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Information content in frequency-dependent, multi-offset GPR data for layered media reconstruction using full-wave inversion

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Water lost through leaks can represent high percentages of the total production in water supply systems and constitutes an important issue. Leak detection can be tackled with various techniques such as the ground-penetrating radar (GPR). Based on this technology, various procedures have been elaborated to characterize a leak and its evolution. In this study, we focus on a new full-wave radar modelling approach for near-field conditions, which takes into account the antenna effects as well as the interactions between the antenna(s) and the medium through frequency-dependent global transmission and reflection coefficients. This approach is applied to layered media for which 3-D Green's functions can be calculated. The model allows for a quantitative estimation of the properties of multilayered media by using full-wave inversion.

This method, however, proves to be limited to provide users with an on-demand assessment as it is generally computationally demanding and time consuming, depending on the medium configuration as well as the number of unknown parameters to retrieve. In that respect, we propose two leads in order to enhance the parameter retrieval step. The first one consists in analyzing the impact of the reduction of the number of frequencies on the information content. For both numerical and laboratory experiments, this operation has been achieved by investigating the response surface topography of objective functions arising from the comparison between measured and modelled data. The second one involves the numerical implementation of multistatic antenna configurations with constant and variable offsets in the model. These two kinds of analyses are then combined in numerical experiments to observe the conjugated effect of the number of frequencies and the offset configuration.

To perform the numerical analyses, synthetic Green's functions were simulated for different multilayered medium configurations. The results show that an antenna offset increase leads to an improvement in the response surface topography, which is more or less marked according to the initial information content. It also highlights the theoretical possibility of significantly reducing the number of frequencies without degrading the information content. This last statement is confirmed with the laboratory experiment which incorporates measurements done with a Vivaldi antenna above a medium composed of one or more sand layers characterized by different water contents. As a conclusion, the offset and frequency analyses highlight the great potential of the model for improving the soil parameter retrieval while reducing the computation time for a given antenna(s) – medium configuration.

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Inflence of fouling on the dielectric constant of railway ballast

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In order to evaluate the level of ballast fouling for Portugal aggregates and the influence of antenna frequency on its measurement several laboratory tests were performed on different materials.
Initially the clean granitic ballast was tested in different water content conditions, from dry to soaked in order to see the influence of water on the dielectric characteristics.
The fouling of the ballast was reproduced in laboratory through mixing the ballast with soil, mainly fine particles, in order to simulate the fouling existing in several old lines in Portugal, where the ballast was placed over the soil without any sub ballast layer.
The soil was also tested for different water contents to register the evolution of its dielectric constant.
Five different fouling levels were reproduced and tested in laboratory, with different water contents, four for each contamination level.
Tests were performed with IDS 400 MHz antenna in two different test positions. The water content was evaluated with nuclear gauge, after each GPR test. In situ test pits were then made, in existing railways with ballast in different condition from recently renewed to significantly fouled ballast. The results were used to validate the values of the dielectric constants obtained in laboratory.
The main results obtained are presented in this paper together with troubleshooting associated to measurement on fouling ballast. This abstract is of interest for COST Action TU1208.

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Numerical Modelling of Ground Penetrating Radar Antennas

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Numerical methods are needed in order to solve Maxwell's equations in complicated and realistic problems. Over the years a number of numerical methods have been developed to do so. Amongst them the most popular are the finite element, finite difference implicit techniques, frequency domain solution of Helmontz equation, the method of moments, transmission line matrix method. However, the finite-difference time-domain method (FDTD) is considered to be one of the most attractive choice basically because of its simplicity, speed and accuracy. FDTD first introduced in 1966 by Kane Yee. Since then, FDTD has been established and developed to be a very rigorous and well defined numerical method for solving Maxwell's equations. The order characteristics, accuracy and limitations are rigorously and mathematically defined. This makes FDTD reliable and easy to use.

Numerical modelling of Ground Penetrating Radar (GPR) is a very useful tool which can be used in order to give us insight into the scattering mechanisms and can also be used as an alternative approach to aid data interpretation. Numerical modelling has been used in a wide range of GPR applications including archeology, geophysics, forensic, landmine detection etc. In engineering, some applications of numerical modelling include the estimation of the effectiveness of GPR to detect voids in bridges, to detect metal bars in concrete, to estimate shielding effectiveness etc. The main challenges in numerical modelling of GPR for engineering applications are A) the implementation of the dielectric properties of the media (soils, concrete etc.) in a realistic way, B) the implementation of the geometry of the media (soils inhomogeneities, rough surface, vegetation, concrete features like fractures and rock fragments etc.) and C) the detailed modelling of the antenna units.

The main focus of this work (which is part of the COST Action TU1208) is the accurate and realistic implementation of GPR antenna units into the FDTD model. Accurate models based on general characteristics of the commercial antennas GSSI 1.5 GHz and MALA 1.2 GHz have been already incorporated in GprMax, a free software which solves Maxwell's equation using a second order in space and time FDTD algorithm. This work presents the implementation of horn antennas with different parameters as well as ridged horn antennas into this FDTD model and their effectiveness is tested in realistic modelled situations. Accurate models of soils and concrete are used to test and compare different antenna units. Stochastic methods are used in order to realistically simulate the geometrical characteristics of the medium. Regarding the dielectric properties, Debye approximations are incorporated in order to simulate realistically the dielectric properties of the medium on the frequency range of interest.

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GPR Image and Signal Processing for Pavement and Road Monitoring on Android Smartphones and Tablets

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Ground Penetrating Radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. This non-destructive method uses electromagnetic radiation and detects the reflected signals from subsurface structures. It can detect objects, changes in material, and voids and cracks. GPR has many applications in a number of fields. In the field of civil engineering one of the most advanced technologies used for road pavement monitoring is based on the deployment of advanced GPR systems. One of the most relevant causes of road pavement damage is often referable to water intrusion in structural layers. In this context, GPR has been recently proposed as a method to estimate moisture content in a porous medium without preventive calibration. Hence, the development of methods to obtain an estimate of the moisture content is a crucial research field involving economic, social and strategic aspects in road safety for a great number of public and private Agencies. In particular, a recent new approach was proposed to estimate moisture content in a porous medium basing on the theory of Rayleigh scattering, showing a shift of the frequency peak of the GPR spectrum towards lower frequencies as the moisture content increases in the soil.

Addressing some of these issues, this work proposes a mobile application, for smartphones and tablets, for GPR image and signal processing. Our application has been designed for the Android mobile operating system, since it is open source and android mobile platforms are selling the most smartphones in the world (2013). The GPR map can be displayed in black/white or color and the user can zoom and navigate into the image. The map can be loaded in two different ways: from the local memory of the portable device or from a remote server. This latter possibility can be very useful for real-time and mobile monitoring of road and pavement inspection. In addition, the application allows analyzing the GPR data also in the frequency domain. It is possible to visualize the GPR spectrum, and the application returns the (abscissa of the) frequency peak of the GPR spectrum. It is also possible to visualize more GPR spectra on the same figure, in order to understand if a frequency shift (related to moisture content) has been observed. Finally, the GPR spectra can be exported as a JPEG file. This application has a strategic and innovative potentiality for all the Agencies involved in roads and highway management in order to improve the onsite efficiency and effectiveness of the works.

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Combining ground penetrating radar and electromagnetic induction for industrial site characterization

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Industrial sites pose specific challenges to the conventional way of characterizing soil and groundwater properties through borehole drilling and well monitoring. The subsurface of old industrial sites typically exhibits a large heterogeneity resulting from various anthropogenic interventions, such as the dumping of construction and demolition debris and industrial waste. Also larger buried structures such as foundations, utility infrastructure and underground storage tanks are frequently present. Spills and leaks from industrial activities and leaching of buried waste may have caused additional soil and groundwater contamination. Trying to characterize such a spatially heterogeneous medium with a limited number of localized observations is often problematic. The deployment of mobile proximal soil sensors may be a useful tool to fill up the gaps in between the conventional observations, as these enable measuring soil properties in a non-destructive way. However, because the output of most soil sensors is affected by more than one soil property, the application of only one sensor is generally insufficient to discriminate between all contributing factors. To test a multi-sensor approach, we selected a study area which was part of a former manufactured gas plant site located in one of the seaport areas of Belgium. It has a surface area of 3400 m^2 and was the location of a phosphate production unit that was demolished at the end of the 1980s. Considering the long and complex history of the site we expected to find a typical "industrial" soil. Furthermore, the studied area was located between buildings of the present industry, entailing additional practical challenges such as the presence of active utilities and aboveground obstacles. The area was surveyed using two proximal soil sensors based on two different geophysical methods: ground penetrating radar (GPR), to image contrasts in dielectric permittivity, and electromagnetic induction (EMI), to measure the apparent soil electrical conductivity (ECa) and magnetic susceptibility (MSa). For both methods one of the latest-generation instruments was used. GPR data were collected using a 3d-Radar stepped-frequency system with multi-channel antenna design. For EMI, this was the multi-receiver DUALEM-21S sensor. This sensor contains four different transmitter-receiver coil pair configurations, which allows to record the ECa and MSa for four different soil volumes at the same time, thereby providing information about the vertical variation of these soil properties. Both the EMI and GPR survey were performed in a mobile set-up with real-time georeferencing to obtain a high-resolution coverage of the area. The results of both surveys were validated with conventional site characterization that was conducted for a soil contamination investigation, and ancillary information such as aerial photographs and utility maps. Both methods were compared on their performance in detecting different types of anomalies. We report on the successes and failures with this multi-sensor approach.

