the measurements. We will show that this necessary drawback can be contained by making use of a prototypal reconfigurable stepped frequency GPR system.

Impact: Cited by 0

[wg1-p1-j3] R. Persico and G. Leucci, "Interference mitigation achieved with a reconfigurable stepped-frequency GPR system, Remote Sensing, vol. 8(11), Article No. 926, 11 pp., November 2016; doi: 10.3390/rs8110926 (Italy; OPEN ACCESS; STSM OUTCOME)

Abstract: In this contribution, some possible effects of large band electromagnetic interferences on Ground Penetrating Radar (GPR) data are shown, and a possible way to counteract them is shown, too. The mitigation of the interferences is implemented thanks to a prototypal reconfigurable stepped frequency GPR system, that allows to program the integration time of the harmonic tones vs. the frequency. In particular, an algorithm for the measurement of the effects of the interferences in the field (linked to the signal to interference ratio) is proposed and tested vs. experimental data. The paper will show some advantages and some drawbacks of the proposed procedure.

Impact: Cited by 0

[wg1-p1-j4] V. Ferrara, A. Pietrelli, S. Chicarella, L. Pajewski, "GPR/GPS/IMU system as buried objects locator," Measurement (Elsevier), vol. TBA, 2017; doi: 10.1016/j.measurement.2017.05.014 (Italy)

Abstract: In the last years, Ground Penetrating Radar (GPR) technology has been extensively used in several different fields, including archaeology and cultural-heritage diagnostics. The integration of GPR with other positioning devices, such as a Global Positioning System (GPS) and an Inertial Measurement Unit (IMU), can significantly improve the accuracy of buried-object location, by means of an efficient control of GPR route and attitude. This article aims at investigating solutions for an accurate location of buried objects when a GPR is pulled by a terrestrial vehicle or carried by an aerial platform. In particular, a low-cost system is presented, which integrates functionalities of GPS and IMU specifically dedicated to GPR use. The device has been designed, realized and finally its performance was tested in the laboratory.

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Impact: Cited by 0

Project 1.2 – Design, modelling and optimisation of GPR antennas

[wg1-p2-j1] C. Warren, A. Giannopoulos, "Experimental and Modeled Performance of a Ground Penetrating Radar Antenna in Lossy Dielectrics," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS), vol. 9(1), pp. 29-36, January 2016; doi: 10.1109/JSTARS.2015.2430933 (United Kingdom; GPR 2014 Special Issue; OPEN ACCESS)

Abstract: The way in which electromagnetic fields are transmitted and received by ground penetrating radar (GPR) antennas is crucial to the performance of GPR systems. Simple antennas have been characterized by analyzing their radiation patterns and directivity. However, there have been limited studies that combine real GPR antennas with realistic environments, which is essential to capture the complex interactions between the antenna and surroundings. We have investigated the radiation characteristics and sensitivity of a GPR antenna in a range of lossy dielectric environments using both physical measurements and a three-dimensional (3-D) finite-difference time-domain (FDTD) model. Experimental data were from measured responses of a target positioned at intervals on the circumference of a circle surrounding the H-plane of the antenna. A series of oil-in-water emulsions as well as tap water were used to simulate homogeneous materials with different permittivities and with complex conductivities. Numerical radiation patterns were created utilizing a detailed 3-D FDTD model of the antenna. Good correlation was shown between the experimental results and modeled data with respect to the strength of the main lobe within the critical angle window. However, there are discrepancies in the strength of main lobe at shallow angles. In all the dielectrics, the main lobes are generally broad due to the near-field observation distance but, as expected, become narrower with increasing permittivity. These results provide confidence for further use of the FDTD antenna model to investigate scenarios such as larger observation distances and heterogeneous environments that are difficult to study experimentally.

Impact: Cited by 5

Citing papers:

1) C. Warren and A. Giannopoulos, “Characterisation of a ground penetrating radar antenna in lossless homogeneous and lossy heterogeneous environments,” Signal Processing, vol. 132, pp. 221-226, 2017.

2) C. Warren, I. Giannakis, and A. Giannopoulos, “Performance of a Ground Penetrating Radar Antenna in Heterogeneous Environments,” 8th Congress of the Balkan Geophysical Society, 2015.

3) W. W. M. Soo, "Statistical Variation in Post-Simulated Electromagnetic Fields," IEEE Transactions on Antennas and Propagation, vol. 64(12), pp. 5320-5325, 2016.

4) A. Fedeli, M. Pastorino and A. Randazzo, "A two-step multifrequency imaging technique for ground penetrating radar," 2016 10th European Conference on Antennas and Propagation (EuCAP), Davos, 2016, pp. 1-4, doi: 10.1109/EuCAP.2016.7482009

5) C. Warren and A. Giannopoulos, "Influence of lossless and lossy, heterogeneous environments on Ground Penetrating Radar antenna behaviour," 2015 IEEE 15th Mediterranean Microwave Symposium (MMS), Lecce, 2015, pp. 1-5, doi: 10.1109/MMS.2015.7375397

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Working Group 2

Project 2.1 – GPR inspection of transport infrastructures

[wg2-p1-j1] F. De Chiara, S. Fontul, E. Fortunato, "GPR Laboratory Tests For Railways Materials Dielectric Properties Assessment," Remote Sensing, vol. 6(10), pp. 9712-9728, October 2014; doi: 10.3390/rs6109712 (Italy, Portugal; OPEN ACCESS)

Abstract: In railways Ground Penetrating Radar (GPR) studies, the evaluation of materials dielectric properties is critical as they are sensitive to water content, to petrographic type of aggregates and to fouling condition of the ballast. Under the load traffic, maintenance actions and climatic effects, ballast condition change due to aggregate breakdown and to subgrade soils pumping, mainly on existing lines with no sub ballast layer. The main purpose of this study was to validate, under controlled conditions, the dielectric values of materials used in Portuguese railways, in order to improve the GPR interpretation using commercial software and consequently the management maintenance planning. Different materials were tested and a broad range of in situ conditions were simulated in laboratory, in physical models. GPR tests were performed with five antennas with frequencies between 400 and 1800 MHz. The variation of the dielectric properties was measured, and the range of values that can be obtained for different material condition was defined. Additionally, in situ GPR measurements and test pits were performed for validation of the dielectric constant of clean ballast. The results obtained are analyzed and the main conclusions are presented herein.

Impact: Cited by 7

Citing papers:

1) T. Stylianides, M. W. Frost, P. R. Fleming, M. Mageean, A. Huetson, "A condition assessment approach for highway filter drains using ground penetrating radar," Procedia Engineering, vol. 143, pp. 1226-1235, 2016.
2) L. Bianchini Ciampoli, A. Calvi, A. Benedetto, F. Tosti, A. M. Alani, "Efficient practices in railway ballast maintenance and quality assessment using GPR," Transport Infrastructure and Systems: Proc. AIIT International Congress on Transport Infrastructure and Systems, Rome, Italy, 10-12 April 2017, CRC Press, pp. 419-423, 2017
3) Ruban, V. P. "Jitter of synchronization of the stroboscopic converter," Telecommunications and Radio Engineering, vol. 75(9), pp. 789-800, 2016.
4) Z. Yang, C. L. Ho, R. Joy, and N. C. Dabhade, "Influence of Water Content on the Behavior of Partially Saturated Fouled Ballast," Proc. 2016 Joint Rail Conference, pp. V001T01A006-V001T01A006, American Society of Mechanical Engineers, April 2016.
5) M. Solla, H. Lorenzo, and V. Pérez-Gracia. "Ground Penetrating Radar: Fundamentals, Methodologies and Applications in Structures and Infrastructure," in Non-Destructive Techniques for the Evaluation of Structures and Infrastructure, 2016, pp. 89-112
6) S. Fontul, R. Mínguez, M. Solla, S. Santos-Assunção, " The Use of Geophysics for the Condition Assessment of Railway Infrastructure," in Non-Destructive Techniques for the Evaluation of Structures and Infrastructure, 2016, pp. 195-216
7) S. Fontul, E. Fortunato, F. De Chiara, R. Burrinha, and M. Baldeiras, " Railways Track Characterization Using Ground Penetrating Radar," Procedia Engineering, vol. 143, pp. 1193-1200, 2016

[wg2-p1-j2] X. Núñez-Nieto, M. Solla, A. Novo, H. Lorenzo, "Three-dimensional ground-penetrating radar methodologies for the characterization and volumetric reconstruction of underground tunneling," Construction and Building Materials (Elsevier), vol. 71, pp. 551–560, November 2014; doi: doi:10.1016/j.conbuildmat.2014.08.083 (Spain, Canada; INDUSTRY INVOLVEMENT; COOPERATION WITH IPC)

Abstract: This work presents the documentation and characterization of an ancient underground concrete tunnel using the ground-penetrating radar (GPR) method. Three-dimensional imaging methodologies were applied to create an accurate volumetric reconstruction of the underground tunneling space and the whole framework of galleries composing the main structure, which enabled for the dimensioning of the structure. Problems of moisture were also detected in a particular sector of the tunnel. In addition, FDTD modeling was used to improve the understanding of the GPR signal propagation and to assist the interpretation of the field GPR data. Both field and synthetic data have shown the capabilities of the method for the evaluation and characterization of this ancient construction.

Impact: Cited by 6

Citing papers:

1) J. Jezova, L. Mertens, S. Lambot, "Ground-penetrating radar for observing tree trunks and other cylindrical objects," Construction and Building Materials, vol. 123, pp. 214-225, October 2016, doi: doi:10.1016/j.conbuildmat.2016.07.005
2) H. Liu, C. Koyama, J. Zhu, Q. Liu, M. Sato, Post-Earthquake Damage Inspection of Wood-Frame Buildings by a Polarimetric GB-SAR System. Remote Sensing, vol. 8(11), 935, 2016.
3) X. Nunez-Nieto, M. Solla, F.J. Prego, H. Lorenzo, "Assessing the applicability of GPR method for tunnelling inspection: Characterization and volumetric reconstruction," Proc. 8th International Workshop on Advanced Ground Penetrating Radar (IWAGPR 2015), 7-10 July 2015, Florence, Italy, pp. 1-4, doi: 10.1109/IWAGPR.2015.7292633
4) M. Solla, H. Lorenzo, and V. Pérez-Gracia. "Ground Penetrating Radar: Fundamentals, Methodologies and Applications

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in Structures and Infrastructure," in Non-Destructive Techniques for the Evaluation of Structures and Infrastructure, 2016, pp. 89-112
5) F. M. Fernandes and P. B. Lourenço. "Mapeamento das fundações com georadar do complexo monástico em torno da Igreja Arminiana," 5as Jornadas Portuguesas de Engenharia de Estruturas, pp. 1-12, 2014 (in Portoguese).
6) G. Daban Castro, M. Solla, "Evaluación no destructiva mediante GPR del relleno de la explanada para el análisis de las zonas de mayor afección," Publishing House: Centro Universitario de la Defensa, ENM, pp. 1-59 (Thesis in Spanish).

[wg2-p1-j3] J. Pedret Rodés, V. Pérez-Gracia, A. Martínez-Reguero, "Evaluation of the GPR frequency spectra in asphalt pavement assessment," Construction and Building Materials (Elsevier), vol. 96, pp. 181–188, October 2015; doi: 10.1016/j.conbuildmat.2015.08.017 (Spain)
Abstract: Ground penetrating radar (GPR) is frequently used in pavement assessments, mainly using the evaluation of wave travel times. However, GPR data provide further information that could be used in order to determine the inner conditions and characteristics about materials. In this paper, the possible analysis of the frequency spectrum of GPR signals is analysed and discussed. Several tests were carried out in a portion of a highway in two different stages of its service life. Results highlight the relationship between the shape of the spectrum and the frequency signature with the structure and conditions of the pavement.

Impact: Cited by 1
Citing paper:
1) S. Santos-Assunçao, S. Krishna, and V. Perez-Gracia. "GPR Analysis of Water Content in Concrete Specimen-Laboratory Test," Near Surface Geoscience 2016-22nd European Meeting of Environmental and Engineering Geophysics. 2016, 10.3997/2214-4609.201601974.

[wg2-p1-j4] J. De Pue, M. Van Meirvenne, W. M. Cornelis, "Accounting for Surface Refraction in Velocity Semblance Analysis With Air-Coupled GPR," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS), vol. 9(1), pp. 60-73, January 2016; doi: 10.1109/JSTARS.2015.2439333 (Belgium; GPR 2014 Special Issue)
Abstract: The aim of this study is to evaluate the velocity semblance analysis technique for air-coupled common midpoint (CMP) measurements with a small antenna offset. The technique was originally developed for seismic surveys, assuming the small spread approximation. Owing to the strong refraction at the sur-face and shallow investigation depth, this assumption is not valid in the case of air-coupled ground-penetrating radar (GPR). To overcome this assumption, a modification to the method is proposed accounting for the refraction at the surface. Synthetic experiments were executed to demonstrate that the traditional method resulted in a persistent overestimation, whereas the modified method improved the results significantly. Two field experiments have been conducted to test the method under different field conditions. In a first experiment on a road test site, the modified method improved the estimation of depth and propagation velocity significantly. However, the technique failed to estimate the propagation velocity and depth or objects in a second field test, due to rough terrain conditions and noise in the data. Therefore, an additional modification was proposed, by incorporating in-line data as well. This improved the depth and velocity estimations significantly. Overall, this study demonstrates that the traditional velocity semblance analysis (TRAD) is not valid for air-coupled GPR. By accounting for the refraction at the surface and incorporating inline data, it is possible to successfully estimate depth and propagation velocity with small offset air-coupled GPR configurations.