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Civil Engineering Applications of Ground Penetrating Radar Recent Advances @ the ELEDIA Research Center

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The application of non-destructive testing and evaluation (NDT/NDE) methodologies in civil engineering has raised a growing interest during the last years because of its potential impact in several different scenarios. As a consequence, Ground Penetrating Radar (GPR) technologies have been widely adopted as an instrument for the inspection of the structural stability of buildings and for the detection of cracks and voids. In this framework, the development and validation of GPR algorithms and methodologies represents one of the most active research areas within the ELEDIA Research Center of the University of Trento. More in detail, great efforts have been devoted towards the development of inversion techniques based on the integration of deterministic and stochastic search algorithms with multi-focusing strategies. These approaches proved to be effective in mitigating the effects of both nonlinearity and ill-posedness of microwave imaging problems, which represent the well-known issues arising in GPR inverse scattering formulations. More in detail, a regularized multi-resolution approach based on the Inexact Newton Method (INM) has been recently applied to subsurface prospecting, showing a remarkable advantage over a single-resolution implementation [1]. Moreover, the use of multi-frequency or frequency-hopping strategies to exploit the information coming from GPR data collected in time domain and transformed into its frequency components has been proposed as well. In this framework, the effectiveness of the multi-resolution multi-frequency techniques has been proven on synthetic data generated with numerical models such as GprMax [2]. The application of inversion algorithms based on Bayesian Compressive Sampling (BCS) [3][4] to GPR is currently under investigation, as well, in order to exploit their capability to provide satisfactory reconstructions in presence of single and multiple sparse scatterers [3][4]. Furthermore, multi-scaling approaches exploiting level-set-based optimization have been developed for the qualitative reconstruction of multiple and disconnected homogeneous scatterers [5]. Finally, the real-time detection and classification of subsurface scatterers has been investigated by means of learning-by-examples (LBE) techniques, such as Support Vector Machines (SVM) [6].

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Investigation of HMA compactability using GPR technique

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In-situ field density is often regarded as one of the most important controls used to ensure that an asphalt pavement being placed is of high quality. The achieved density results from the effectiveness of the applied compaction mode on the Hot Mix Asphalt (HMA) layer. It is worthwhile mentioning that the proper compaction of HMA increases pavement fatigue life, decreases the amount of permanent deformation or rutting, reduces the amount of oxidation or aging, decreases moisture damage or stripping, increases strength and internal stability, and may decrease slightly the amount of low-temperature cracking that may occur in the mix.

Conventionally, the HMA density in the field is assessed by direct destructive methods, including through the cutting of samples or drilling cores. These methods are characterized by a high accuracy, although they are intrusive and time consuming. In addition, they provide local information, i.e. information only for the exact test location. To overcome these limitations, the use of non-intrusive techniques is often recommended. The Ground Penetrating Radar (GPR) technique is an example of a non-intrusive technique that has been increasingly used for pavement investigations over the years. GPR technology is practical and application-oriented with the overall design concept, as well as the hardware, usually dependent on the target type and the material composing the target and its surroundings. As the sophistication of operating practices increases, the technology matures and GPR becomes an intelligent sensor system. The intelligent sensing deals with the expanded range of GPR applications in pavements such as determining layer thickness, detecting subsurface distresses, estimating moisture content, detecting voids and others. In addition, the practice of using GPR to predict in-situ field density of compacted asphalt mixture material is still under development and research; however the related research findings seem to be promising. Actually, the prediction is not regulated by any standards or specifications, although the practice is considered to be workable.

In view of the above, an extensive experiment was carried out in both the laboratory and the field based on a trial asphalt pavement section under construction. In the laboratory, the study focused on the estimation of the density of HMA specimens achieved through three different roller compaction modes (static, vibratory and a combination of both) targeted to simulate field compaction and assess the asphalt mix compactability. In the field, the different compaction modes were successively implemented on three subsections of the trial pavement section. Along each subsection, GPR data was collected in order to determine the new material's dielectric properties and based on that, to predict its density using proper algorithm. Thus, cores were extracted to be used as ground truth data. The comparison of the new asphalt material compactability as obtained from the laboratory specimens, the predictions based on GPR data and the field cores provided useful information that facilitated the selection of the most effective compaction mode yielding the proper compaction degree in the field.

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GPR used in combination with other NDT methods for assessing pavements in PPP projects

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In the recent decades, Public-Private Partnerships (PPP) has been adopted for highway infrastructure procurement in many countries. PPP projects typically take the form of a section of highway and connecting roadways which are to be construction and managed for a given concession period. Over the course of the highway concession period, the private agency takes over the pavement maintenance and rehabilitation duties. On this purpose, it is critical to find the most cost effective way to maintain the infrastructure in compliance with the agreed upon performance measures and a Pavement Management Systems (PMS) is critical to the success of this process.

For the prosperous operation of a PMS it is necessary to have appropriate procedures for pavement monitoring and evaluation, which is important in many areas of pavement engineering. Non Destructive Testing (NDT) has played a major role in pavement condition monitoring, assessments and evaluation accomplishing continuous and quick collection of pavement data. The analysis of this data can lead to indicators related to trigger values (criteria) that define the pavement condition based on which the pavement “health” is perceived helping decide whether there is the need or not to intervene in the pavement. The accomplished perception appoints required management activities for preserving pavements in favor not only of the involved highway/road agencies but also of users’ service.

Amongst NDT methods Ground Penetrating Radar (GPR) seems to be a very powerful toll, as it provides a range of condition and construction pavement information. It can support effectively the implementation of PMS activities in the framework of pavement monitoring and evaluation. Given that, the present work aims to the development and adaptation of a protocol for the use of GPR in combination with other NDT methods, such as Falling Weight Deflectometer (FWD), for assessing pavements in PPP projects. It is based on the experience of Laboratory of Pavement Engineering of National Technical University of Athens (NTUA) gained through its research activities in various Greek PPP projects as well its involvement in several related European and International scientific actions. It is suggested that the implementation of such protocol could support the pavement management activities with respect to the needs of a PPP project. This is accomplished through the resulted advantages that include simplicity in application, economic benefits and familiarity that are very important factors towards the optimization of the resources and the utilization of the available information; both of them are required for the orderly operation of a PPP project.

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GPR and ultrasonic measurements for the seismic vulnerability assessment of a XVI century university building in Turin (Italy).

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Seismic Evaluation of Existing Buildings has a fundamental and strategic role in a country with high seismicity, like Italy, in order to determine potential earthquake hazards and to identify whole structures or elements that represent unacceptable risk to human life.
Regarding the New National Technical Codes, Polytechnic of Turin has started guidelines and evaluation analysis of the structural behavior of the Engineering and Architectural Faculty. Specially, in this project we will refer to the “Valentino’s Castle”, holding the Architectural Faculty, which was built in masonry in the second half of the XVI century and achieved its final shape in the XIX century.
All aspects of building performance are investigated, with geometric and material tests, in order to identify typical structural mechanisms which can lead to failure of structural elements reaching partial or total collapse. In the article GPR and ultrasonic (US) measurements carried out on the ground floor, on some columns of the outside porticos and of the “Hall of columns” are described.
The columns of the outside porticos are Dorian columns which support the load of a double staircase at the entrance which lead on to a loggia with direct access to the hall. In the “Hall of columns” there are six columns which support the great hall in the floor above, currently used as a conference room. Due to the large loads they are subjected, these columns play a main role for the static behavior of the structure.
The columns are made of “Macchiavecchia” stone which is a sedimentary rock (limestone breccia) member of the lower Jurassic (Lias). The composition is partially dolomite and the stone has excellent workability and good physical/mechanical performances. However its breccia structure gives an overall lack of mechanical homogeneity. The quarries were active from the fifteenth century to 2009, and are located in Arzo (Canton Ticino, Switzerland). Historically this breccia has been used in northern Italy and South Europe.
On two selected columns we carried out both GPR and US measurements. We used an IDS Aladdin 2 GHz antenna, with TE and TM polarization, sliding it along 8 vertical lines each one about 1.4 m long. We also made, with the same antenna, on each column, 11 horizontal circular profiles 0.15 m apart one above the other. US measurements were made with a PUNDIT instrument, with 100 kHz transducers, measuring the transit times along two orthogonal diameters every 0.15 m in height.
Both GPR, either in vertical or in horizontal sections, and US show a diffuse heterogeneity in the properties of the columns material. Somewhere the anomalies are clearly due to physical property differences derived from restoration works. In many parts clutters prevents from a clear attribution of the reflection to discontinuities or to interfaces between inclusions and cement.
GPR and US results indicates that care must be taken in modeling dynamical behaviour of the columns: heterogeneity (GPR) and anisotropy (US) should be account for a more realistic seismic vulnerability assessment of the building.

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Permittivity Investigations of the Road Construction Raw Materials for Purposes of GPR Data Interpretations

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Permittivity is the major material property governing the formation of GPR response signal in diagnostic measurements. Every quantitative interpretation refers explicitly or implicitly to discussion of permittivity values. Thus, the recognition of permittivity for materials typical of the given technological area is necessary to make use of diagnostic measurements.
Collection of several tens of stone cores representing different outcrops was investigated in order to obtain cross-sectional view of permittivity for stone materials being in use in Polish road construction industry as components of stone-asphalt mixtures. The main task was to estimate the typical permittivity values for stone materials treated as representation of several major petrological types. The capacimetry (at 50 MHz) was used as major and very efficient method of permittivity assessment and formation of the samples was subordinated to demands of this method. This method allows for determination of permittivity variability on the lateral surface of the cylindrical sample, giving the insight into the major features of the permittivity spatial distribution characteristic for the given rock. For the most homogeneous samples (in terms of permittivity distribution) the permittivity was measured also on the core top at frequency 2 GHz using impulse GPR reflectometry. No clear proofs for considerable permittivity frequency dependence were found (in the frame of the two methods precision) for these rocks. This conclusion can be related generally to major rock-forming minerals at least in dry igneous rocks.
Only solid rocks obtained from regular massive outcrops were included to this first cross-sectional sampling, while artificial synthetic materials and natural gravels of postglacial origin were omitted since additional problems occur in these cases. This first experience allowed to recognize practical problems related to the sampling procedure. The collected data allow for provisional identification of the major rock component type in stone-asphalt mixture on the base of the pavement reflection amplitude. More precise considerations need use of the assumed recipe of the mixture, because the stone fraction usually consists of several different rock types.
The direction and development of these efforts were inspired by discussions and activities in the frame of the COST Action TU1208 "Civil engineering applications of ground penetrating radar" and research was supported by Road and Bridge Research Institute (PW.S-647).

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Applications of Non-destructive methods (GPR and 3D Laser Scanner) in Historic Masonry Arch Bridge Assessment

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Abstract – There exist approximately 70,000 masonry arch bridge spans (brick and stone) in the UK with tens of thousands more throughout Europe. A significant number of these bridges are still in operation and form part of the road and rail network systems in many countries. A great majority of these bridges are in desperate need of repair and maintenance. Applications of non-destructive testing methods such as ground penetrating radar (GPR), 3D laser scanning, accelerometer sensors and vibration detecting sensors amongst many others have been used to assess and monitor such structures in the past few years. This presentation provides results of the applications of a 2GHz GPR antenna system and a 3D laser scanner on a historic masonry arch bridge (the Old Bridge, Aylesford) located in Kent, in the south east of England. The older part of the bridge (the mid-span) is 860 years old. The bridge was the subject of a major alteration in 1811. This presentation forms part of a larger ongoing study which is using the two above mentioned non-destructive methods for long-term monitoring of the bridge. The adopted survey planning strategy and technique, data acquisition and processing as well as challenges encountered during actual survey and fieldworks have been discussed in this presentation. As a result of this study the position of different layers of the deck structure has been established with the identification of the original stone base of the bridge. This information in addition to the location of a number of structural ties (anchors – remedial work carried out previously) in the absence of reliable and accurate design details proved to be extremely useful for the modelling of the bridge using the finite element method. Results of the 3D laser scanning of the bridge have also been presented which have provided invaluable data essential for the accurate modelling of the bridge as well as the long term monitoring of the bridge.

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The Neglected Exactness

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Having a look into geophysical text books, you will find for all the described methods detailed lists of good practice. The variety of annotations specifies how to perform a reliable, trusty and plausible geophysical survey. Much space is used for considerations about all the necessary parameters like target depth, contrast, frequency, sampling, resolution and many other boundary conditions that account for a high quality report. But you will find rather fewer comments on locating and positioning. It seems to be self-evident in times of GNSS (Global Navigation Satellite Systems) and high performance laser total stations that positioning is a solved issue.

This seems to apply for all geophysical methods that operate at walking speed or slower and for typical geoscientific or environmental investigation sites like brownfields, wasteland or archaeological spots, usually of nearly rectangular size. Using of measuring tapes, ropes and ranging poles here is also good practice.

In civil engineering applications we observe lots of rectangular shaped inspection areas too but we as well get many linear structures like elongated bridge decks, dikes, railway tracks, runways and roads. Surveying of an archaeological place of 60 m by 82 m width requires a different positioning technology than surveying 5000 m along a highway although both sites have the same areal extent of around 5000 m^2. If we furthermore take into account that during the last years GPR evolved into one of the fastest investigation methods in geophysics, survey speed becomes an important item. While examining railway tracks or roads today it is common to make use of these high speed capabilities. GPR services are typically performed at speeds of 80 km/h or even with higher velocities.

Standard positioning methods do not longer apply to this problem. With speeds of more than 22 m/sec the internal latency of surveying systems gets quite relevant and even the effect of rounding within survey wheel systems is not negligible any more. Locating for example the exact position of joints, rebars on site, getting correct calibration information or overlaying measurements of independent methods requires high accuracy positioning for all data.

Different technologies of synchronizing and stabilizing are discussed in this presentation. Furthermore a scale problem for interdisciplinary work between the geotechnical engineer, the civil engineer, the surveyor and the geophysicist is presented. Manufacturers as well as users are addressed to work on a unified methodology that could be implemented in future.

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On the Analysis Methods for the Time Domain and Frequency Domain Response of a Buried Objects*

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There has been a continuous interest in the analysis of ground-penetrating radar systems and related applications in civil engineering [1]. Consequently, a deeper insight of scattering phenomena occurring in a lossy half-space, as well as the development of sophisticated numerical methods based on Finite Difference Time Domain (FDTD) method, Finite Element Method (FEM), Boundary Element Method (BEM), Method of Moments (MoM) and various hybrid methods, is required, e.g. [2], [3]. The present paper deals with certain techniques for time and frequency domain analysis, respectively, of buried conducting and dielectric objects.

Time domain analysis is related to the assessment of a transient response of a horizontal straight thin wire buried in a lossy half-space using a rigorous antenna theory (AT) approach. The AT approach is based on the space-time integral equation of the Pocklington type (time domain electric field integral equation for thin wires). The influence of the earth-air interface is taken into account via the simplified reflection coefficient arising from the Modified Image Theory (MIT). The obtained results for the transient current induced along the electrode due to the transmitted plane wave excitation are compared to the numerical results calculated via an approximate transmission line (TL) approach and the AT approach based on the space-frequency variant of the Pocklington integro-differential approach, respectively. It is worth noting that the space-frequency Pocklington equation is numerically solved via the Galerkin-Bubnov variant of the Indirect Boundary Element Method (GB-IBEM) and the corresponding transient response is obtained by the aid of inverse fast Fourier transform (IFFT). The results calculated by means of different approaches agree satisfactorily.

Frequency domain analysis is related to the assessment of frequency domain response of dielectric sphere using the full wave model based on the set of coupled electric field integral equations for surfaces. The numerical solution is carried out by means of the improved variant of the Method of Moments (MoM) providing numerically stable and an efficient procedure for the extraction of singularities arising in integral expressions. The proposed analysis method is compared to the results obtained by using some commercial software packages. A satisfactory agreement has been achieved.

Both approaches discussed throughout this work and demonstrated on canonical geometries could be also useful for benchmark purpose.