Impact: Cited by 1
Citing paper:
1) F. Benedetto and F. Tosti, "A signal processing methodology for assessing the performance of ASTM standard test methods for GPR SYSTEMS," Signal Processing (Elsevier), vol. 132, pp. 327–337, March 2017, doi: doi:10.1016/j.sigpro.2016.06.030

[wg2-p1-j5] S. Fontul, E. Fortunato, F. De Chiara, R. Burrinha, M. Balderais, "Railways Track Characterization Using Ground Penetrating Radar," Procedia Engineering | Advances in Transportation Geotechnics III, vol. 143, pp. 1193-1200, February 2016, doi: doi:10.1016/j.proeng.2016.06.120 (Italy, Portugal; OPEN ACCESS)
Abstract: A proper quality control of the railway track condition and its monitoring since the construction phase are key factors for a long life cycle and for an efficient maintenance policy. For this purpose, suitable techniques, such as non-destructive tests, represent an efficient monitoring solution as they allow evaluating infrastructure characteristics continuously, saving time and costs, with minimal interferences on track use. Ground Penetrating Radar (GPR) is a fast and effective electromagnetic survey technique that enables the measuring of layers thickness, detection of changes on structure or on materials properties along the line. It can also detect different types of defects such as ballast pockets, fouled ballast, poor drainage, subgrade settlement and transitions problems, depending on their extension. These defects are

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generally the causes of vertical deviations in track geometry and they cannot be detected by the common monitoring procedures, namely the measurements of track geometry. GPR application to railways infrastructures at network level is relatively recent. In Portugal, rail inspection is performed with Plasser & Theurer EM120 equipment and recently 400 MHz IDS antennas were installed on it. GPR tests were performed on the Portuguese rail network and, as case study, a section of an in service tracks is addressed in this paper. A combined monitoring approach is presented, based on interpretation of the geometric parameter measurement, currently utilized for maintenance planning, together with GPR results, in order to detect the causes of the track deterioration and to plan more appropriate maintenance interventions.

Impact: Cited by 0

[wg2-p1-j6] C. Plati, P. Georgiou, A. Loizos, "A Comprehensive Approach for the Assessment of in-situ Pavement Density Using GPR technique," EAGE Near Surface Geophysics (NSG), vol. 14(2), pp. 117-126, April 2016, doi: 10.3997/1873-0604.2015043 (Greece; TU1208 NSG Special Issue)

Abstract: With the focus on quality assurance practices during pavement construction, the present research aims at investigating the compactability of hot mix asphalt using the ground-penetrating radar technique. Thus, density as an indicator of the compactability of hot mix asphalt is predicted using three different electromagnetic-mixing-theory-based density models (namely, the complex refractive index model, Rayleigh model, and Al-Qadi, Lahouar and Leng model), and the prediction performance is also investigated. The investigations are based on experimental data acquired, both in the laboratory and field, from new full-scale asphalt pavement sections with varying asphalt mixture compositions. The laboratory experiment, which involved the compaction of asphalt mixtures using the steel-segmented roller compactor, indicated that compaction mode affects the compactability of hot mix asphalt, whereas the analysis of field ground-penetrating radar experimental data revealed that the estimated electric permittivity εHMA during the compaction process could be considered a measure of the asphalt mix field compactability. The prediction performance of the three density models was evaluated using different methodological approaches with respect to the backcalculation of εs of the mix aggregates. The results indicated that, by utilizing the ground-penetrating radar field measured εHMA for the assessment of εs, the predicted Gmb values from the implementation of the above density models closely approach the ground-truth field-core bulk densities. Comparative evaluation of the three density models showed that the Al-Qadi, Lahouar, and Leng model exhibits the best prediction performance, which is comparable to nuclear/non-nuclear methods. In light of this, it could be argued that the ground-penetrating radar methodology coupled with novel algorithms can be an effective and efficient tool to improve the asphalt mix compaction process and assessment of in situ density.

Impact: Cited by 1

Citing paper:

1) Dong, Z., Ye, S., Gao, Y., Fang, G., Zhang, X., Xue, Z., & Zhang, T. (2016). Rapid Detection Methods for Asphalt Pavement Thicknesses and Defects by a Vehicle-Mounted Ground Penetrating Radar (GPR) System. Sensors, 16(12), 2067.

[wg2-p1-j7] A. Benedetto, F. Tosti, L. Bianchini Ciampoli, A. Calvi, M. G. Brancadoro, A. M. Alani, "Railway ballast condition assessment using ground-penetrating radar – An experimental, numerical simulation and modelling development," Construction and Building Materials, vol. 140, pp. 508–520, June 2017, doi:10.1016/j.conbuildmat.2017.02.110 (Italy, United Kingdom; TU1208 CBM Special Issue)

Abstract: This paper reports on the ground-penetrating radar (GPR)-based assessment of railway ballast which was progressively "polluted" with a fine-grained silty soil material. It is known how the proper operation of a ballast track bed may be undermined by the presence of fine-grained material which can fill progressively the voids between the ballast aggregates and affect the original strength mechanisms. This occurrence is typically defined as "fouling". To this effect, a square-based methacrylate tank was filled with ballast aggregates in the laboratory environment and then silty soil (pollutant) was added in different quantities. In order to simulate a real-life scenario within the context of railway structures, a total of four different ballast/pollutant mixes were introduced from 100% ballast (clean) to highly-fouled (24%). GPR systems equipped with different air-coupled antennas and central frequencies of 1000 MHz and 2000 MHz were used for testing purposes. Several processing methods were applied in order to obtain the dielectric permittivity of the ballast system under investigation. The results were validated using the "volumetric mixing approach" (available within the literature) as well as by performing a numerical simulation on the physical models used in the laboratory. It is important to emphasize the significance of the random-sequential absorption (RSA) paradigm coupled with the finite-difference time-domain (FDTD) technique

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used during the data processing. This was proved to be crucial and effective for the simulation of the GPR signal as well as in generating synthetic GPR responses close to the experimental data.

Impact: Cited by 0

[wg2-p1-j8] F. Benedetto, F. Tosti, A. M. Alani, "An Entropy-Based Analysis of GPR Data for the Assessment of Railway Ballast Conditions," IEEE Transactions on Geoscience and Remote Sensing, vol. 55(7), pp. 3900-3908, July 2017, doi: 10.1109/TGRS.2017.2683507 (Italy, United Kingdom)

Abstract: The effective monitoring of ballasted railway track beds is fundamental for maintaining safe operational conditions of railways and lowering maintenance costs. Railway ballast can be damaged over time by the breakdown of aggregates or by the upward migration of fine clay particles from the founda- tion, along with capillary water. This may cause critical track settlements. To that effect, early stage detection of fouling is of paramount importance. Within this context, ground penetrating radar (GPR) is a rapid nondestructive testing technique, which is being increasingly used for the assessment and health monitoring of railway track substructures. In this paper, we propose a novel and efficient signal processing approach based on entropy analysis, which was applied to GPR data for the assessment of the railway ballast conditions and the detection of fouling. In order to recreate a real-life scenario within the context of railway structures, four different ballast/pollutant mixes were introduced, ranging from clean to highly fouled ballast. GPR sys- tems equipped with two different antennas, ground-coupled (600 and 1600 MHz) and air-coupled (1000 and 2000 MHz), were used for testing purposes. The proposed methodology aims at rapidly identifying distinctive areas of interest related to fouling, thereby lowering significantly the amount of data to be processed and the time required for specialist data processing. Prominent information on the use of suitable frequencies of investigation from the investigated set, as well as the relevant probability values of detection and false alarm, is provided.

Impact: Cited by 0

[wg2-p1-j9] L. B. Ciampoli, F. Tosti, M. G. Brancadoro, F. D'Amico, A.M. Alani, A. Benedetto, "A spectral analysis of ground-penetrating radar data for the assessment of the railway ballast geometric properties," Non-Destructive Testing and Evaluation International (Elsevier), vol. 90, pp. 39-47, September 2017, doi: 10.1016/j.ndteint.2017.05.005 (Italy, United Kingdom)

Abstract: This paper presents a methodology for the assessment of railway ballast using ground-penetrating radar (GPR – 2 GHz horn antenna). The primary approach in this endeavour was the finite-difference time-domain (FDTD) simulations of ballast (a multi-stage process in terms of ballast size). To this effect, a combination of random sequential adsorption (RSA) and FDTD algorithms were applied. The results of the numerical simulation then were used to compare with the experimental investigations results using a container (methacrylate material) of the 1.5 1.5 0.5 m dimensions. Finally, the modelling of the frequency spectrum peak and the equivalent diameter of the ballast aggregates was developed.

Impact: Cited by 0

Project 2.2 – GPR inspection of buildings

No journal papers on the GPR inspection of modern buildings, so far. Please see "WG4 – Archaeology and cultural heritage" for paper on the GPR inspection of historical buildings.

Project 2.3 – GPR detection and localisation of buried utilities and voids, with a main focus to urban areas

[wg2-p3-j1] F. Sagnard, C. Norgeot, X. Dérobert, V. Baltazart, E. Merliot, F. Derkx, B. Lebental, "Utility detection and positioning on the urban site Sense-City using Ground-Penetrating Radar systems," Measurement, vol. 88, pp. 318-330, June 2016; doi: 10.1016/j.measurement.2016.03.044 (France; INDUSTRY INVOLVEMENT; TU1208 Test site)

Abstract: This paper presents the design of a novel Ground-Penetrating Radar (GPR) test site that has been integrated into the mini-city demonstrator Sense-City located at University Paris-Est (France). This test site provides several sources of measurement interest expressed by the presence of a multilayered soil with significant dielectric contrasts, and various dielectric pipes and blades buried at various depths in trenches filled with a backfill soil different from the natural soil. This paper presents experimental Bscans associated with the pipe zone acquired by three different GPR systems at frequencies ranging from 300 MHz to 1.5 GHz. The interpretation and comparison of the raw Bscans have allowed to characterize the

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dielectric properties of the soil layers, and to detect the hyperbola signatures of the buried pipes. The results of this study will help to guide future developments on polarization, operating frequency and signal processing to extract parameters (orientation, dielectric characteristics, position and size) associated with pipes.

Impact: Cited by 0

Project 2.4 – GPR inspection of construction materials

[wg2-p4-j1] X. Xiao, A. Ihamouten, G. Villain, X. Dérobert, "Use of Electromagnetic Two-layer Wave-Guided Propagation in the GPR Frequency Range to Characterize Water Transfer in Concrete," Non-Destructive Testing and Evaluation International (Elsevier), vol. 86, pp. 164-174, March 2016; doi: 10.1016/j.ndteint.2016.08.001 (France)

Abstract: The objective of this paper is to adapt a recent innovative technique for extracting and exploiting the Electromagnetic (EM) waveguide dispersion of civil engineering materials by means of GPR, and allowing to monitor the water ingress front during the absorption process for various concrete mixes. This technique is based on an inversion procedure that applies the Electromagnetic Waveguide Model (WGM) to invert phase velocity dispersion curves in their modal form. A Parallel homogenization model, derived from the Lichtenecker-Rother equation, has been employed to extend the waveguide model from a one-layer to a two-layer medium. The WGM outputs are then used to estimate the geometric parameters of the propagation medium and offer a primary application to water transfer monitoring in concrete through capillarity effects. The initial WGM validation is carried out on FDTD-simulated propagation signals, while the second validation relies on GPR data acquired from homogeneous materials. Then, a broad-based experimental study is conducted for the purpose of correlating electromagnetic waveguide dispersion parameters with both the geometric and hydric characteristics of various concrete mixes. Results obtained using the two-layer WGM serve to monitor the water ingress front during an absorption process. These results are then compared to the moisture gradients generated on cores using gammadensimetry, which is set as the reference. This procedure yields a number of trends, which in turn provide key information on the conditioning state of the studied concretes.

Impact: Cited by 0

[wg2-p4-j2] H. Reci, T. Chinh Maï, Z. Mehdi Sbartaï, L. Pajewski, E. Kiri, "Non-destructive evaluation of moisture content in wood by using Ground Penetrating Radar," Geoscientific Instrumentation, Methods and Data Systems, vol. 5, pp. 575-581, December 2016, doi: 10.5194/gi-5-575-2016 (Albania, France, Italy; COOPERATION WITH NNC; STSM Outcome; INVITED PAPER; OPEN ACCESS)

Abstract: This paper presents the results of a series of laboratory measurements carried out to study how the Ground Penetrating Radar (GPR) signal is affected by moisture variation in wood material. The effects of the wood fiber direction, with respect to the polarisation of the electromagnetic field, are investigated. The relative permittivity of wood and the amplitude of the electric field received by the radar are measured for different humidity levels, by using the direct-wave method in Wide Angle Radar Reflection configuration, where one GPR antenna is moved while the other is kept in a fixed position. The received signal is recorded for different separations between transmitting and receiving antennas. Direct waves are compared to reflected waves: it is observed that they show a different behaviour when the moisture content varies, due to their different propagation paths.