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Analyses and Measures of GPR Signal with Superimposed Noise

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The influence of EM noises and environmental hard conditions on the GPR surveys has been examined analytically [1]. In the case of pulse radar GPR, many unwanted signals as stationary clutter, non-stationary clutter, random noise, and time jitter, influence the measurement signal. When GPR is motionless, stationary clutter is the most dominant signal component due to the reflections of static objects different from the investigated target, and to the direct antenna coupling. Moving objects like e.g. persons and vehicles, and the swaying of tree crown, produce non-stationary clutter. Device internal noise and narrowband jamming are e.g. two potential sources of random noises. Finally, trigger instabilities generate random jitter. In order to estimate the effective influence of these noise signal components, we organized some experimental setup of measurement. At first, we evaluated for the case of a GPR basic detection, simpler image processing of radargram. In the future, we foresee experimental measurements for detection of the Doppler frequency changes induced by movements of targets (like physiological movements of survivors under debris). We obtain image processing of radargram by using of GSSI SIR® 2000 GPR system together with the UWB UHF GPR-antenna (SUB-ECHO HBD 300, a model manufactured by Radarteam company). Our work includes both characterization of GPR signal without (or almost without) a superimposed noise, and the effect of jamming originated from the coexistence of a different radio signal. For characterizing GPR signal, we organized a measurement setup that includes the following instruments: mod. FSP 30 spectrum analyser by Rohde & Schwarz which operates in the frequency range 9 KHz – 30 GHz, mod. Sucoflex 104 cable by Huber Suhner (10 MHz – 18 GHz), and HL050 antenna by Rohde & Schwarz (bandwidth: from 850 MHz to 26.5 GHz). The next analysis of superimposed jamming will examine two different signal sources: by a cellular phone and by a transmitter operating in the Instrumental Scientific Medical (ISM) band (around 2.4 GHz). In the first case, signal of cellular phone is considered as an actual noise, and the measure should provide guidance on its electromagnetic compatibility, in the sense of operating limits of the GPR conditioning from the presence of signal transmitted by a cellular phone. Whereas, the analysis of superimposed signals in the ISM band is oriented to the implementation of a mobile GPR system that includes a transceiver, such as XBee, for transmitting results of localization (e.g. of buried people) to a remote station.

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Civil Engineering Applications of Ground Penetrating Radar in Finland

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Ground penetrating radar (GPR) has been used in Finland since 1980's for civil engineering applications. First applications in this field were road surveys and dam inspections. Common GPR applications in road surveys include the thickness evaluation of the pavement, subgrade soil evaluation and evaluation of the soil moisture and frost susceptibility. Since the 1990's, GPR has been used in combination with other non-destructive testing (NDT) methods in road surveys. Recently, more GPR applications have been adopted, such as evaluating bridges, tunnels, railways and concrete elements. Nowadays, compared with other countries GPR is relatively widely used in Finland for road surveys. Quite many companies, universities and research centers in Finland have their own GPR equipment and are involved in the teaching and research of the GPR method. However, further research and promotion of the GPR techniques are still needed since GPR could be used more routinely.

GPR has been used to evaluate the air void content of asphalt pavements for years. Air void content is an important quality measure of pavement condition for both the new and old asphalt pavements. The first Finnish guideline was released in 1999 for the method. Air void content is obtained from the GPR data by measuring the dielectric value as continuous record. To obtain air void content data, few pavement cores must be taken for calibration. Accuracy of the method is however questioned because there are other factors that affect the dielectric value of the asphalt layer, in addition to the air void content. Therefore, a research project is currently carried out at Aalto University in Finland. The overall objective is to investigate if the existing GPR technique used in Finland is accurate enough to be used as QC/QA tool in assessing the compaction of asphalt pavements. The project is funded by the Finnish Transport Agency. Further research interests at Aalto University include developing new microwave asphalt radar for the thickness evaluation of thin asphalt layers.

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GPR applications in Civil Engineering in Spain - state-of-the-art

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GPR was introduced in Spain in 1990, and the first significant work was the PhD thesis of H. Lorenzo in 1994. Due to its versatile applicability, the employ has been increased and actually, GPR is extensively used in detection of pipes, wiring and urban services mainly. During the last years, this method was also widely utilized in the detection of graves from the civil war and in forensic studies, with irregular results. It was also commonly applied in archaeology.
Actually exists more than 20 private companies offering geotechnical services by means of GPR. Also, several public institutions as Universities and Research Institutes base part of their research in GPR or in GPR applications. Notwithstanding, no training courses of specific formation on GPR is offered, but in several doctorate programs it is possible to work with GPR. Also, in many schools, GPR is part of the geophysical formation of graduate students.
However, no national guidelines and rules exist, and each company defines the investigation protocols. Nevertheless, one of the aims of the Comisión Española de Geodesia y Geofísica (Spanish Committee for Geodesy and Geophysics) is to define guidelines for the GPR studies. Probably, the existence of national guidelines or perhaps European guidelines could be the most effective way to promote the responsible use of GPR in different domains. On the other hand, perhaps recommendations on the use of combined methodologies could be a practical way to persuade in the application of geophysical non-destructive technologies.
The CEDEX, Centro de Estudios y Experimentación de Obras Públicas (Center for Studies and Experimentation in Civil Engineering), which is a civil engineering research agency in Spain, offers different test sites to calibrate and evaluate the method. It is an autonomous organization, organically ascribed at present to the Ministry of Fomento, and functionally ascribed to the Ministries of Fomento and Medioambiente of Spain, giving assistance to various administrations, public institutions and private companies. What is more, some of the existing private companies have also minor test sites to analyze the behavior of the signal and its propagation depending on the type of asphalt concrete.
GPR is used mainly in detection of pipes and urban services and various private companies are specialized in these tasks. Another widespread application is archaeological survey; one private company is also specialized in archaeology evaluations, using GPR combined with magnetometer. Forensic examinations are also common applications in Spain. Other less common applications are: regular inspection of roads, bridges and tunnels, cultural heritage buildings assessment, shallow geology studies and quality control in civil engineering.

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GPR Technologies and Methodologies in Italy: A Review

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GPR techniques and technologies have been subject of intense research activities at the Italian level in the last 15 years because of their potential applications specifically to civil engineering. More in detail, several innovative approaches and models have been developed to inspect road pavements to measure the thickness of their layers as well as to diagnose or prevent damage. Moreover, new frontiers in bridge inspection as well as in geotechnical applications such as slides and flows have been investigated using GPR. From the methodological viewpoint, innovative techniques have been developed to solve GPR forward-scattering problems, as well to locate and classify subsurface targets in real-time and to retrieve their properties through multi-resolution strategies, and linear and non-linear methodologies. Furthermore, the application of GPR and other non-destructive testing methods in archaeological prospecting, cultural heritage diagnostics, and in the localization and detection of vital signs of trapped people has been widely investigated. More recently, new theoretical and empirical paradigms regarding water moisture evaluation in various porous media and soil characterization have been published as the results of long terms research activities. Pioneer studies are also currently under development with the scope to correlate GPR measurement with mechanical characteristics of bound and unbound construction materials. In such a framework, this abstract will be aimed at reviewing some of the most recent advances of GPR techniques and technologies within the Italian industrial and academic communities [also including their application within international projects such as FP7 ISTIMES (http://www.istimes.eu)], and at envisaging some of the most promising research trends currently under development.

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Research perspectives in the field of ground penetrating radars in Armenia

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Armenia is a country located in a very complicated region from geophysical point of view. It is situated on a cross of several tectonic plates and a lot of dormant volcanoes. The main danger is earthquakes and the last big disaster was in 1988 in the northwest part of contemporary Armenia. As a consequence, the main direction of geophysical research is directed towards monitoring and data analysis of seismic activity. National Academy of Sciences of Armenia is conducting these activities in the Institute of Geological Sciences and in the Institute of Geophysics and Engineering Seismology.

Research in the field of ground penetrating radars is considered in Armenia as an advanced and perspective complement to the already exploiting research tools. The previous achievements of Armenia in the fields of radiophysics, antenna measurements, laser physics and existing relevant research would permit to initiate new promising area of research in the direction of theory and experiments of ground penetrating radars.

One of the key problems in the operation of ground penetrating radars is correct analysis of peculiarities of electromagnetic wave interaction with different layers of the earth. For this, the well-known methods of electromagnetic boundary problem solutions are applied. In addition to the existing methods our research group of Fiber Optics Communication Laboratory at the State Engineering University of Armenia declares its interest in exploring the possibilities of new non-traditional method of boundary problems solution for electromagnetic wave interaction with the ground. This new method for solving boundary problems of electrodynamics is called the method of single expression (MSE) [1-3]. The distinctive feature of this method is denial from the presentation of wave equation's solution in the form of counter-propagating waves, i.e. denial from the superposition principal application. This permits to solve linear and nonlinear (field intensity-dependent) problems with the same exactness, without any approximations. It is favourable also since in solution of boundary problems in the MSE there is no necessity in applying absorbing boundary conditions at the model edges by terminating the computational domain. In the MSE the computational process starts from the rear side of any multilayer structure that ensures the uniqueness of problem solution without application of any artificial absorbing boundary conditions.

Previous success of the MSE application in optical domain gives us confidence in successful extension of this method's use for solution of different problems related to electromagnetic wave interaction with the layers of the earth and buried objects in the ground.