Impact: Cited by 0

[wg2-p4-j3] I. Rodríguez-Abad, G. Klysz, R. Martínez-Sala, J. P. Balayssac, J. Mené-Aparicio, "Application of ground-penetrating radar technique to evaluate the waterfront location in hardened concrete," Geoscientific Instrumentation, Methods and Data Systems, vol. 5, pp. 567–574, December 2016; doi: 10.5194/gi-5-567-2016 (France, Spain; STSM Outcome; INVITED PAPER; OPEN ACCESS)

Abstract: The long term performance of concrete structures is directly tied to two factors: concrete durability and strength. When assessing the durability of concrete structures, the study of the water penetration is paramount, because almost all reactions like corrosion, alkali-silica, sulfate, etc., which produce their deterioration, require the presence of water. Ground-penetrating radar (GPR) has shown to be very sensitive to water variations. On this basis, the objective of this experimental study is, firstly, to analyze the correlation between the water penetration depth in concrete samples and the GPR wave parameters. To do this, the samples were immersed into water for different time intervals and the wave parameters were obtained from signals registered when the antenna was placed on the immersed surface

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of the samples. Secondly, a procedure has been developed to be able to determine, from those signals, the reliability in the detection and location of waterfront depths. The results have revealed that GPR may have an enormous potential in this field, because excellent agreements were found between the correlated variables. In addition, when comparing the waterfront depths calculated from GPR measurements and those visually registered after breaking the samples, we observed that they totally agreed when the waterfront was more than 4 cm depth.

Impact: Cited by 0

[wg2-p4-j4] S. Araujo, L. Delbreilh, L. Laguerre, H. Dumont, E. Dargent, C. Fauchard, "Rock permittivity characterization and application of electromagnetic mixing models for density/compactness assessment of HMA by means of step-frequency radar," EAGE Near Surface Geophysics (NSG), vol. 14(6), pp. 551–562, December 2016, doi: 10.3997/1873-0604.2016031 (France)

Abstract: This work aims to determine the compactness/density of hot mix asphalt by measuring its permittivity by means of step-frequency radar. As hot mix asphalt is mainly made of rocks; their dielectric properties are measured in the frequency range of 0.5 - 4 Ghz with step-frequency radar, using cylindrical cavities. The results show that the rocks can be considered as low-loss dielectric. As electromagnetic mixing models are required to translate measured permittivity to the compactness, power law models and unified mixing rules are needed for laboratory experimental data. The slab permittivity of various compactness is determined with the help of the step-frequency radar system. This study shows that: (i) the selection of the electromagnetic mixing model has a critical impact on the accuracy of the calculated compactness; (ii) the choice of the host matrix for a family of unified mixing rules has huge consequences; and (iii) the best assessment of compactness/density is given by the complex refractive index model and Rayleigh and Böttcher models with an aggregate matrix.

Impact: Cited by 0

[wg2-p4-j5] X. Dérobert, J. F. Lataste, J.-P. Balayssac, S. Laurens, "Evaluation of chloride contamination in concrete using electromagnetic non-destructive testing methods," NDT & E International, vol. 89, pp. 19-29, July 2017, doi: 10.1016/j.ndteint.2017.03.006 (France)

Abstract: We present the results of the sensitivity of some electromagnetic non-destructive testing (NDT) methods to chloride contamination. The NDT methods are resistivity, using a quadripole probe, capacitive technique, with few sets of electrodes, and radar technique, using different bistatic configurations. A laboratory study was carried out involving three different concretes with different water to cement ratios. The concretes were conditioned with different degrees of NaCl saturation by means of three solutions containing 0 g/L, 30 g/l or 120 g/l. The solution was homogenized in the concrete by using a specific procedure. Results show that the EM techniques are very sensitive to the chloride content and saturation rate and, on a second level, to the porosity. Multi-linear regression processing was performed to estimate the level of sensitivity of the NDT measurements to the three indicators. Values of ten ND observables are presented and discussed. At last, the uncertainties of the regression models are studied on a real structure in a tidal zone.

Impact: Cited by 0

Project 2.5 – GPR estimation of water content in soil

[wg2-p5-j1] A. Benedetto, F. Tosti, B. Ortuani, M. Giudici, M. Mele, "Mapping the spatial variation of soil moisture at the large scale using GPR for pavement applications," EAGE Near Surface Geophysics (NSG), vol. 13(3), pp. 269-278, June 2015; doi: 10.3997/1873-0604.2015006 (Italy)

Abstract: The characterization of shallow soil moisture spatial variability at the large scale is a crucial issue in many research studies and fields of application ranging from agriculture and geology to civil and environmental engineering. In this framework, this work contributes to the research in the area of pavement engineering for preventing damages and planning effective management. High spatial variations of subsurface water content can lead to unexpected damage of the load-bearing layers; accordingly, both safety and operability of roads become lower, thereby affecting an increase in expected accidents. A pulsed ground-penetrating radar system with ground-coupled antennas, i.e., 600-MHz and 1600-MHz center frequencies of investigation, was used to collect data in a 16 m × 16 m study site in the Po Valley area in northern Italy. Two ground-penetrating radar techniques were employed to non- destructively retrieve the subsurface moisture spatial profile. The first technique is based on the evalu- ation of the dielectric permittivity from the attenuation of signal amplitudes. Therefore, dielectrics were converted into

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moisture values using soil-specific coefficients from Topp's relationship. Ground- penetrating-radar-derived values of soil moisture were then compared with measurements from eight capacitance probes. The second technique is based on the Rayleigh scattering of the signal from the Fresnel theory, wherein the shifts of the peaks of frequency spectra are assumed comprehensive indi- cators for characterizing the spatial variability of moisture. Both ground-penetrating radar methods have shown great promise for mapping the spatial variability of soil moisture at the large scale.

Impact: Cited by 7

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1) E. Kellner and J. A. Hubbart. "A comparison of the spatial distribution of vadose zone water in forested and agricultural floodplains a century after harvest." Science of the Total Environment 542 (2016): 153-161.
2) F. Tosti, A. Benedetto, A. Calvi, L. Bianchini Ciampoli, "Laboratory investigations for the electromagnetic characterization of railway ballast through GPR," Proc. 16th International Conference on GPR, June 2016, pp. 1-6
3) F. A. Afshar, S. Ayoubi, A. Castrignanò, R. Quarto, M.R.M. Ardekani, "Using ground-penetrating radar to explore the cemented soil horizon in an arid region in Iran," Near Surface Geophysics, vol 15(1), pp. 103-110, February 2017
4) F. Tosti, A. Benedetto, L. Bianchini Ciampoli, A. Calvi, F. D'Amico, "Prediction of rutting evolution in flexible pavement life cycle at the road network scale using an air-launched ground-penetrating radar system," Proc. 16th International Conference on GPR, June 2016, pp. 1-7
5) E. Kellner, "The Long-Term Impacts of Forest Removal on Floodplain Subsurface Hydrology by Kellner," Ph.D. Thesis, University of Missouri – Colombia, 153 pp., 2015.
6) A. Benedetto, F. Tosti, L. Bianchini Ciampoli, F. D'Amico, "GPR Applications Across Engineering and Geosciences Disciplines in Italy: A Review," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9(7), pp. 2952-2965, 2016
7) M. Giudici, M. Mele, S. Inzoli, A. Comunian, R. Bersezio, "Aplicación de la hidrogeofísica para estudiar servicios de los ecosistemas acuáticos de llanuras aluviales," First Break, vol. 33(8), pp. 55-60, 2015.

[wg2-p5-j2] F. Tosti, A. Benedetto, L. Bianchini Ciampoli, S. Lambot, C. Patriarca, E.C. Slob, "GPR analysis of clayey soil behaviour in unsaturated conditions for pavement engineering and geoscience applications," EAGE Near Surface Geophysics (NSG), vol. 14(2), pp. 127-144, April 2016, doi: 10.3997/1873-0604.2016011 (Belgium, Italy, Netherlands, United Kingdom; TU1208 NSG Special Issue)

Abstract: Clay content is one of the primary causes of pavement damages, such as subgrade failures, cracks, and pavement rutting, thereby playing a crucial role in road safety issues as an indirect cause of accidents. In this paper, several ground-penetrating radar methods and analysis techniques were used to nondestructively investigate the electromagnetic behaviour of sub-asphalt compacted clayey layers and subgrade soils in unsaturated conditions. Typical road materials employed for load-bearing layers construction, classified as A1, A2, and A3 by the American Association of State Highway and Transportation Officials soil classification system, were used for the laboratory tests. Clay-free and clay-rich soil samples were manufactured and adequately compacted in electrically and hydraulically isolated formworks. The samples were tested at different moisture conditions from dry to saturated. Measurements were carried out for each water content using a vector network analyser spanning the 1 GHz–3 GHz frequency range, and a pulsed radar system with ground-coupled antennas, with 500-MHz centre frequency. Different theoretically based methods were used for data processing. Promising insights are shown to single out the influence of clay in load-bearing layers and subgrade soils, and its impact on their electromagnetic response at variable moisture conditions.

Impact: Cited by 6

Citing papers:

1) Tosti, F., Benedetto, A., Calvi, A., & Ciampoli, L. B. (2016, June). Laboratory investigations for the electromagnetic characterization of railway ballast through GPR. In Ground Penetrating Radar (GPR), 2016 16th International Conference on (pp. 1-6). IEEE.
2) Benedetto, F., & Tosti, F. (2017). A signal processing methodology for assessing the performance of ASTM standard test methods for GPR systems. Signal Processing, 132, 327-337.
3) Benedetto, A., Tosti, F., Ciampoli, L. B., Calvi, A., Brancadoro, M. G., & Alani, A. M. (2017). Railway ballast condition assessment using ground-penetrating radar–An experimental, numerical simulation and modelling development. Construction and Building Materials, 140, 508-520.
4) Tosti, F., Benedetto, A., Ciampoli, L. B., Calvi, A., & D'Amico, F. (2016, June). Prediction of rutting evolution in flexible pavement life cycle at the road network scale using an air-launched ground-penetrating radar system. In Ground Penetrating Radar (GPR), 2016 16th International Conference on (pp. 1-7). IEEE.
5) Benedetto, A., Tosti, F., Ciampoli, L. B., & D'Amico, F. (2016). GPR Applications Across Engineering and Geosciences Disciplines in Italy: A Review. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 9(7), 2952-2965.
6) Benedetto, A., Tosti, F., Ciampoli, L. B., Pajewski, L., Pirrone, D., Umiliaco, A., & Brancadoro, M. G. (2016, June). A simulation-based approach for railway applications using GPR. In Ground Penetrating Radar (GPR), 2016 16th International Conference on (pp. 1-6). IEEE.

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Working Group 3

Project 3.1 – Electromagnetic modelling for GPR

[wg3-p1-j1] F. Frezza, L. Pajewski, C. Ponti, G. Schettini, "Through-wall electromagnetic scattering by N conducting cylinders," Journal of the Optical Society of America A, vol. 30(8), pp. 1632-1639, Aug. 2013; doi: 10.1364/JOSAA.30.001632 (Italy)

Abstract: A spectral-domain analysis is presented for the scattering by perfectly conducting cylindrical objects behind a dielectric wall. The solution is developed with an analytical-numerical technique, based on the cylindrical wave approach. Suitable cylindrical functions and their spectral representations are introduced as basis functions for the scattered fields, to deal with their interaction with the planar interfaces bounding the wall. The numerical solution is given in TE and TM polarizations states, and in both near- and far-field zones. The model yields an accurate computation of direct scattering that can be useful for through-wall-imaging applications. A stack of three different dielectric media is considered in the theoretical model. In the numerical results, the upper medium, where the incident field is generated, is assumed to be filled by air, the central layer represents the wall, and the lower medium, which contains the scatterers, is air filled, too. Also general problems of scattering by buried objects can be simulated, being the cylinders buried in a medium of arbitrary permittivity, placed below a dielectric layer.

Impact: Cited by 9

Citing papers:

1) Ponti, C. (2015). Methods for the Electromagnetic Forward Scattering by Buried Objects. In Civil Engineering Applications of Ground Penetrating Radar (pp. 197-217). Springer International Publishing.
2) Ponti, C., & Vellucci, S. (2015). Scattering by conducting cylinders below a dielectric layer with a fast noniterative approach. IEEE Transactions on Microwave Theory and Techniques, 63(1), 30-39.
3) Xiong H, Si L-G, Yang X, Wu Y. Analytic descriptions of cylindrical electromagnetic waves in a nonlinear medium. Scientific Reports. 2015;5:11071. doi:10.1038/srep11071.
4) Ponti, C., Pajewski, L., & Schettini, G. (2014, November). The cylindrical-wave approach as a useful tool for defining reference scenarios for inverse and imaging techniques. In Antenna Measurements & Applications (CAMA), 2014 IEEE Conference on (pp. 1-3). IEEE.
5) Ponti, C., Pajewski, L., & Schettini, G. (2014, June). Simulation of scattering by cylindrical targets hidden behind a layer. In Ground Penetrating Radar (GPR), 2014 15th International Conference on (pp. 560-564). IEEE.
6) Ceccuzzi, S., Jandieri, V., Baccarelli, P., Ponti, C., & Schettini, G. (2016). On beam shaping of the field radiated by a line source coupled to finite or infinite photonic crystals. JOSA A, 33(4), 764-770.
7) Ponti, Cristina, Massimo Santarsiero, and Giuseppe Schettini. "Recent advancements in the forward scattering with the Cylindrical Wave Approach." Electromagnetic Theory (EMTS), 2016 URSI International Symposium on. IEEE, 2016.
8) Baghdasaryan, Hovik, Marian Marciniak, and Lara Pajewski. "Civil engineering applications of Ground Penetrating Radar: research activities in COST Action TU1208," iRPhe Conference 2014.
9) Multiple Scattering: Interaction of Time-Harmonic Waves with N Obstacles, P. A. Martin, Cambridge University Press, 2006, xii+437 pp., ISBN13 978-0-521-86554-8, CORRECTIONS AND ADDITIONS, November 14, 2016

[wg3-p1-j2] F. Tosti, A. Umiliaco, "FDTD Simulation of the GPR Signal for Preventing the Risk of Accidents due to Pavement Damages," International Journal of Interdisciplinary Telecommunications and Networking, vol. 6(1), pp. 1-9, Jan-Mar 2014; doi: 10.4018/ijitn.2014010101 (Italy)

Abstract: It is well known that road safety issues are closely dependent on both pavement structural damages and surface unevenness, whose occurrence is often related to ineffective pavement asset management. The evaluation of road pavement operability is traditionally carried out through distress identification manuals on the basis of standardized comprehensive indexes, as a result of visual inspections or measurements, wherein the failure causes can be partially detected. In this regard, ground-penetrating radar (GPR) has proven to be over the past decades an effective and efficient technique to enable better management of pavement assets and better diagnosis of the causes of pavement failures. In this study, one of the main causes (i.e. subgrade failures) of surface damage is analyzed through finite-difference time-domain (FDTD) simulation of the GPR signal. The GprMax 2D numerical simulator for GPR is used on three different types of flexible pavement to retrieve the numerical solution of Maxwell's equations in the time domain. Results show the high potential of GPR in detecting the causes of such damage.