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A Test Study to Display Buried Anti-Tank Landmines with GPR and Research Soil Characteristics with CRS

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An anti-tank mine (AT mine) is a type of land mine designed to damage or destroy vehicles including tanks and armored fighting vehicles. Anti-tank mines typically have a much larger explosive charge, and a fuze designed only to be triggered by vehicles or, in some cases, tampering with the mine. There are a lot of AT mine types. In our test study, MK4 and MK5 AT mine types has been used. The Mk 5 was a cylindrical metal cased U.K. anti-tank blast mine that entered service in 1943, during the Second World War. General Specifications of them are 203 mm diameter, 127 mm height, 4.4-5.7 kg weight, 2.05-3.75 kg of TNT explosive content and 350 lbs operating pressure respectively.
The aims of the test study were to image anti-tank landmine with GPR method and to analyse the soil characteristics before the mines made explode and after made be exploded and determine changing of the soil characteristics. We realized data measurement on the real 6 unexploded anti-tank landmine buried approximately 15 cm in depth. The mines spaced 3 m were buried in two lines. Space between lines was 1.5 m. We gathered data on the profiles, approximately 7 m, with a Ramac CUII system and 800 MHz shielded antenna. We collected soil samples on the mines, near and around the mines, on the area in village. We collected soil samples before exploding and after exploding mines. We imaged anti-tank landmines on the depth slices of the GPR data and in their interactive transparent 3D subsets successfully. We used polarized microscope and confocal Raman spectroscopy (CRS) to identify soil characteristic before and after exploitation. The results presented that GPR method and its 3D imaging were successful to determine AT mines, and there was no important changing on mineralogical and petrographical characterization of the soil before and after exploding processing.
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The use of Ground Penetrating Radar in coastal research, archeaological investigations, lake studies, peat layer measurments and applied research in Estonia

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Ground Penetrating Radar (GPR) is mainly used for scientific research in coastal geology in the Institute of Ecology at Tallinn University. We currently use SIR-3000 radar with 100, 270 , 300 and 500 MHz antennae. Our main targets have been detecting the thickness of soil and sand layers and finding out the layers in coastal sediments which reflect extreme storm events. Our GPR studies in various settings have suggested that the internal structures of the ridge-dune complexes are dominated by numerous layers dipping in various directions. Such information helps us to reconstruct and understand prevailing processes during their formation (e.g. seaward dipping lamination in coastal ridge-dune complexes indicating cross-shore and wave-induced transport of the sediments). Currently, we are trying to elaborate methodology for distinguishing the differences between aeolian and wave transported sediments by using GPR. However, paludified landscapes (often covered by water), very rough surface (numerous bushes and soft surface), moderate micro topography has slowed this process significantly. Moreover, we have been able to use GPR during the winter period (applied on ice or snow) and compare the quality of our results with the measurements taken during the summer period. We have found that smooth surface (in winter) helps detecting very strong signal differences (border between different sediment types – sand, peat, silt, etc.) but reduces the quality of the signal to the level where the detection of sedimentation patterns within one material (e.g. tilted layers in sand) is difficult.

We have carried out several other science-related studies using GPR. These studies include determining the thickness of peat layer in bogs (to calculate the volume of accumulated peat or to find most suitable locations for coring), measuring the thickness of mud and gyttja layer in lakes (to find most suitable locations for coring, reconstructing initial water level of the lake or calculating the volume of stored carbon in the lake).

Additionally, we have done several archaeology-related research including the search of buried city walls and caves (Tallinn old town), buried Viking ship (Saaremaa Island) and several other archaeological objects. We have also done some applied studies including the search of underground power cables, heating pipes, melioration systems, ammunition warehouses (from World War II) and buried ammunition from the military training fields.

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Inverse scattering and GPR data processing: an Introduction

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Inverse scattering and GPR data processing: an Introduction

Raffaele Persico

This abstract is meant to propose a brief overview of the book “Introduction to Ground Penetrating Radar: Inverse scattering and data processing”, edited by Wiley Press (ISBN 9781118305003). The reason why I propose this contribution is the fact that, in spite of the large relevant literature, to the best of my knowledge it is not very common to find a text entirely devoted to the physical-mathematical aspects (a part of them, of course) of GPR data processing. Also due to this, probably a sort of gap between the GPR practice and the underlying theory has been created, and indeed we can meet practitioners convinced that the quality of the achieved results is indefinitely improvable by making narrower the spatial step of the data, or that it is desirable to have extremely directive antennas because this would improve the resolution. In order to provide a work hopefully able to address these and other aspects and hopefully able to give a contribution to the correction of these imprecise beliefs, a dealing from the beginning has been proposed, i.e. a sequential, relatively plane, and as much as possible self consistent, dealing starting from the Maxwell’s equations and reaching the most commonly exploited migration formulas and linear inversion algorithms, both within a 2D and a 3D framework. This follows the didactic aim to provide to the reader an insight about what can be reasonably achieved and what should be reasonably done in the field and during the processing phase in order to achieve satisfying results. In particular, the reader will be hopefully made aware not only of the mathematical passages, but also of the involved approximations, the needed assumptions and the physical limits of the final algorithms. The results have been also back-upped with numerical exercises and with some experimental tests, all of which conceived on purpose for this text, and some questions with the relative answers have been inserted at the end of many chapters. On the other hand, it seemed also well advised to stress the fact that, within a GPR prospecting, the main involved parameters (especially the propagation velocity of the electromagnetic waves in the soil) and the same useful datum, i.e. “the scattered field”, in most cases have to be worked out from the same GPR data. In particular, usually we don’t have the possibility to measure apart the “incident field” and then retrieve the scattered field by means of an immediate subtraction operation. Indeed, these aspects are an intrinsic part of the GPR data processing, and should not left out from a text on this topic. In the end, GPR data processing has its own specificities within the larger framework of the inverse scattering problems, and the book has tried to put into evidence this fact too.
Finally, even if this text is not focused on electronics, it was important to account for the fact that there are two categories of GPR systems, namely those working in time domain and those working in frequency domain. This implies some consequences in terms of the parametric choices in order to gather and process correctly the data, which has been devoted some attention too.
The main aim of the book is to resume and gather together things mostly already known, but usually spread within different texts and contexts, often dealt with different approaches and expressed, let say, with different languages. The book is mainly thought of for Ph.D. students, students of master courses and university students at their last year in geophysics end engineering, but it is accessible to any GPR user with some minimal basis (i.e. at university level) on electromagnetism.
Some small research work has been performed too, as e.g. with regard to the calculation in closed form of the Hermitian images for stepped frequency systems, or with respect to the introduction of the effective maximum view angle, or in order to propose a new plane demonstration of the ill-posedness of the problem.
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Detecting a subsurface cylinder by a Time Reversal MUSIC like method

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In this contribution the problem of imaging a buried homogeneous circular cylinder is dealt with for a two-dimensional scalar geometry. Though the addressed geometry is extremely simple as compared to real world scenarios, it can be considered of interest for a classical GPR civil engineering applicative context: that is the subsurface prospecting of urban area in order to detect and locate buried utilities.

A large body of methods for subsurface imaging have been presented in literature [1], ranging from migration algorithms to non-linear inverse scattering approaches. More recently, also spectral estimation methods, which benefit from sub-array data arrangement, have been proposed and compared in [2].Here a Time Reversal MUSIC (TRM) like method is employed.

TRM has been initially conceived to detect point-like scatterers and then generalized to the case of extended scatterers [3]. In the latter case, no a priori information about the scatterers is exploited. However, utilities often can be schematized as circular cylinders. Here, we develop a TRM variant which use this information to properly tailor the steering vector while implementing TRM. Accordingly, instead of a spatial map [3], the imaging procedure returns the scatterer's parameters such as its center position, radius and dielectric permittivity.

The study is developed by numerical simulations. First the free-space case is considered in order to more easily introduce the idea and the problem mathematical structure. Then the analysis is extended to the half-space case. In both situations a FDTD forward solver is used to generate the synthetic data. As usual in TRM, a multi-view/multi-static single-frequency configuration is considered and emphasis is put on the role played by the number of available sensors.

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Multi-Focusing Procedure based on the Inexact-Newton Method for Electromagnetic Subsurface Prospecting

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Ground penetrating radars (GPRs) are key instruments for subsurface monitoring and imaging. They can be used in different applicative fields, e.g., for the assessment of the structural stability of concrete structures and for the detection of targets buried inside inaccessible materials. In this framework, imaging systems based on the solution of the underlying inverse electromagnetic scattering problem have been acquiring an ever growing interest in the scientific community. In fact, they are able – at least in principle – to provide a quantitative reconstruction of the distributions of the dielectric properties (e.g., the dielectric permittivity and the electric conductivity) of the investigated scenario. Although good results have been obtained in recent years, there is still the need of further research, especially concerning the development of inversion procedure able to deal with the limitations arising from the non-linearity and ill-posedness of the underlying electromagnetic imaging formulation.

In this work, a novel electromagnetic inverse scattering method is proposed for the reconstruction of shallow buried objects. The inversion procedure is based on the combination of different imaging modalities. In particular, an iterative multi-scaling approach [1] is adopted for focusing the reconstruction only on limited subdomains of the original investigation region. The data inversion is performed by applying an inexact-Newton method (which exhibits very good regularization properties) within the second-order Born approximation [2]. The use of this approximation allows a reduction of the problem unknowns and a mitigation of the nonlinear effects. The proposed approach has been validated by means of several numerical simulations. In particular, the reconstruction performances have been evaluated in terms of accuracy, robustness, noise levels, and computational efficiency, with particular emphasis on the comparisons with the results obtained by using the standard “bare” approach.

This work is a contribution to COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar".

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COST Action TU1206 "SUB-URBAN - A European network to improve understanding and use of the ground beneath our cities"

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Sustainable urbanisation is the focus of SUB-URBAN, a European Cooperation in Science and Technology (COST) Action TU1206 - A European network to improve understanding and use of the ground beneath our cities. This aims to transform relationships between experts who develop urban subsurface geoscience knowledge - principally national Geological Survey Organisations (GSOs), and those who can most benefit from it - urban decision makers, planners, practitioners and the wider research community.

Under COST's Transport and Urban Development Domain, SUB-URBAN has established a network of GSOs and other researchers in over 20 countries, to draw together and evaluate collective urban geoscience research in 3D/4D characterisation, prediction and visualisation. Knowledge exchange between researchers and City-partners within 'SUB-URBAN' is already facilitating new city-scale subsurface projects, and is developing a tool-box of good-practice guidance, decision-support tools, and cost-effective methodologies that are appropriate to local needs and circumstances. These are intended to act as catalysts in the transformation of relationships between geoscientists and urban decision-makers more generally. As a result, the importance of the urban sub-surface in the sustainable development of our cities will be better appreciated, and the conflicting demands currently placed on it will be acknowledged, and resolved appropriately.

Existing city-scale 3D/4D model exemplars are being developed by partners in the UK (Glasgow, London), Germany (Hamburg) and France (Paris). These draw on extensive ground investigation (10s-100s of thousands of boreholes) and other data. Model linkage enables prediction of groundwater, heat, SuDS, and engineering properties. Combined subsurface and above-ground (CityGML, BIMs) models are in preparation. These models will provide valuable tools for more holistic urban planning; identifying subsurface opportunities and saving costs by reducing uncertainty in ground conditions.

A key area of interest, and one of potential collaboration with COST Action TU1208, is in characterising and parameterising the very near urban subsurface, and especially the anthropogenic deposits, to assist decision-making by civil engineers, and others. Anthropogenic deposits may be many metres thick, are typically very heterogeneous, have complex histories of accumulation, and may including important archaeological assets. They display complex stratigraphies which are difficult to resolve using traditional methodologies, even with extensive invasive ground investigation. Ground Penetrating Radar, and other non-destructive methods of ground investigation hold considerable promise in greatly improving the resolution, understanding, and modelling, of these and other near-surface deposits in particular.
This work is a contribution both to COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar" and to COST Action TU1206 "SUB-URBAN - A European network to improve understanding and use of the ground beneath our cities"

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Ground-penetrating radar research in Belgium: from developments to applications

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Ground-penetrating radar research in Belgium spans a series of developments and applications, including mainly ultra wideband radar antenna design and optimization, non-destructive testing for the characterization of the electrical properties of soils and materials, and high-resolution subsurface imaging in agricultural engineering, archeology and transport infrastructures (e.g., road inspection and pipe detection). Security applications have also been the topic of active research for several years (i.e. landmine detection) and developments in forestry have recently been initiated (i.e. for root zone and tree trunk imaging and characterization). In particular, longstanding research has been devoted to the intrinsic modeling of antenna-medium systems for full-wave inversion, thereby providing an effective way for retrieving the electrical properties of soils and materials. Full-wave modeling is a prerequisite for benefiting from the full information contained in the radar data and is necessary to provide robust and accurate estimates of the properties of interest. Nevertheless, this has remained a major challenge in geophysics and electromagnetics for many years, mainly due to the complex interactions between the antennas and the media as well as to the significant computing resources that are usually required. Efforts have also been dedicated to the development of specific inversion strategies to cope with the complexity of the inverse problems usually dealt with as well as ill-posedness issues that arise from a lack of information in the radar data. To circumvent this last limitation, antenna arrays have been developed and modeled in order to provide additional information. Moreover, data fusion ways have been investigated, by mainly combining GPR data with electromagnetic induction complementary information in joint interpretation analyses and inversion procedures. Finally, inversions have been regularized by combining electromagnetics models together with soil hydrodynamic models in mechanistic data assimilation frameworks, assuming process knowledge as information as well.

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GPR Use and Activities in Denmark

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Academic work on GPR in Denmark is performed both by the Technical University of Denmark (DTU) and the University of Copenhagen (KU). The work at DTU includes development of antennas and systems, e.g. an airborne ice-sounder GPR system (POLARIS) that today is in frequent use for monitoring of ice thickness in Greenland. DTU often collaborates with ESA (European Space Agency) regarding electromagnetic development projects. At KU there is an ongoing work with GPR applied to water resources. The main objective is to study flux of water and matter across different hydrological domains. There are several recent publications from KU describing research for data analysis and modelling as well as hydro geophysical applications. Also the Geological Survey of Denmark and Greenland (GEUS) performs frequent geological mapping with GPR.

There have been mainly two actors on the Danish commercial market for several years: FalkGeo and Ramboll. Falkgeo has been active for many years acquiring data for several different applications such as archeology, utilities and roads. Their equipment pool comprises both a multichannel Terravision system form GSSI and a 2D system from Mala Geoscience with a comprehensive range of antennas.

Ramboll has performed GPR surveys for two decades mainly with 2D systems from GSSI. In recent years Ramboll has also obtained a system with RTA antennas from Mala Geoscience and a multichannel system from 3D-Radar. These systems have opened markets both for deeper geological mapping and for shallow mapping. The geological mapping with the Mala system has often been combined with resistivity imaging (CVES) and refraction seismic. The 3D system has been applied in airports and on road for mapping of layer thicknesses, delamination and for control of asphalt works. Other areas comprise bridge deck evaluation and utility mapping. Ramboll also acts as client advisor for BaneDanmark, a state owned company who operates and develops the Danish state railway network. For this Ramboll has written a guideline for application of GPR on BaneDanmark railways.

There are no national guidelines or test sites in Denmark.

The use of GPR on roads is very limited in Denmark compared to our neighboring countries. This is possibly due to conservatism in the industry and due to the fact that Denmark decided not to participate in a collaboration between some of our neighboring countries about preparation of guidelines for application of GPR on roads, the Mara Nord Project. An improvement in accuracy and more automatized routines for mapping of delamination and stripping would also widen the market for application of GPR in airports and on roads. International guidelines for application of GPR in several fields would also help to make authorities recognize it as a valid complement and alternative to other established methods.

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High-resolution monitoring of root water uptake dynamics in laboratory conditions using full-wave inversion of near-field radar

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Root water uptake dynamics at local scale can be studied in laboratory conditions by growing plants in rhizotron containing sand and by imaging the water content evolution of the medium using light transmission. This technique allows to retrieve the water content with high resolution but cannot be applied in opaque media such as leaf-mold or clay, which is a major limitation for more realistic applications.

Recently, ground-penetrating radar (GPR) has proven to be one of the most promising techniques for high-resolution digital soil mapping at the field scale. Particularly, by using full-wave inverse modeling of near-field GPR data with a high frequency antenna, the electrical properties of soil and their correlated water content can be reconstructed with a high spatiotemporal resolution. In this study, we applied the approach by using an ultra-wideband frequency-domain radar with a transmitting and receiving horn antenna operating in the frequency range 3-6 GHz for imaging, in near-field conditions, a rhizotron containing sand subject to different water content conditions. Synthetic radar data were also generated to examine the well-posedness of the full-waveform inverse problem at high frequencies. Finally, we compared the water content obtained by GPR and light transmission measurements.

The results have shown that the near-field modeled and measured GPR data match very well in the frequency and time domains for both dry and wet sands. In the case of the dry sand, the estimated water content based on GPR and light transmission data was retrieved with small differences.

This research shows the potential of the GPR system and near-field full-wave antenna-medium model to accurately estimate the water content of soils with a high spatial resolution. Future studies will focus on the use of GPR to monitor root water uptake dynamics of plants in field conditions.