Impact: Cited by 1

Citing paper:

1) Benedetto, A., Tosti, F., Ciampoli, L. B., & D'Amico, F. (2016). GPR Applications Across Engineering and Geosciences Disciplines in Italy: A Review. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 9(7), 2952-2965.

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[wg3-p1-j3] D. Poljak, V. Dorić, "Transmitted field in the lossy ground from ground penetrating radar (GPR) dipole antenna," WIT Transactions on Modelling and Simulation, vol. 59, pp. 3-11, May 2015; doi: 10.2495/CMEM150011 (Croatia)

Abstract: The paper deals with the evaluation of transmitted electric field in the ground due to the GPR dipole antenna. The frequency domain formulation is based on the integro-differential equation of the Pocklington type. The influence of the earth–air interface is taken into account via the simplified reflection/transmission coefficient arising from the Modified Image Theory (MIT). The space-frequency Pocklington equation is solved via the Galerkin Bubnov variant of the Indirect Boundary Element Method (GB-IBEM) and the corresponding transmitted field is obtained by numerically computing field integrals. Some preliminary results for the electric field transmitted into material media are presented.

Impact: Cited by 1

Citing paper:

1) Šušnjara, A., Poljak, D., Šesnić, S., & Dorić, V. (2016, September). Time domain and frequency domain integral equation method for the analysis of ground penetrating radar (GPR) antenna. In Software, Telecommunications and Computer Networks (SoftCOM), 2016 24th International Conference on (pp. 1-4). IEEE.

[wg3-p1-j4] S. Šesnić, S. Lalléchère, D. Poljak, P. Bonnet, K. E. K. Drissi, "Stochastic collocation analysis of the transient current induced along the wire buried in a lossy medium," WIT Transactions on Modelling and Simulation, vol. 59, pp. 47-58, May 2015; doi: 10.2495/CMEM150051 (Croatia, France)

Abstract: The paper deals with the stochastic collocation analysis of a time domain response of a straight thin wire scatterer buried in a lossy half-space. The wire is excited by a plane wave transmitted through the air-ground interface. Transient current induced at the centre of the wire, governed by corresponding Pocklington integro-differential equation is determined. This configuration, as is the case with many electromagnetic compatibility (EMC) issues, suffers from uncertainties in various parameters, such as ground properties, wire dimensions, position, etc. The obtained results yield additional statistical information thus enabling more accurate and efficient analysis of buried wire configurations.

Impact: Cited by 4

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1) Šesnić, S., Lalléchère, S., Poljak, D., Bonnet, P., & Drissi, K. E. K. (2016). A Stochastic Analysis of the Transient Current Induced along the Thin Wire Scatterer Buried in a Lossy Medium. International Journal of Antennas and Propagation, 2016.

2) Fedeli, A., Pastorino, M., & Randazzo, A. (2016, April). A two-step multifrequency imaging technique for ground penetrating radar. In Antennas and Propagation (EuCAP), 2016 10th European Conference on (pp. 1-4). IEEE.

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4) Poljak, D., Šesnić, S., Cvetković, M., Lallechere, S., & Drissi, K. E. K. (2016, September). On some applications of stochastic collocation method in computational electromagnetics: Applications in ground penetrating radar, bioelectromagnetics, grounding systems and buried lines. In Software, Telecommunications and Computer Networks (SoftCOM), 2016 24th International Conference on (pp. 1-5). IEEE.

[wg3-p1-j5] D. Poljak, S. Antonijević, S. Šesnić, S. Lalléchère, K. E. K. Drissi, "On deterministic-stochastic time domain study of dipole antenna for GPR applications," Engineering Analysis with Boundary Elements (Elsevier), vol. 73, pp. 14-20, December 2016; doi: 10.1016/j.enganabound.2016.08.011 (Croatia, France)

Abstract: A deterministic-stochastic transient study of Ground Penetrating Radar (GPR) dipole antenna radiating in a presence of a two-media configuration is carried out in the paper. A deterministic direct time domain formulation is based on the corresponding space-time Hallen integral equation. The numerical solution is carried out via the improved space-time variant of the Galerkin-Bubnov Indirect Boundary Element Method (GB-IBEM). The Stochastic-Collocation (SC) method is then applied to determine accurate confidence intervals due to the random variations of GPR input parameters. Once obtaining the current along the dipole antenna, it is possible to calculate other parameters of interest for GPR dipole antenna behavior, such as the field reflected from the interface of two media, or the field transmitted into a lower half-space. Some illustrative numerical results for the transient current along the dipole antenna and transient electric field transmitted into the lower half-space are given.

Impact: Cited by 1

Citing paper:

1) Lallechere, S., and S. Girard. "Analyse de matériaux composites à structure tridimensionnelle aléatoire à l'aide d'outils de simulation électromagnétique." Journal International de Technologie, de l'Innovation, de la Physique, de l'Energie et de l'Environnement 2.1 (2016).

[wg3-p1-j6] C. Warren, A. Giannopoulos, I. Giannakis, "gprMax: Open source software to simulate

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electromagnetic wave propagation for Ground Penetrating Radar," Computer Physics Communications, vol. 209, pp. 163-170, December 2016; doi: 10.1016/j.cpc.2016.08.020 (United Kingdom; **OPEN ACCESS**)

Abstract: gprMax is open source software that simulates electromagnetic wave propagation, using the Finite-Difference Time-Domain (FDTD) method, for the numerical modelling of Ground Penetrating Radar (GPR). gprMax was originally developed in 1996 when numerical modelling using the FDTD method and, in general, the numerical modelling of GPR were in their infancy. Current computing resources offer the opportunity to build detailed and complex FDTD models of GPR to an extent that was not previously possible. To enable these types of simulations to be more easily realised, and also to facilitate the addition of more advanced features, gprMax has been redeveloped and significantly modernised. The original C-based code has been completely rewritten using a combination of Python and Cython programming languages. Standard and robust file formats have been chosen for geometry and field output files. New advanced modelling features have been added including: an unsplit implementation of higher order Perfectly Matched Layers (PMLs) using a recursive integration approach; diagonally anisotropic materials; dispersive media using multi-pole Debye, Drude or Lorenz expressions; soil modelling using a semi-empirical formulation for dielectric properties and fractals for geometric characteristics; rough surface generation; and the ability to embed complex transducers and targets.

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Citing paper:

1) Hu, S., Zhao, Y., Qin, T., Rao, C., & An, C. (2017). Traveltime tomography of crosshole ground-penetrating radar based on an arctangent functional with compactness constraints. Geophysics, 82(3), H1-H14.

[wg3-p1-j7] D. Poljak, S. Sesnic, S. Lallechere and K. El Khamlichi Drissi, "Stochastic post-processing of the deterministic boundary element modelling of the transient electric field from GPR dipole antenna propagating through lower half-space," International Journal of Computational Methods and Experimental Measurements, vol. 5(5), pp. 678 – 685, 2017, doi: 10.2495/CMEM-V5-N5-678-685 (Croatia, France; OPEN ACCESS)

Abstract: The paper deals with time domain-deterministic stochastic assessment of a transient electric field generated by a ground penetrating radar (GPR) dipole antenna and transmitted into a lower half-space. The deterministic time domain formulation is based on the space-time Hallen integral equation for half-space problems. The Hallen equation is solved via the Galerkin–Bubnov variant of the Indirect Boundary Element Method (GB-IBEM) and the space-time current distribution along the dipole antenna is obtained, thus providing the field calculation. The field transmitted into the lower medium is obtained by solving the corresponding field integrals. As GPR systems are subjected to a rather complex environment, some input parameters, for example the antenna height over ground or earth properties, are partly or entirely unknown and, therefore, a simple stochastic collocation (SC) method is used to properly access relevant statistics about GPR time responses. The SC approach also aids in the assessment of corresponding confidence intervals from the set of obtained numerical results. The expansion of statistical output in terms of mean and variance over a polynomial basis, via the SC method, is shown to be a robust and efficient approach providing a satisfactory convergence rate.

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[wg3-p1-j8] F. Mangini and N. Tedeschi, "Scattering of an electromagnetic plane wave by a sphere embedded in a cylinder," Journal of the Optical Society of America A, vol. 34(5), pp. 760 – 769, May 2017, doi: 10.1364/JOSAA.34.000760 (Italy)

Abstract: In this paper, we face the problem of the scattering of a plane wave by a sphere embedded in an infinitely long circular cylinder. The problems of scattering by both a sphere and a cylinder are canonical problems in optics. However, the scattering problems involving different objects with different geometries have not been solved analytically in the literature: only asymptotic or approximated solutions are available. The problem of scattering by cylinders and spheres concurrently present can be of great importance in several areas, from optical microscopy to biomedical applications, and from metamaterials to civil engineering applications. To solve the problem, the incident wave is expressed as a superposition of cylindrical harmonics. The scattered wave by the cylinder, being a cylindrical wave as well, has been expressed as a superposition of spherical harmonics in order to take into account the interaction with the sphere. The theoretical procedure returns a linear system of equations for the computation of the unknown coefficients of the series. A numerical code is presented to compute the scattered field, where a suitable truncation criterion for the series expansions has been proposed. Comparisons with a finite-element method have been presented to validate the results.

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[wg3-p1-j9] C. Warren, S. Sesnic, A. Ventura, L. Pajewski, D. Poljak, A. Giannopoulos, "Comparison of Time-Domain Finite-Difference, Finite-Integration, and Integral-Equation Methods for Dipole Radiation in Half-space Environments," Progress in Electromagnetic Research M (PIER M), vol. 57, pp. 175-183, 2017, doi: 10.2528/PIERM17021602 (Croatia, Italy, United Kingdom; STSM Outcome; OPEN ACCESS)

Abstract: In this paper we compare current implementations of commonly used numerical techniques — the Finite-Difference Time-Domain (FDTD) method, the Finite-Integration Technique (FIT), and Time-Domain Integral Equations (TDIE) — to solve the canonical problem of a horizontal dipole antenna radiating over lossless and lossy half-spaces. These types of environment are important starting points for simulating many Ground Penetrating Radar (GPR) applications which operate in the near- field of the antenna, where the interaction between the antenna, the ground, and targets is important. We analysed the simulated current at the centre of the dipole antenna, as well as the electric field at different distances from the centre of the antenna inside the half-space. We observed that the results from the simulations using the FDTD and FIT methods agreed well with each other in all of the environments. Comparisons of the electric field showed that the TDIE technique agreed with the FDTD and FIT methods when observation distances were towards the far-field of the antenna but degraded closer to the antenna. These results provide evidence necessary to develop a hybridisation of current implementations of the FDTD and TDIE methods to capitalise on the strengths of each technique.

Project 3.2 – Imaging and inversion techniques for GPR

[wg3-p2-j1] S. Meschino, L. Pajewski, G. Schettini, "A SAP-DOA Method for the Location of Two Buried Objects," International Journal on Antennas and Propagation (Special Issue on "Inverse Scattering and Microwave Tomography in Safety, Security, and Health"), vol. 2013, Article ID 702176, 10 pp., 2013; doi: 10.1155/2013/702176 (Italy; OPEN ACCESS)

Abstract: A localization technique for buried metallic and dielectric objects is proposed and tested. An array of isotropic antennas investigates a scenario with cylindrical targets buried in a dielectric soil. The targets are in the near field of the array, and a Sub-Array Processing (SAP) approach is adopted: the array is partitioned into subarrays, and Direction of Arrival (DoA) algorithms are used to process the electromagnetic field received by each subarray and estimate the dominant arrival direction of the signal. By triangulating all the estimated DoAs, a crossing pattern is obtained. It is filtered by a Poisson-based procedure and subsequently elaborated by the k-means clustering method in order to distinguish between targets and background, estimate the number of targets, and find their position. Several simulations have been performed to compare different DoA algorithms and to test the localization method in the presence of two buried cylinders. Different values of the permittivity of the involved dielectric materials have been considered; the target positions and size have also been varied. The proposed procedure can be useful for ground-penetrating radar applications, near-surface probing, and for the detection and localization of defects in a hosting medium.