This abstract is of interest for COST Action TU1208.

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Rigorous and asymptotic models of coherent scattering from random rough layers with applications to roadways and geoscience

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This paper presents the rigorous efficient PILE (Propagation-Inside-Layer Expansion) numerical method [1] and an extension of the Ament model [2] to calculate the field scattered by three homogeneous media separated by two random rough surfaces. Here, the study is applied to ground penetrating radar (GPR) (nadir angle, wide band) for nondestructive survey by taking the roughness of the surfaces into account and by calculating the contribution of each echo coming from the multiple scattering inside the layer. Applications to roadways and geoscience are investigated.

The PILE method starts from the Method of Moments (MoM), and the impedance matrix is inverted by blocks from the Taylor series expansion of the inverse of the Schur complement. Its great advantage is that it is rigorous, with a simple formulation and has a straightforward physical interpretation. Actually, this last property relies on the fact that each block of the impedance matrix is linked to a particular and quasi-independent physical process occurring during the multiple scattering between the two rough surfaces. Furthermore, the PILE method allows us to use any acceleration algorithm (MLFMM, BMIA/CAG, Forward-Backward with or without Spectral Acceleration, etc.) developed for a single interface.

In addition, an asymptotic approach is extended to rough layered media: the scalar Kirchhoff-tangent plane approximation (SKA), for calculating the coherent scattering from the rough layer. The numerical rigorous PILE method is used as a reference to validate this asymptotic model. The study focuses on 2D problems with so-called 1D surfaces, for computational ease of the reference numerical method. Nevertheless, it must be highlighted that the SKA approach can readily be applied to 3D problems. This approach is applied to rough layers with two slightly rough surfaces characterized by either Gaussian or exponential correlation functions. The height probability density function (PDF) is assumed to be Gaussian.

The SKA model was shown to correctly predict the coherent scattered field for typical configurations in pavement survey by GPR at nadir, in the whole frequency band [0.5; 10] GHz [2]. This analysis will then be extended to geoscience applications. By taking into account the time delay of each echo in this new model, this direct simple EM model can be a good candidate for its use in signal processing algorithms for the estimation of physical parameters of the layer like its thickness H and also and more important, for the estimation of the RMS (root mean square) heights of two the rough interfaces simultaneously.

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Characterisation and optimisation of Ground Penetrating Radar antennas

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Research on the characterisation and optimisation of Ground Penetrating Radar (GPR) antennas will be presented as part of COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar". This work falls within the remit of Working Group 1 – "Novel GPR instrumentation" which focuses on the design of innovative GPR equipment for Civil Engineering (CE) applications, on the building of prototypes and on the testing and optimisation of new systems.

The diversity of applications of GPR has meant there are a number of different GPR antenna designs available to the end-user as well as those being used in the research community. The type and size of a GPR antenna is usually dependent on the application, e.g. low frequency antennas, which are physically larger, are used where significant depth of penetration is important, whereas high frequency antennas, which are physically smaller, are used where less penetration and better resolution are required. Understanding how energy is transmitted and received by a particular GPR antenna has many benefits: it could lead to more informed usage of the antenna in GPR surveys; improvements in antenna design; and better interpretation of GPR signal returns from the ground/structure. The radiation characteristics of a particular antenna are usually investigated by studying the radiation patterns and directivity. For GPR antennas it is also important to study these characteristics when the antenna is in different environments that would typically be encountered in GPR surveys.

In this work Finite-Difference Time-Domain (FDTD) numerical models of GPR antennas have been developed. These antenna models replicate all the detailed geometry and main components of the real antennas. The models are representative of typical high-frequency, high-resolution GPR antennas primarily used in CE for the evaluation of structural features in concrete: the location of rebar, conduits, and post-tensioned cables, as well as the estimation of material thickness on bridge decks and pavements. Radiation patterns obtained using the antenna models as well as physical measurements have been used to investigate the radiation characteristics of high-frequency GPR antennas. Studies were conducted with homogeneous materials of different dielectric constants (Er=3, 10, 30, & 72) and at a range of observation distances. The first objective was to compare, using the FDTD antenna model, 'traditional' transmitted field patterns with field patterns obtained using responses from a target spaced at regular intervals around the circumference of a circle, i.e. received energy. Our initial results show, for the same dielectric and observation distance, E- and H-field patterns obtained using the received energy approach have a significantly narrower main lobe than the traditional transmitted patterns. This raises the question of which approach is more beneficial for the characterisation of GPR antennas, and hence better interpretation of GPR responses. The second objective was to compare modelled field patterns with measured patterns obtained from a commercial high-frequency GPR antenna using the received energy approach. The measurements were made in different oil-in-water emulsions which were used to simulate materials with different permittivities and conductivities. Initial comparisons of the measured and modelled data show a very good correlation, which validates use of the antenna model for further studies.

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On-site inspections of pavement damages evolution using GPR

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Ground-penetrating radar (GPR) is being increasingly used for pavements maintenance due to the wide range of applications spanning from physical to geometrical inspections, thereby allowing for a reliable diagnosis of the main causes of road structural damages.

In this work, an off-ground GPR system was used to investigate a large-scale rural road network. Two sets of surveys were carried out in different time periods, with the main goals to i) localize the most critical sections; *ii)* monitor the evolution of previous damages and localize newborn deep faults, although not revealed at the pavement surface level; *iii)* analyze the causes of both evolution and emergence of faults by considering environmental and human factors.

A 1-GHz GPR air-launched antenna was linked to an instrumented van for collecting data at traffic speed. Other support techniques (e.g. GPS data logger, odometer, HD video camera) were used for cross-checking,. Such centre frequency of investigation along with a 25-ns time window allow for a signal penetration of 900 mm, consistent with the deepest layer interfaces. The bottom of the array was 400 mm over the surface, with a minimum distance of 1200 mm from the van body. Scan length of maximum 10 km were provided for avoiding heavy computational loads.

The rural road network was located in the District of Rieti, 100 km north from Rome, Italy, and mostly develops in a hilly and mountainous landscape. In most of the investigated roads, the carriageway consists in two lanes of 3.75 meters wide and two shoulders of 0.50 meters wide. A typical road section includes a HMA layer (65 mm average thickness), a base layer (100 mm average thickness), and a subbase layer (300 mm average thickness), as described by pavement design charts.

The first set of surveys was carried out in two days at the beginning of spring in moderately dry conditions. Overall, 320-km-long inspections were performed in both travel directions, thereby showing a productivity of approximately 160 km/day at 40 km/h speed, on the average.

After processing and first-checking, GPR profiles were divided into homogeneous sections according to the combination of different parameters (e.g. route analyzed, long distance conditions of regularity/irregularity in layers arrangement). In such context, a high consistency between surface damages, mismatches from the GPR scans, and boundary environmental conditions was demonstrated. In addition, deep mismatches were detected even for early-stage or unrevealed faults.

The second set of surveys was carried out in autumn in high humidity conditions, due to recent rainfalls. 160 km of relevant routes from the same road network were investigated.

Results showed a high consistency with those collected during the first-stage of surveys. Minor changes were found in those sections with low traffic loads (e.g. farther away from the biggest town of Rieti), whereas major mismatches were detected in wetlands (e.g. close to rivers), work zones, and nearby those sections already deeply damaged in the past.

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Fouling detection in buried water pipelines by observation of the scattered electromagnetic field

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The electromagnetic scattered field by a buried pipeline is calculated by means of frequency-domain numerical simulations and by making use of the scattered-field formulation. The pipeline, supposed to be used for water conveyance, is modeled as a cylindrical shell made of poly-vinyl chloride (PVC) material buried in a wall or pavement composed of cement with very low losses and filled with water. In order to make the model simpler, the pipeline is supposed running parallel to the air-cement interface. To excite the model, a linearly-polarized plane wave impinging normally on the above-mentioned interface is adopted. We consider two different polarizations in order to determine the most useful in terms of scattered-field sensitivity. Moreover, a preliminary frequency sweep allows us to choose the most suitable operating frequency depending on the dimensions of the pipeline cross-section. All the three components of the scattered field are monitored along a line just above the interface. The electromagnetic properties of the materials employed in this study are present in the literature and, since a frequency-domain technique is adopted, no further approximation is needed. Once the ideal problem has been studied, we further complicate the model by introducing two fouling scenarios due to limestone formation on the pipeline walls. In the first case, the fouling is deposited at the bottom of the pipeline when the water pressure is low enough and the second one considers the fouling to deposit on the entire internal perimeter of the pipeline's cross-section by forming an additional limestone cylindrical layer. The results obtained in these cases are compared with those of the initial problem with the goal of determining the scattered field dependency on the fouling geometrical characteristics. One of the practical applications in the field of Civil Engineering of this study may be the use of ground penetrating radar (GPR) techniques to monitor the fouling conditions of water pipelines without the need to intervene destructively in the structure.