Impact: Cited by 6

Citing papers:

1) Meschino, S., & Pajewski, L. (2015, November). Application of a SAP-DoA method to GPR data for the location of reinforcing elements in concrete. In Microwave Symposium (MMS), 2015 IEEE 15th Mediterranean (pp. 1-4). IEEE.
2) Li, C., Wang, W., Shi, L., & Wang, X. (2014). Recognition and parameter extraction of one-dimensional electronic scanning for 3D radar. International Journal of Antennas and Propagation, 2014.
3) Fedeli, A., Pastorino, M., & Randazzo, A. (2016, April). A two-step multifrequency imaging technique for ground penetrating radar. In Antennas and Propagation (EuCAP), 2016 10th European Conference on (pp. 1-4). IEEE.
4) Pajewski, L., Giannopoulos, A., Lambot, S., Marciniak, M., Meschino, S., Pinel, N., ... & Warren, C. (2016, April). Short-Term Scientific Missions on electromagnetic modelling and inversion techniques for Ground Penetrating Radar-COST Action TU1208. In Antennas and Propagation (EuCAP), 2016 10th European Conference on (pp. 1-5). IEEE.
5) Baghdasaryan, H., Marciniak, M., & Pajewski, L. Civil engineering applications of Ground Penetrating Radar: research activities in COST Action TU1208, IRPHE 2014 Conference.
6) Salucci, M., Poli, L., Anselmi, N., & Massa, A. (2017). Multifrequency Particle Swarm Optimization for Enhanced Multiresolution GPR Microwave Imaging. IEEE Transactions on Geoscience and Remote Sensing, 55(3), 1305-1317.

[wg3-p1-j2] S. Nounouh, C. Eyraud, A. Litman, H. Tortel, "Near-subsurface imaging in an absorbing embedding medium with a multistatic/single frequency scanner," Near Surface Geophysics (EAGE), vol. 13(3), pp. 211-218, June 2015; doi: 10.3997/1873-0604.2014046 (France)

Abstract: Probing the near subsurface in the presence of absorbing media is a very challenging problem. Within that framework, we analyze the capabilities of a mono-frequency/multistatic set-up for detecting

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shallowly buried targets. As the antennas constitute an important part of the probing device, an accurate method for modelling the antennas behaviour is proposed. This modelling, performed thanks to a correct balanced set of elementary sources, is then incorporated in the calculation of the scattered field, performed with a home-made Finite Element Method software. Efforts have also been put into the measurement procedure. The measured fields are thus post-processed with an efficient method which takes profit of the spectral bandwidth properties of the scattered field. These fields serve as input data for the inversion algorithm, an extension of the DORT method to elongated targets. This qualitative and fast imaging procedure, which exploits the spectral properties of the multi static scattering matrix, has been adapted to the present stratified configuration. Imaging results of shallowly buried targets embedded in a high losses medium are presented to assess the well-behaviour of the proposed methodology.

Impact: Cited by 1

Citing paper:

1) S. Nounouh, C. Eyraud, A. Litman, and H. Tortel, "Quantitative Imaging With Incident Field Modeling From Multistatic Measurements on Line Segments," IEEE Antennas and Wireless Propagation Letters, vol. 14, pp. 253-256, 2015.

[wg3-p2-j3] M. Salucci, G. Oliveri, A. Massa, "GPR Prospecting Through an Inverse-Scattering Frequency-Hopping Multifocusing Approach," IEEE Transactions on Geoscience and Remote Sensing, vol. 53(12), pp. 6573-6592, December 2015; doi: 10.1109/TGRS.2015.2444391 (France, Italy)

Abstract: An innovative information-acquisition approach to 2-D ground-penetrating radar (GPR) prospecting is presented. A microwave inverse-scattering nested scheme combining a frequency hopping (FH) procedure and a multifocusing (MF) technique is proposed. On the one hand, the FH scheme effectively handles multifrequency GPR data, whereas on the other hand, MF techniques have been proven to be effective tools in reducing the occurrence of multilocal minima affecting GPR investigations. This allows the use of a local search technique based on the conjugate gradient method to iteratively solve the inverse problem at hand. Selected results are reported and analyzed to give some insights to the interested readers on the advantages and limitations of such an approach when handling synthetically generated and experimental GPR data.

Impact: Cited by 13

Citing papers:

1) Salucci, M., Poli, L., & Massa, A. (2017). Advanced multi-frequency GPR data processing for non-linear deterministic imaging. Signal Processing, 132, 306-318.

2) Hoarau, Q., Ginolhac, G., Atto, A. M., & Nicolas, J. M. (2017). Robust adaptive detection of buried pipes using GPR. Signal Processing, 132, 293-305.

3) Tenuti, L., Oliveri, G., Viani, F., Polo, A., Donelli, M., & Massa, A. (2015, November). A frequency-hopping BCS strategy for imaging buried objects. In Microwave Symposium (MMS), 2015 IEEE 15th Mediterranean (pp. 1-4). IEEE.

4) Salucci, M., Tenuti, L., Randazzo, A., & Rocca, P. (2016, August). Multi-resolution approaches for GPR-data inversion. In Electromagnetic Theory (EMTS), 2016 URSI International Symposium on (pp. 16-18). IEEE.

5) Salucci, M., Ahmed, S., & Massa, A. (2016, April). An adaptive Learning-by-Examples strategy for efficient Eddy Current Testing of conductive structures. In Antennas and Propagation (EuCAP), 2016 10th European Conference on (pp. 1-4). IEEE.

6) Fedeli, A., Pastorino, M., & Randazzo, A. (2016, April). A two-step multifrequency imaging technique for ground penetrating radar. In Antennas and Propagation (EuCAP), 2016 10th European Conference on (pp. 1-4). IEEE.

7) Salucci, M., Tenuti, L., Poli, L., Oliveri, G., & Massa, A. (2016, October). A computational method for the inversion of wide-band GPR measurements. In Journal of Physics: Conference Series (Vol. 756, No. 1, p. 012008). IOP Publishing.

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9) Oliveri, G., Salucci, M., Tenuti, L., & Massa, A., Enhancing GPR microwave imaging through innovative information acquisition techniques, in Probing Matter with Electromagnetic Waves, Journées scientifiques 24/25 mars 2015.

10) Salucci, M., Anselmi, N., Oliveri, G., Calmon, P., Miorelli, R., Reboud, C., & Massa, A. (2016). Real-Time NDT-NDE Through an Innovative Adaptive Partial Least Squares SVR Inversion Approach. IEEE Transactions on Geoscience and Remote Sensing, 54(11), 6818-6832.

11) Salucci, M., Poli, L., Anselmi, N., & Massa, A. (2017). Multifrequency Particle Swarm Optimization for Enhanced Multiresolution GPR Microwave Imaging. IEEE Transactions on Geoscience and Remote Sensing, 55(3), 1305-1317.

12) Oliveri, G., Rocca, P., Poli, L., Anselmi, N., Salucci, M., Moriyama, T., ... & Massa, A. (2016, August). Real-time eddy-current-testing of metallic structures through statistical learning methodology. In Progress in Electromagnetic Research Symposium (PIERS) (pp. 3957-3958). IEEE.

13) Liu, Y., Zhao, Z., Yang, Y., Wang, B., Zhu, X., Nie, Z., & Liu, Q. H. (2016). A Frequency-Hopping Subspace-Based Optimization Method for Reconstruction of 2-D Large Uniaxial Anisotropic Scatterers With TE Illumination. IEEE Transactions on Geoscience and Remote Sensing, 54(10), 6091-6099.

[wg3-p2-j4] M. Sun, C. Le Bastard, Y. Wang, N. Pinel, "Time-Delay Estimation Using ESPRIT With Extended Improved Spatial Smoothing Techniques for Radar Signals," IEEE Geoscience and Remote Sensing Letters, vol. 13(1), pp. 73-77, January 2016; doi: 10.1109/LGRS.2015.2497378 (France, China; COOPERATION WITH IPC; INDUSTRY INVOLVEMENT)

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Abstract: In the electromagnetic field, radar is widely used to measure or estimate the media parameters or to detect targets through obstructions. For horizontally stratified media, the layer thickness can be deduced from the time delays of backscattered echoes and the dielectric constants. The high-resolution method estimation of signal parameters via rotation invariance techniques (ESPRIT) has been proposed for time-delay estimation. In practice with a radar, backscattered echoes are correlated. In order to apply the ESPRIT method, in this letter, we propose to use two adaptive improved spatial smoothing techniques with the propagator method for fighting against the correlation between the echoes. The proposed solution does not use any approximation. Numerical examples are provided to show the performance of the algorithm.

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Citing papers:

1) Sun, M., Le Bastard, C., Pinel, N., Wang, Y., Li, J., Pan, J., & Yu, Z. (2017). Estimation of time delay and interface roughness by GPR using modified MUSIC. Signal Processing, 132, 272-283.

2) Le Bastard, C., Chahine, K., Wang, Y., Baltazart, V., Pinel, N., Bourlier, C., & Derobert, X. (2016). Microwave Non‐Destructive Testing of Non‐Dispersive and Dispersive Media Using High‐Resolution Methods. In Non-Destructive Testing. InTech.

[wg3-p4-j5] L. Mertens, R. Persico, L. Matera, S. Lambot, "Automated Detection of Reflection Hyperbolas in Complex GPR Images With No A Priori Knowledge on the Medium," IEEE Transactions of Geoscience and Remote Sensing, Vol. 54(1), January 2016, pp. 580-596; doi: 10.1109/TGRS.2015.2462727 (Belgium, Italy)

Abstract: In this paper, we propose an automated detection algorithm for well- and ill-shaped ground-penetrating radar re- flection hyperbolas for complex media, calibrated with human recognition principles. The algorithm detects the apex of the hyperbolas by fitting an analytical function of a hyperbola to the profile edge dots detected with a Canny filter. The existence of a hyperbola is determined using a set of carefully chosen criteria calibrated in order to fit the ambiguity zone for the human brain. The inherent misshapedness of field hyperbolas is further consid- ered by defining a buffer zone around the theoretical hyperbola. First, the method was tested in the laboratory over tree roots and PVC pipes and on field images over tree root systems. Both time- and frequency-domain radars were used on-ground. After around 1–3 min of computation time for 10 000 edge dots in a MATLAB environment (single 1.96-GHz processor), the results showed rates of false alarm and nondetection of maximum 20% and 28%, respectively. In comparison with the semiautomated hyperbola detection provided by a commercial software, these rates were lower. Second, we conducted a sensitivity analysis to estimate the validity of the fitting of a hyperbola equation neglecting the object radius. The fitting was close, but the derivation of the relative permittivity from the analytical equation neglecting the radius led to high errors. In conclusion, owing to the low computational time and its good performances, the proposed algorithm is suitable for complex environments.

Impact: Cited by 10

Citing papers:

1) Dou, Q., Wei, L., Magee, D. R., & Cohn, A. G. (2017). Real-Time Hyperbola Recognition and Fitting in GPR Data. IEEE Transactions on Geoscience and Remote Sensing, 55(1), 51-62.

2) Persico, R., Matera, L., Desantis, V., Congedo, F., Lambot, S., & Got, J. B. (2016, June). Some Limits of the Method of the Diffraction Hyperbolas and a Proposal for its overcoming. In Ground Penetrating Radar (GPR), 2016 16th International Conference on (pp. 1-5). IEEE.

3) Li, W., Cui, X., Guo, L., Chen, J., Chen, X., & Cao, X. (2016). Tree root automatic recognition in ground penetrating radar profiles based on randomized hough transform. Remote Sensing, 8(5), 430.

4) Pe'er, U., & Dy, J. G. (2017). Automated Target Detection for Geophysical Applications. IEEE Transactions on Geoscience and Remote Sensing, 55(3), 1563-1572.

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6) Dou, Q., Wei, L., Magee, D. R., Atkins, P. R., Chapman, D. N., Curioni, G., ... & Muggleton, J. (2016). 3D buried utility location using a marching-cross-section algorithm for multi-sensor data fusion. Sensors, 16(11), 1827.

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9) Masarik, M. P., Thelen, B. T., & Xique, I. J. (2016, May). Enhancements to GPR buried UXO detection using the apex-shifted hyperbolic radon tansform. In SPIE Defense+ Security (pp. 98231B-98231B). International Society for Optics and Photonics.

10) Persico, R., & Leucci, G. (2016). Interference Mitigation Achieved with a Reconfigurable Stepped Frequency GPR System. Remote Sensing, 8(11), 926.

[wg3-p2-j6] M. Sun, C. Le Bastard, N. Pinel, Y. Wang, J. Li, "Road surface layers geometric

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parameters estimation by ground penetrating radar using Estimation of Signal Parameters via Rotational Invariance Techniques method," IET Radar, Sonar & Navigation, vol. 10(3), pp. 603-609, March 2016; doi: 10.1049/iet-rsn.2015.0374 (**France**, **China**; **COOPERATION WITH IPC; INDUSTRY INVOLVEMENT**)

Abstract: In civil engineering, ground penetrating radar is widely used to assess the roadway structures. This study evaluates the influence of interface roughness. A modified estimation of signal parameters by rotational invariance techniques algorithm is proposed with a spectral smoothing technique for efficiently estimating the time delay, the permittivity of the layers and the interface roughness. To reduce the impact of noise, a preprocessing method called propagator is used to estimate the noise variance. The algorithm is tested on simulated data obtained by the rigorous numerical method called PILE (propagation inside layer expansion). Numerical simulations are conducted to assess the performance of the algorithm. The simulation results show that the proposed algorithm can estimate road parameters with small relative root mean square error.

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Citing paper:

1) Sun, M., Le Bastard, C., Pinel, N., Wang, Y., Li, J., Pan, J., & Yu, Z. (2017). Estimation of time delay and interface roughness by GPR using modified MUSIC. Signal Processing, 132, 272-283.

[wg3-p2-j7] M. Salucci, L. Tenuti, L. Poli, G. Oliveri, A. Massa, "A computational method for the inversion of wide-band GPR measurements," Journal of Physics: Conference series, vol. 756, Article No. 012008, pp. 1-7, October 2016, doi: 10.1088/1742-6596/756/1/012008 (France, Italy; OPEN ACCESS)

Abstract: An innovative method for the inversion of ground penetrating radar (GPR) measurements is presented. The proposed inverse scattering (IS) approach is based on the exploitation of wide-band data according to a multi-frequency (MF) strategy, and integrates a customized particle swarm optimizer (PSO) within the iterative multi-scaling approach (IMSA) to counteract the high non-linearity of the optimized cost function. If from the one hand the IMSA provides a reduction of the ratio between problem unknowns and informative data, on the other hand the stochastic nature of the PSO solver allows to "escape" from the high density of false solutions of the MF-IS subsurface problem. A set of representative numerical results verifies the effectiveness of the developed approach, as well as its superiority with respect to a deterministic implementation.

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[wg3-p2-j8] M. Salucci, L. Poli, A. Massa, "Advanced multi-frequency GPR data processing for non-linear deterministic imaging," Signal Processing (Elsevier), vol. 132, pp. 306–318, March 2017, doi: 10.1016/j.sigpro.2016.06.019 (France, Italy; TU1208 SP Special Issue)

Abstract: In this paper, the quantitative imaging of the dielectric characteristics of unknown targets buried in a lossy half-space is performed by suitably processing wide-band ground penetrating radar (GPR) measurements. 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) is proposed. Representative results from numerical test cases are presented to provide the interested readers with some indications on the effectiveness, as well as the current limitations, of the proposed approach when directly compared to a state-of-the-art frequency-hopping (FH) based method formulated in the same framework. Such a validation points out that if, on the one hand, the proposed MF strategy is computationally more efficient than the FH one, on the other hand, it turns out to be less reliable and accurate in several situations.

Impact: Cited by 1

Citing paper:

1) Economou, N., Benedetto, F., Bano, M., Tzanis, A., Nyquist, J., Sandmeier, K. J., & Cassidy, N. (2017). Advanced Ground Penetrating Radar Signal Processing Techniques. Signal Processing, 132, 197-200.

[wg3-p2-j9] M. Sun, C. Le Bastard, N. Pinel, Y. Wang, J. Li, J. Pana, Z. Yud, "Estimation of time delay and interface roughness by GPR using modified MUSIC," Signal Processing (Elsevier), vol. 132, pp. 272–283, March 2017, doi: 10.1016/j.sigpro.2016.05.029 (France, China; COOPERATION WITH IPC; INDUSTRY INVOLVEMENT; TU1208 SP Special Issue)

Abstract: In civil engineering, roadway structure evaluation is an important application which can be carried out by ground penetrating radar. In this paper, firstly a signal model taking into account the influence of interfaces roughness (surface and interlayer) is proposed. In order to estimate the time delay and interface roughness, we propose a method composed of 2 steps: 1) a modified MUSIC algorithm is

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proposed for time delay estimation; 2) the interface roughness is estimated by using Maximum Likelihood method (MLE) with the estimated time delays. The proposed algorithms are tested on data obtained by a method of moments (MoM). Numerical examples are provided to demonstrate the performance of the proposed algorithm.

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Citing paper:

1) Economou, N., Benedetto, F., Bano, M., Tzanis, A., Nyquist, J., Sandmeier, K. J., & Cassidy, N. (2017). Advanced Ground Penetrating Radar Signal Processing Techniques. Signal Processing, 132, 197-200.

[wg3-p2-j10] M. Salucci, L. Poli, N. Anselmi, A. Massa, "Multifrequency Particle Swarm Optimization for Enhanced Multiresolution GPR Microwave Imaging," IEEE Transactions on Geoscience and Remote Sensing, vol. 55(3), pp. 1305-1317, March 2017, doi: 10.1109/TGRS.2016.2622061 (France, Italy)

Abstract: An innovative inverse scattering (IS) technique for the simultaneous processing of multifrequency (MF) ground-penetrating radar (GPR) measurements is proposed. The nonlinear IS problem is solved by profitably integrating a customized MF version of the particle swarm optimizer (PSO) within the iterative multiscaling approach (IMSA) to jointly exploit the reduction of the ratio between unknowns and uncorrelated data with a pervasive exploration of the multidimensional search space for minimizing the probability that the solution is trapped into local minima corresponding to false solutions of the problem at hand. Both numerical and experimental test cases are reported to assess the reliability of the MF-IMSA-PSO method toward accurate GPR tomography as well as improvements with respect to the competitive state-of-the-art inversion approaches.

Impact: Cited by 0

[wg3-p2-j11] A. Ristic, Z. Bugarinovic, M. Vrtunski, Miro Govedarica, "Point Coordinates Extraction from Localized Hyperbolic Reflections in GPR Data," Journal of Applied Geophysics, vol. TBD, pp. TBA, 2017; doi: 10.1016/j.jappgeo.2017.06.003 (Serbia)

Abstract: In this paper, we propose an automated detection algorithm for the localization of apexes and points on the prongs of hyperbolic reflection incurred as a result of GPR scanning technology. The objects of interest encompass cylindrical underground utilities that have a distinctive form of hyperbolic reflection in radargram. Algorithm involves application of trained neural network to analyze radargram in the form of raster image, resulting with extracted segments of interest that contain hyperbolic reflections. This significantly reduces the amount of data for further analysis. Extracted segments represent the zone for localization of apices. This is followed by extraction of points on prongs of hyperbolic reflections which is carried out until stopping criterion is satisfied, regardless the borders of segment of interest. In final step a classification of false hyperbolic reflections caused by the constructive interference and their removal is done. The algorithm is implemented in MATLAB environment. There are several advantages of the proposed algorithm. It can successfully recognize true hyperbolic reflections in radargram images and extracts coordinates, with very low rate of false detections and without prior knowledge about the number of hyperbolic reflections or buried utilities. It can be applied to radargrams containing single and multiple hyperbolic reflections, intersected, distorted, as well as incomplete (asymmetric) hyperbolic reflections, all in the presence of higher level of noise. Special feature of algorithm is developed procedure for analysis and removal of false hyperbolic reflections generated by the constructive interference from reflectors associated with the utilities. Algorithm was tested on a number of synthetic and radargram acquired in the field survey. To illustrate the performances of the proposed algorithm, we present the characteristics of the algorithm through five representative radargrams obtained in real conditions. In these examples we present different acquisition scenarios by varying the number of buried objects, their disposition, size, and level of noise. Example with highest complexity was tested also as a synthetic radargram generated by gprMax. Processing time in examples with one or two hyperbolic reflections is from 0.1 to 0.3 s, while for the most complex examples it is from 2.2 to 4.9 s. In general, the obtained experimental results show that the proposed algorithm exhibits promising performances both in terms of utility detection and processing speed of the algorithm.

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Project 3.3 – Intrinsic models for describing near-field antenna effects

[wg3-p3-j1] F. André, S. Lambot, "Intrinsic Modeling of Near-Field Electromagnetic Induction Antennas for Layered Medium Characterization," IEEE Transactions on Geoscience and Remote

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Sensing, vol. 52(11), pp. 7457-7469, November 2014; doi: 10.1109/TGRS.2014.2312816 (Belgium)
Abstract: We present a closed-form equation for intrinsic modeling of near-field electromagnetic induction (EMI) antennas for planar layered media characterization. Resorting to a decomposition of the backscattered EM field into elementary distributions over the antenna aperture, the EMI transmitting and receiving antennas are modeled using infinitesimal magnetic dipoles and field points, and characteristic frequency-dependent global reflection and transmission coefficients. Low-frequency propagation of the EM fields in the medium is described using 3-D planar layered media Green's functions. We performed measurements with a loop antenna situated at different heights, ranging from near-field to far-field conditions, above water of known electrical conductivity to determine its intrinsic properties, and a range of salinity conditions was applied to subsequently validate the proposed model. The EMI system was set up using a vector network analyzer equipped with a prototype EMI antenna specifically designed for this application. The model showed good accuracy for reproducing the observed data, and model inversion provided good estimates of the medium electrical conductivity. Yet, insensitivity of the EMI signal to water electrical conductivity was encountered for low salinity due to the presence of a copper sheet as the bottom boundary condition of the experimental setup. Moreover, the efficiency of the antenna decreased rapidly as antenna height above water surface increases, leading to increasing discrepancies between estimated and measured water electrical conductivity values as the antenna moves away from the water surface. Although some technical improvements are still needed, the proposed approach is promising for quantitative estimation of soil electrical conductivity from EMI data.

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Citing papers:

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2) Guan, B., Ihamouten, A., Guilbert, D., Bosc, F., Derobert, X., Villain, G., & Lambot, S. (2016, June). Modeling of stepped-frequency radar wave propagation through partially wet limestone. In Ground Penetrating Radar (GPR), 2016 16th International Conference on (pp. 1-6). IEEE.
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[wg3-p3-j2] A. De Coster, A. P. Tran, S. Lambot, "Fundamental Analyses on Layered Media Reconstruction Using GPR and Full-Wave Inversion in Near-Field Conditions," IEEE Transactions on Geoscience and Remote Sensing, vol. 54(9), pp. 5143-5158, September 2016; doi: 10.1109/TGRS.2016.2556862 (Belgium, United States; COOPERATION WITH IPC)
Abstract: An innovative information-acquisition approach to 2-D ground-penetrating radar (GPR) prospecting is presented. A microwave inverse-scattering nested scheme combining a frequency hopping (FH) procedure and a multifocusing (MF) technique is proposed. On the one hand, the FH scheme effectively handles multifrequency GPR data, whereas on the other hand, MF techniques have been proven to be effective tools in reducing the occurrence of multilocal minima affecting GPR investigations. This allows the use of a local search technique based on the conjugate gradient method to iteratively solve the inverse problem at hand. Selected results are reported and analyzed to give some insights to the interested readers on the advantages and limitations of such an approach when handling synthetically generated and experimental GPR data.

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Project 3.4 – Data processing for GPR

[wg3-p4-j1] M. Manataki, A. Vafidis, A. Sarris, "Application of empirical mode decomposition methods to ground penetrating radar data," First Break (EAGE), vol. 32, pp. 67-71, August 2014 (Greece)
Abstract: Empirical Mode Decomposition (EMD) is a relatively new technique introduced by Huang et al., (1998) for analysing non-linear and non-stationary time series. The decomposition is based on a signal's local extrema, which define different oscillation modes present in the signal. What EMD does is the separation of those differ- ent oscillatory modes into a finite and usually small number of stationary sub-signals called Instrinsic Mode Functions (IMFs). EMD suffers from mode mixing which limits the frequency separation among the different modes and makes the physical meaning of the IMFs unclear.
The introduction of Ensemble Empirical Mode Decomposition (EEMD) by Wu and Huang (2009) as an EMD-based noise assistance method improved the modes separation by eliminating the mode-mixing problem. The signal is not fully reconstructed by the IMFs calculated from EEMD. The latter lead Torres et

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al. (2011) to propose another modification, the Complete Ensemble Empirical Mode Decomposition (CEEMD). CEEMD is also a noise assisted and adaptive method where the original signal can be fully reconstructed. EMD-based algorithms have been applied to seismic reflection data (Battista et al., 2007; Bekara and Van der Baan, 2009). Battista et al. (2009) used EMD to remove wow noise from Ground Penetrating Radar (GPR) data. Chen and Jeng, (2011), applied EEMD to enhance GPR data and provided promising results. Here, we compare the empirical mode decomposition methods using both synthetic and real GPR data. In particular, we examine: (1) the separation of high-frequency wavelets from the low frequency ones and (2) the noise level that yields better decomposition for EEMD and CEEMD. We also examined the capability of these decomposition methods to remove random and coherent noise from real GPR data.

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2) Manataki, M., Sarris, A., & Vafidis, A. (2015, July). Combining CEEMD and predictive deconvolution for the suppression of multiple reflections and coherent noise in GPR signals. In Advanced Ground Penetrating Radar (IWAGPR), 2015 8th International Workshop on (pp. 1-4). IEEE.

[wg3-p4-j2] M. Varela-González, M. Solla, J. Martínez-Sánchez, P. Arias, "A semi-automatic processing and visualisation tool for ground-penetrating radar pavement thickness data," Automation in Construction (Elsevier), vol. 45, pp. 42-49, September 2014; doi: 10.1016/j.autcon.2014.05.004 (Spain)

Abstract: Ground-penetrating radar (GPR) is a recommendable and cost-effective non-destructive technique for measuring the thickness of pavement layers because data acquisition can take place at normal traffic speeds. On the other hand, the large amount of data collected is difficult to process. Given that processing is conducted by qualified practitioners, it is a key to obtain software tools that allow for accurate thickness measurements and fast processing times. This paper presents a new semi-automatic program for the processing and visualisation of GPR data to measure pavement thicknesses. The results showed that an optimisation in the execution time allowed for a near-immediate response in data processing even when dealing with large data sets. Different data set lengths, ranging from 100 m to 20 km, were analysed, and the processing times required to complete the entire process were examined taking into account three different hardware configurations (i3, i5 and i7 processors). In all cases, the processing times did not exceed 30 s. An additional test was performed to evaluate the reproducibility of the algorithm on a well-defined and preconditioned concrete asphalt course. Furthermore, the visualisation application allows for the georeferencing of the field GPR data by using additional GPS data.

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[wg3-p4-j3] J. Li, C. Le Bastard, Y. Wang, G. Wei, B. Ma, M. Sun, "Enhanced GPR Signal for Layered Media Time-Delay Estimation in Low-SNR Scenario," IEEE Geoscience and Remote Sensing Letters, vol. 13(3), pp. 299-303, March 2016; doi: 10.1109/LGRS.2015.2502662 (France, China; COOPERATION WITH IPC)

Abstract: In this letter, a new method is proposed to enhance the ground-penetrating radar (GPR) signal

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for time-delay estimation in a low signal-to-noise ratio. It is based on a subspace method and a clustering technique. The proposed method makes it possible to improve the estimation accuracy in a noisy context. It is used with a compressive sensing method to estimate the time delay of layered media backscattered echoes coming from the GPR signal. Several simulations and an experiment are presented to show the effectiveness of signal enhancement.

Impact: Cited by 1

Citing paper:

1) Benedetto, F., & Tosti, F. (2017). A signal processing methodology for assessing the performance of ASTM standard test methods for GPR systems. Signal Processing, 132, 327-337.

[w3-p4-j4] N. Economou, "Time-varying band-pass filtering GPR data by self-inverse filtering," EAGE Near Surface Geophysics (NSG), vol. 14(2), pp. 207-217, April 2016, doi: 10.3997/1873-0604.2016015 (Greece; TU1208 NSG Special Issue)

Abstract: Even though ground penetrating radar data signal processing has already been studied by many researchers, more research is needed and expected from automatic ground penetrating radar data analysis. An automatic band-pass filtering procedure can lead to sufficient real-time data interpretation as signal buried in noise could be amplified. Ground penetrating radar traces are highly nonstationary, requiring time-varying processing techniques. An algorithm, based on self-inverse filtering, which is a special case of inverse filtering, was implemented. It is a ground penetrating radar trace filtering approach and is implemented by applying inverse filtering in each time sample in the time-frequency domain. Applied on a synthetic trace, this algorithm performed better than a stationary band-pass filter and empirical mode decomposition family methods, whereas its application on real ground penetrating radar data from two different sites enhanced reflections buried in noise without the need to test different high-frequency band stops and with minimum distortion of the signal and the initial temporal resolution of the data.

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[wg3-p4-j5] A. Benedetto, F. Tosti, L. Bianchini Ciampoli, F. D'Amico, "An overview of ground-penetrating radar signal processing techniques for road inspections," Signal Processing (Elsevier), vol. 132, pp. 201-209, March 2017, doi: 10.1016/j.sigpro.2016.05.016 (Italy, United Kingdom; TU1208 SP Special Issue)

Abstract: Ground-penetrating radar (GPR) was firstly used in traffic infrastructure surveys during the first half of the Seventies for testing in tunnel applications. From that time onwards, such non-destructive testing (NDT) technique has found exactly in the field of road engineering one of the application areas of major interest for its capability in performing accurate continuous profiles of pavement layers and detecting major causes of structural failure at traffic speed. This work provides an overview on the main signal processing techniques employed in road engineering, and theoretical insights and instructions on the proper use of the processing in relation to the quality of the data acquired and the purposes of the surveys.

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[wg3-p4-j6] F. Benedetto, F. Tosti, "A signal processing methodology for assessing the performance of ASTM standard test methods for GPR SYSTEMS," Signal Processing (Elsevier), vol. 132, pp. 327–337, March 2017, doi: doi:10.1016/j.sigpro.2016.06.030 (Italy, United Kingdom; TU1208 SP Special Issue)

Abstract: Ground penetrating radar (GPR) is one of the most promising and effective non-destructive testing techniques (NDTs), particularly for the interpretation of the soil properties. Within the framework of international Agencies dealing with the standardization of NDTs, the American Society for Testing and Materials (ASTM) has published several standard test methods related to GPR, none of which is focused on a detailed analysis of the system performance, particularly in terms of precision and bias of the testing variable under consideration. This work proposes 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

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assess the performance of the above standard test methods for GPR systems. The (theoretical) expressions of the bias and variance of the estimation error are here investigated by a reduced Taylor's expansion up to the second order. Therefore, a closed form expression for theoretically tuning the optimal threshold according to a fixed target value of the GPR signal stability is proposed. Finally, the study is extended to GPR systems with different antenna frequencies to analyze the specific relationship between the frequency of investigation, the optimal thresholds, and the signal stability.

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Citing papers:

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Working Group 4

Archaeology & Cultural heritage

[wg4-ACH-j1] V. Pérez-Gracia, J. O. Caselles, J. Clapés, G. Martinez, R. Osorio, "Non-destructive analysis in cultural heritage buildings: Evaluating the Mallorca cathedral supporting structures," Non Destructive Testing and Evaluation International (Elsevier), vol. 59, pp. 40–47, October 2013; doi: 10.1016/j.ndteint.2013.04.014 (Spain)

Abstract: Geophysical prospecting surveys are being increasingly used in non-destructive evaluations of structures, and several methods can be applied in the evaluation of cultural heritage buildings. However, accurate studies of cultural heritage structures usually need the application of combined techniques, historic and structural knowledge also being necessary. The present paper describes the application of two non-destructive testing techniques: ground-penetrating radar and seismic tomography, in the analysis of some structural elements' inner geometries and physical properties. This job is part of a more complete project developed to define the Mallorca Cathedral structural behaviour. Both geophysical methods are used in a complementary way. GPR allows the detection of small anomalies (changes of about centimetres), and the results are used to select the most appropriate seismic tomography initial model. The aim of the study is to define the internal structural configuration as well as the stone quality. Results reveal the internal structure of columns, walls and buttresses, showing different structural elements. Even when the visual inspection points to external damages, the detailed NDT evaluation indicates that the inner structure is in good condition and the ashlars are of good quality.

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[wg4-ACH-j2] M. Solla, R. Asorey-Cacheda, X. Núñez-Nieto, B. Conde-Carnero, “Evaluation of historical bridges through recreation of GPR models with the FDTD algorithm,” Construction and Building Materials (Elsevier), vol. 77, pp. 19-27, January 2016; doi: 10.1016/j.ndteint.2015.09.003 (Spain)

Abstract: This work presents the evaluation of a medieval masonry bridge that has suffered different restorations throughout history. Ground penetrating radar was used to define the internal state of the structure. Given that the heterogeneity in masonry complicates the interpretation of field data, numerical modelling was employed to improve such interpretation. The combination of photogrammetric and thermographic data, jointly with the development of custom algorithms, was used to create the synthetic model; while real GPR data supported the media characterization. The resulting data allowed for the interpretation of both composition and distribution of different materials in the interior of the bridge.

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[wg4-ACH-j2] S. Santos-Assunçao, K. Dimitriadis, Y. Konstantakis, V. Perez-Gracia, E. Anagnostopoulou, R. Gonzalez-Drigo, "Ground-penetrating radar evaluation of the ancient Mycenaean monument Tholos Acharnon tomb," EAGE Near Surface Geophysics (NSG), vol. 14(2), pp. 197-205, April 2016, doi: 10.3997/1873-0604.2015030 (Spain, Greece; STSM Outcome; INDUSTRY INVOLVEMENT; TU1208 NSG Special Issue)

Abstract: The assessment of cultural heritage requires high-resolution and non-destructive methodologies. Ground-penetrating radar is widely applied in the inspection of historical buildings. However, some structures with curved surfaces make the radar data acquisition process difficult and consequently the following data interpretation. This paper describes a case study concerning a circular and buried Greek monument. This monument is a magnificent tomb buried with irregular stones. However, its structure and the internal stones arrangement are unknown. Therefore, a radar survey was carried out to achieve two main objectives: (i) identification of hidden elements and arrangement of the stones and (ii) detection of specific zones where further restoration and maintenance should be recommended. The methodology for the radar data acquisition involves the use of a laser scan in order to define accurately each radar line, covering all the internal surface of the tomb. Radar data processing was developed by converting Cartesian coordinates into polar coordinates. This proce- dure allows defining better the internal anomalies, improving the radar data interpretation. The main results of the survey were three: (i) the presence of a hidden target

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buried in the corridor access to the tomb; (ii) the description of the internal structure of the walls of the tomb, defining the stones arrangement and the position and depth to the keystone; and (iii) the existence of delimited zones where the signal is highly attenuated, probably due to a high salt content.

Impact: Cited by 1

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Geology, Geophysics & Geotechnics

[wg4-GGG-j1] M. Zajc, B. Celarc, A. Gosar, "Structural–geological and karst feature investigations of the limestone–flysch thrust-fault contact using low-frequency ground penetrating radar (Adria–Dinarides thrust zone, SW Slovenia)," Environmental Earth Sciences (Springer), vol. 73(12), pp. 8237-8249, June 2015; doi: 10.1007/s12665-014-3987-x (Slovenia)

Abstract: The Karstic thrust edge, a pronounced geomorphologic step, which is a result of the tectonostratigraphic evolution of the active Adria–Dinarides thrust zone, represents a major obstacle for the planned new railway route Divača–Koper. Thus, the geotechnical and structural properties as well as the geometry of the thrust-fault planes in this area are of great importance. Since geological mapping cannot give insight into the subsurface to reveal a complex 3D structure, and the numerous boreholes needed to investigate the area would be too expensive and time consuming, the application of a geophysical method such as ground penetrating radar (GPR) is needed. To test the method for determining near surface features and detecting low-angle inclined thrusts, a low frequency GPR system with 50 MHz rough terrain antenna was used to record 13 GPR profiles along all three floors of the Črnotiče quarry, where the spatial position of the Socerb thrust fault that separates limestones above and flysch layers below is relatively well documented. The profiles were positioned across selected existing boreholes. The GPR results were correlated with borehole data as well as geological mapping results. The GPR provided not only precise information on the geometry of the Socerb thrust fault, but was also very useful for establishing the position of some known as well as several potential cavities, both air- and sediment-filled. In areas further from the thrust-fault zone, where the limestone is less tectonically damaged, it was also possible to determine apparent dip angles of the strata, which after reconstruction matched the true dips gathered from geological mapping.

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[wg4-GGG-j2] S. Santos-Assunçao, V. Perez-Gracia, V. Salinas, O. Caselles, R. Gonzalez-Drigo, L. G. Pujades, N. Lantada, "GPR Backscattering Intensity Analysis Applied to Detect Paleochannels and Infilled Streams for Seismic Nanozonation in Urban Environments," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS), vol. 9(1), pp. 167-177, January 2016; doi: 10.1109/JSTARS.2015.2466235 (Spain; GPR 2014 Special Issue)

Abstract: Seismic microzonation of urban areas is used to be determined from few soils' response measurements in each area. In consequence, results can be considered correct only in the case of possible depth-dependent soils, being the existence of lateral soil changes the cause of imprecision. Ground-penetrating radar (GPR) could be a useful tool to determine, previously to the pas- sive seismic measurements, the location of geological structures. Moreover, depending on the ground materials, the GPR energy is randomly backscattered. Consequently, the background noise in the radar scans increases. Therefore, the analysis of the amplitude of the noise could be a useful method to determine changes on the ground characteristics. The analysis of the background GPR amplitude noise is tested in two radar lines, crossing the city of Barcelona. The results show significant differences in the back- ground noise amplitude in the A-scans that could be used to define zones in the city depending on the noise level. These changes on the amplitude are associated with the backscattered energy as a conse- quence of soil characteristics.

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Hence, the analysis of the variation in the background noise amplitude allows defining the possible location of subterranean streams, paleochannels, and other struc- tures crossing the plain of the city. Radar results are also compared to ambient vibration measurements, using the spectral horizontal- to-vertical (H/V) quotient, and to historical and contemporary information. The application of the methodology underscores the ability of the evaluation of the backscattering associated with the background noise in the scans in the detection of sharp geological changes in sedimentary deposits.

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[wg4-GGG-j3] A. Gosar, T. Čeru, "Search for an artificially buried karst cave entrance using ground penetrating radar: a successful case of locating the S-19 Cave in the Mt. Kanin massif (NW Slovenia)," International Journal of Speleology, vol. 45(2), pp. 135-147, May 2016; doi: 10.5038/1827-806X.45.2.1979 (Slovenia; OPEN ACCESS)

Abstract: The S-19 Cave was with its explored depth of 177 m one of the most important caves of the Mt. Kanin massif, but after its discovery in 1974, a huge snow avalanche protection dyke was constructed across the cave entrance. To excavate the buried cave, the accurate location of the cave had to be determined first. Since the entrance coordinates were incorrect and no markers were available, application of geophysical techniques was necessary to do this. A Ground Penetrating Radar (GPR) with special 50 MHz rough terrain antennas was selected as the single suitable geophysical method for the given conditions where thick debris overlay a rugged limestone surface. Nevertheless, it was not possible to directly detect the relatively narrow cave entrance itself due to data resolution limits. However, a historical photo of the area showed that the cave entrance was located in a local depression, which therefore represented the main target of the GPR survey. Seven GPR profiles were measured across the rough and steep surface causing difficulties in traversing the area with sensitive research equipment. In all recorded radargrams a small depression was clearly imaged under debris, and recognized as a topographic feature with the cave entrance. Based on the GPR data interpretation, the exact location for digging was determined and the thickness of debris assessed at 6.5–7 m. A massive excavation by a dredger resulted in a successful opening of the cave entrance, confirming both its geophysically determined location and its estimated depth. The application of an advanced geophysical method was therefore proven successful in providing a solution to this specific case in karst exploration and an important cave was saved.

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Humanitarian applications of GPR: Vital signs of buried and trapped people - UXO

[wg4-H-j1] X. Núñez-Nieto, M. Solla, P. Gómez-Pérez, H. Lorenzo "GPR Signal Characterization for Automated Landmine and UXO Detection Based on Machine Learning Techniques," Remote Sensing, vol. 6(10), pp. 9729-9748, October 2014; doi:10.3390/rs6109729 (Spain; OPEN ACCESS)

Abstract: Landmine clearance is an ongoing problem that currently affects millions of people around the world. This study evaluates the effectiveness of ground penetrating radar (GPR) in demining and unexploded ordnance detection using 2.3-GHz and 1-GHz high-frequency antennas. An automated detection tool based on machine learning techniques is also presented with the aim of automatically detecting underground explosive artifacts. A GPR survey was conducted on a designed scenario that included the most commonly buried items in historic battle fields, such as mines, projectiles and mortar grenades. The buried targets were identified using both frequencies, although the higher vertical resolution provided by the 2.3-GHz antenna allowed for better recognition of the reflection patterns. The targets were also detected automatically using machine learning techniques. Neural networks and logistic regression algorithms were shown to be able to discriminate between potential targets and clutter. The neural network had the most success, with accuracies ranging from 89% to 92% for the 1-GHz and 2.3-GHz antennas, respectively.

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3) Kadioğlu, S., & Kadioğlu, Y. K. (2016). Visualization of buried anti-tank landmines and soil pollution: analyses using ground penetrating radar method with attributes and petrographical methods. Near Surface Geophysics, 14(2), 183-195.
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[wg4-H-j2] V. Ferrara, "Technical Survey About Available Technologies For Detecting Buried People Under Rubble Or Avalanches," WIT Transaction on The Built Environment, vol. 150, pp. 91-101, May 2015; doi: 10.2495/DMAN150091 (Italy; OPEN ACCESS)

Abstract: Among all activities carried out in disaster scenarios, such as collapsed buildings, earthquakes, and avalanches, the detection and rescue of buried or trapped people have the priority. The paper aims at presenting the progress in the technological development of electronic devices and systems used to detect people buried under rubbles or avalanches. Many technologies realize detection, but only electromagnetic ones assure best results in terms of speed and accuracy of a relief, working also in a noisy environment. We can divide the methodologies using electromagnetic propagation in the three main. One is based on detection of active or passive electronic devices carried by the victim; the second one detects the body of a person as perturbation of the backscattered electromagnetic wave, due to dielectric discontinuity in the medium; the third case is based on the detection of vital signs. Both last two methodologies can be suitable for detecting people trapped under rubbles that can be free to move, also partially. More frequently, a buried person is motionless, because he is unconscious or the ruins block him. Consequently, the detection of vital signs, such as heartbeat or breathing, is the unique possible only. Performances and limits of each method is presented in the article, together with possible innovations.

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[wg4-H-j3] S. Kadioğlu, Y.K. Kadioğlu, "Visualization of buried anti-tank landmines and soil pollution: analyses using ground penetrating radar method with attributes and petrographical methods," EAGE Near Surface Geophysics (NSG), vol. 14(2), pp. 183-195, April 2016; doi: 10.3997/1873-0604.2016010 (Turkey; TU1208 NSG Special Issue)

Abstract: This paper presents an approximation to display buried anti-tank landmines with ground-penetrating radar method, including physical data attributes by measuring data in a special military field and determination of soil pollution using mineralogical and chemical features of the soil obtained by confocal Raman spectrometry and polarized energy dispersive X-ray fluorescence, which are petrographical methods, before and after bursting the mine. Two-dimensional ground penetrating radar data were acquired on parallel profiles using 800-MHz shielded antenna on unexploded anti-tank landmines buried approximately 10 cm–15 cm in depth. After general processing in the time domain, we employed migration, a frequency–wavenumber (F–K) filter, and ground-penetrating radar data attributes with an amplitude envelope, spectral whitening, and first-time derivative to activate anti-tank landmine visualization. Finally, we obtained three-dimensional half bird's eye view of the processed volume with each separate attribute. We also derived the transparent threedimensional volumes by assigning opacity to the amplitude–colour range. The results showed that the depth slices including attributes and the transparent three-dimensional depth–volumes could clearly image the anti-tank landmine. In addition, migration and F–K filter during special processing were very important in removing data noise. Ground-penetrating radar data attributes—particularly amplitude enveloping— could suppress small phase shifts in the neighbouring traces of the landmine amplitude anomalies and helped to obtain more complete results showing location and depth in the three-dimensional volume. The results of the analyses of the major oxide elements and heavy metal elements, such as Fe2O3, Pb, Zn, As, Mn, Mo, Co, Ni, Sb, and Sn, in the test area revealed that there were almost no major differences before and after blasting the anti-tank landmines. This indicates that one-time bursting of the anti-tank landmines in the field has not polluted the soil in this area.

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[wg4-E-j1] J. Jezova, L. Mertens, S. Lambot, "Ground-penetrating radar for observing tree trunks and other cylindrical objects," Construction and Building Materials, vol. 123, pp. 214-225, October 2016, doi: doi:10.1016/j.conbuildmat.2016.07.005 (Belgium)

Abstract: To improve forest management and to prevent collapses of trees, it is necessary to investigate the internal part of tree trunks. In order to do it non-invasively, ground-penetrating radar (GPR) appears as a promising inspection device. The objective of this paper is to investigate particularities of tree trunks radar images, considering the circumferential data acquisition geometry, as a function of the radar configuration and trunk section structures. In order to better understand this kind of data, a target reflection curve was analytically described, then, the total internal reflection (TIR) phenomenon was explained and illustrated. Subsequently, classical radar measurements were compared with an application of differently shaped (planar and circular) metal shields acting as perfect electrical conductors (PEC). For comparing the methods, three experiments were performed: (1) numerical simulations using the software gprMax2D, based on Finite-Difference Time-Domain method, (2) GPR investigation of a laboratory model of a tree trunk, (3) real tree trunk measurements. The use of a planar or circular PEC increased the visibility of the medium edges, so, these GPR images were considered of a better quality. Internal object reflection curve and TIR detection were essential for general description of a GPR image. All experiments showed satisfactorily the internal inhomogeneity and the information will be useful for future tomographic reconstruction.

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1) Nakata, R., Clemens, S., Martin, D., Jaquiro, C., & Lubecke, V. (2016, March). Unmanned aerial vehicle platform stabilization for remote radar life sensing. In Wireless Information Technology and Systems (ICWITS) and Applied Computational Electromagnetics (ACES), 2016 IEEE/ACES International Conference on (pp. 1-2). IEEE.

Combined use of GPR & other NDT techniques in civil engineering

[wg4-NDT-j1] J. Domitrović, T. Rukavina, "Application of GPR and FWD in assessing pavement bearing capacity," Romanian Journal of Transport Infrastructure, vol. 2(2), pp. 11-21, December 2013; ISSN 2286-2218 ISSN-L 2286-2218 (Croatia; OPEN ACCESS)

Abstract: The process of pavement maintenance and rehabilitation starts by collecting the data which will form the base for evaluation of pavement functional and structural condition. Collection of data can be performed by destructive and non-destructive testing. Usually preferred are the non-destructive methods, that do not damage the pavement, and the process of pavement evaluation is objective and repeatable. Non-destructive testing methods are becoming more and more popular, especially for assessing the structural condition of the pavement. Non-destructive testing by a Falling Weight Deflectometer (FWD) and the analysis of so collected data by the process of backcalculations is today the usual tool for assessing pavement bearing capacity. One of the basic input parameters for analysis of the data collected by FWD is pavement layers thickness. The practice in Croatia is to determine pavement layers thickness by coring. This destructive method affects pavement integrity, so the number of such tests should be kept to the minimum. By coring the accurate thickness of all pavement layers is obtained on specific point locations. Thus, numerous deviations in layer thickness remain unnoticed, and in the end, use of such data for the process of backcalculations does not provide ac urate values of layer moduli. Coring can be replaced with non-destructive method of testing by Ground Penetrating Radar (GPR), which provides continuous information on thickness of all pavement layers. The paper shows the method for assessing the bearing capacity of the pavement based on the data collected by FWD, GPR and coring. The calculation for layer moduli was performed by the ELMOD software, separately for the layers thickness data obtained by coring, and separately for the thickness obtained by GPR tests. Analysis and comparison of the results of calculated elasticity moduli obtained by using various methods for collecting layer thickness data were performed in the paper.

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2) Marecos, V., Solla, M., Fontul, S., & Antunes, V. (2017). Assessing the pavement subgrade by combining different non-destructive methods. Construction and Building Materials, 135, 76-85.

[wg4-NDT-j2] M. Solla, S. Lagüela, H. González-Jorge, P. Arias, "Approach to identify cracking in asphalt pavement using GPR and infrared thermographic methods: Preliminary findings," Elsevier

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Non Destructive Testing and Evaluation (NDT&E) International, vol. 62, pp. 55-65, March 2014; doi: 10.1016/ j.ndteint.2013.11.006 (Spain)

Abstract: Pavement condition is a factor of major interest due to its direct contribution to safety and comfort of the users of the road. Consequently, road inspections imply the evaluation of different parameters such as roughness of the pavement, skid resistance, and presence and condition of cracks. Although the first two parameters can be quantitatively evaluated with different sensors, the latter is usually only qualitatively assessed by visual inspection. This paper deals with this drawback through the combined application of Ground Penetrating Radar and Infrared Thermography to the detection and characterization of cracks in pavement and their origins.

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18) Baghdasaryan, H., Marciniak, M., & Pajewski, L. Civil engineering applications of Ground Penetrating Radar: research activities in COST Action TU1208. irPHE 2014 Conference.

[wg4-NDT-j3] S. Santos-Assunçao, V. Perez-Gracia, O. Caselles, J. Clapes, and V. Salinas, "Assessment of Complex Masonry Structures with GPR Compared to Other Non-Destructive Testing Studies," Remote Sensing, vol. 6(10), pp. 8220-8237, August 2014; doi: 10.3390/rs6098220 (Spain; OPEN ACCESS)

Abstract: Columns are one of the most usual supporting structures in a large number of cultural heritage buildings. However, it is difficult to obtain accurate information about their inner structure. Non-destructive testing (NDT) methodologies are usually applied, but results depend on the complexity of the column. Non-flat external surfaces and unknown and irregular internal materials complicate the interpretation of data. This work presents the study of one column by using ground-penetrating radar (GPR) combined with seismic tomography, under laboratory conditions, in order to obtain the maximum information about the

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structure. This column belongs to a “Modernista” building from Barcelona (Spain). These columns are built with irregular and fragmented clay bricks and mortar. The internal irregular and complex structure causes complicated 2D images, evidencing the existence of many different targets. However, 3D images provide valuable information about the presence and the state of an internal tube and show, in addition, that the column is made of uneven and broken bricks. GPR images present high correlation with seismic data and endoscopy observation carried out in situ. In conclusion, the final result of the study provides information and 3D images of damaged areas and inner structures. Comparing the different methods to the real structure of the column, the potential and limitations of GPR were evaluated.

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[wg4-NDT-j4] S. Lagüela-López, M. Solla-Carracelas, L. Díaz-Vilariño, Julia Armesto-González, “Inspection of radiant heating floor applying non-destructive testing techniques: GPR AND IRT,” DYNA, vol. 82(190), pp. 221-226, March-April 2015; doi: 10.15446/dyna.v82n190.43913 (Spain; OPEN ACCESS)

Abstract: The inspection of radiant heating floors requires the use of non-destructive techniques, trying to minimize inspection impact, time and cost, and maximize the information acquired so that the best possible diagnosis is given. With this goal, we propose the application of infrared thermography (IRT) and ground penetrating radar (GPR) for the inspection of radiant heating floors with different floor coatings, in order to evaluate the capabilities and information acquirable with each technique. Specifically, two common floor coatings have been inspected: ceramic tiles and parquet flooring. Results show that each technique provides different information: condition of the pipelines (IRT), geometry and configuration (GPR), concluding that the optimal inspection is constituted by the combination of the two techniques.

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[wg4-NDT-j5] V. Marecos, M. Solla, S. Fontul, and V. Antunes, “Assessing the pavement subgrade by combining different non-destructive methods,” Construction and Building Materials, vol. 135, pp. 76-85, March 2017, doi: 10.1016/j.conbuildmat.2017.01.003 (Spain, Portugal; STSM Outcome)

Abstract: The subgrade provides support to the pavement system and assures an effective distribution of traffic loads in depth. Therefore, a failure in the subgrade will have consequences on the entire pavement behaviour. This work presents an integrated approach for the analysis of the road subgrade condition by combining different Non-Destructive Testing (NDT) techniques. Different Ground Penetrating Radar (GPR) systems, both antennas configuration and frequencies, were tested in order to achieve the best methodology for subgrade cracking detection. Additionally, NDT load tests were performed with two deflectometers, Falling Weight Deflectometer (FWD) and Light Weight Deflectometer (LWD), aiming to determine the elastic modulus of the subgrade and consequently detect damaged areas. The tests were conducted at a real scale test section built to simulate pavement foundation layers consisting of clay soil subgrade, frequently used in African countries. The main tests performed are presented and analysed in this paper. Troubleshooting’s are referred mainly related with GPR wave propagation on clayey materials, due to high absorption. Recommendations are made regarding the use of GPR antennas as air-coupled antennas lead to a better identification of pavement layer interfaces while ground-coupled antennas were preferable to detect anomalous areas, namely cracking and debonding. The results showed good agreement between both NDT methods (GPR and load tests) in the identification of the anomalous areas and were validated with some in-situ cores extracted.

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