This Abstract is a contribution to COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar".

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Assessment of asphalt mixtures characteristics through GPR testing

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Road pavements are composed by granular and asphalt layers, placed over the pavement subgrade, which are designed to resist to traffic and climatic effects. Pavement distresses include permanent deformation mainly due to the contribution of the subgrade and fatigue cracking in the asphalt layers. Fatigue cracking is the main pavement distress and is responsible for the main rehabilitations carried out in road pavements which leads, in most cases, to the pavement reconstruction due to the severity of the cracking observed in many roads.

For a given aggregate gradation, the fatigue cracking resistance is related to the proportions of the components in the asphalt mixtures, namely the void content and the binder content. Also the presence of water, or moisture, has an important influence in the fatigue resistance, and its effect is characterized by a reduction in the fatigue cracking resistance.

The characteristics of the asphalt mixtures applied in road pavements can be assessed in laboratory through the testing of cores extracted from the pavement. These cores are extracted some representative section of the pavement, usually equally spaced in the road. Due to the construction process, the representative sections of the pavement don’t allow to identify the quality of the whole pavement. Thus, the use of continuous measurement is essential to ensure the perfect assessment of the pavement quality and the use of the GPR assumes a paramount importance.

Thus, this communication presents several GPR tests carried out on pavement slabs produced in laboratory with different void content, binder content and moisture content in order to establish different classifiers that will allow the identification of this condition during regular inspections. Furthermore, tests carried on specimens before and after fatigue tests will allow to calculate similar parameters to estimate the state of conservation of pavements in terms of stiffness and the presence of cracks.

This work is a contribution to COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar".

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Investigation of mechanical properties of pavement through electromagnetic techniques

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Ground-penetrating radar (GPR) is considered as one of the most flexible geophysical tools that can be effectively and efficiently used in many different applications. In the field of pavement engineering, GPR can cover a wide range of uses, spanning from physical to geometrical inspections of pavements. Traditionally, such inferred information are integrated with mechanical measurements from other traditional (e.g. plate bearing test) or non-destructive (e.g. falling weight deflectometer) techniques, thereby resulting, respectively, in time-consuming and low-significant measurements, or in a high use of technological resources. In this regard, the new challenge of retrieving mechanical properties of road pavements and materials from electromagnetic measurements could represent a further step towards a greater saving of economic resources.

As far as concerns unpaved and bound layers it is well-known that strength and deformation properties are mostly affected, respectively, by inter-particle friction and cohesion of soil particles and aggregates, and by bitumen adhesion, whose variability is expressed by the Young modulus of elasticity. In that respect, by assuming a relationship between electromagnetic response (e.g. signal amplitudes) and bulk density of materials, a reasonable correlation between mechanical and electric properties of substructure is therefore expected.

In such framework, a pulse GPR system with ground-coupled antennae, 600 MHz and 1600 MHz centre frequencies was used over a 4-m$\times$30-m test site composed by a flexible pavement structure. The horizontal sampling resolution amounted to 2.4$\times$10-2 m. A square regular grid mesh of 836 nodes with a 0.40-m spacing between the GPR acquisition tracks was surveyed.

Accordingly, a light falling weight deflectometer (LFWD) was used for measuring the elastic modulus of pavement at each node. The setup of such instrument consisted of a 10-kg falling mass and a 100-mm loading plate so that the influence domain of the elasticity measure could be comparable to that of the radar signal. Good agreement were found between high Young modulus values and repaved zones, whereas damaged areas were characterized by lower values of E.

Tomographic maps of amplitudes along the z axis were extracted up to a depth of z <200 mm, consistent with the depth domain of the LFWD, and some values on the nodes were randomly selected and thus related to the corresponding elastic modulus both for calibration and validation of the model.

Comparison between predicted and measured elastic modulus showed relatively good results. Percentage errors ranging from -44% and +34% demonstrated an overall underestimate of the model with respect to the real truth. Future research activities could be addressed towards an improvement of the model by calibrating in laboratory environment under controlled conditions, and by using different GPR centre frequencies of investigation.

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GPR in Ramboll

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The Ramboll Group is a large (10.000 employees worldwide) engineering and consultancy company, with offices in 21 countries. Ramboll has been working with geophysics for about 20 years and at the time of writing there are about 25 geophysicist employed in the group, 20 of these are employed in Ramboll Denmark. Ramboll offers an extensive range of geophysical methods: different types of seismic, borehole wireline logging, electric and electromagnetic surveys, magnetic resonance soundings and well as marine geophysical and hydrographic surveys. The geophysical group at Ramboll operates in different industries comprising: Infrastructure, environmental assessments, mineral exploration, energy and offshore constructions.

In the recent years our GPR activities has increased significantly. Today Ramboll Denmark owns three separate GPR systems: One GSSI SIR-3000 with antennas ranging from 16MHz to 2GHz, One Mala geoscience ProEx system with a 100MHz RTA antenna and one 3D-radar Geoscope MKIV system with two DX antennas of different size. The main services are geological mapping with our ProEx system from Malå Geoscience, road mapping with a GSSI system and different shallow mapping with our 3D system from 3D Radar.

With our 2D systems we have performed mapping of peat in different places in Norway, mapping of sediments at various places in the Nordic countries and mapping of glacier thickness in Greenland. In this type of investigations we often combine GPR with resistivity imaging (CVES) and refraction seismic to ensure a more reliable interpretation. We have performed occasional utility or UXO surveys where GPR has been used together with EM or magnetic measurements.

The mapping on roads with the GSSI system is performed by our RST (Road Surface Testing) department in Malmö, Sweden. The measurements on roads are often combined with laser scanning and photo registration of the surface. Various software have been developed to automatize the interpretation. The RST group has contributed to aninternational collaboration between several countries about preparation of guidelines for application of GPR on roads, the Mara Nord Project.

Our 3D system is used for various types of surveys. In airports mapping has been performed both on runways, taxiways and aprons with the aim of mapping layer thicknesses and delamination for planning of maintenance work. Acquisition has also been done on roads for control of asphalt works and mapping of the road bed. On bridges mapping of rebars and structure has been performed. The 3D system is also used for determination of space behind frost insulation walls in tunnels in Norway. This work is based on a pilot project made by SINTEF in Norway.

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Non-destructive assessment of the Ancient “Tholos Acharnon” Tomb building geometry

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Ancient Greek Monuments are considered glorious buildings that still remain on the modern times. Tombs were specifically built according to the architecture of respective epoch. Hence, the main function was to royal families in Greece and other countries. The lack of systematic preservation could promote the damage of the structure. Therefore, a correct maintenance can diminish the impact of the main causes of pathologies. Schist, limestone and sandstone have been the main geological building materials of the Greek Ancient tombs.

In order to preserve several of these monumental tombs, in depth non-destructive evaluation by means of Ground-penetrating radar (GPR) is proposed in a scientific mission with partners from Greece and Spain surveying with the 1 GHz and 2.3 GHz antennas. High frequency antennas are able to identify small size cracks or voids. Grandjean et al. [1] used the 300 MHz and 900 MHz antennas, obtaining 2 cm and 5 cm of resolution. Later on, Faize et al. [2] employed a 2.3 GHz antenna to detect anomalies and create a pathological model.

The structure of this Mycenaean Tomb (14th – 13th c. BC) is composed by a corridor which is supported by irregular stones and the inner is 8.74 m high and 8.35 m diameter. The surface of the wall is composed by diverse geological materials of irregular shapes that enhance the GPR acquisition difficulty: 1) Passing the GPR antenna in a waved surface may randomly change the directivity of the emission. 2) The roof of the tomb is described by a pseudo-conical form with a decreasing radio for higher levels, with a particular beehive. If the roof of the Tomb is defined by a decreasing radius, innovative processes must be carried out with GPR to non constant radius structures. With GPR, the objective is to define the wall thickness, voids and/or cracks detection as well as other structural heterogeneities. Therefore, the aim is to create a three dimensional model based in the interpolation of the circular profiles.

Three dimensional interpolations of the circular profiles according to cylindrical coordinates and the decreasing ratio may be able to map with accuracy the wall structure and to create in a second step a structural dynamic model for the sustainable preservation of the Monument.

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Wire-grid electromagnetic modelling of metallic cylindrical objects with arbitrary section, for Ground Penetrating Radar applications

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This work deals with the electromagnetic wire-grid modelling of metallic cylindrical objects, buried in the ground or embedded in a structure, for example in a wall or in a concrete slab.

Wire-grid modelling of conducting objects was introduced by Richmond in 1966 [1] and, since then, this method has been extensively used over the years to simulate arbitrarily-shaped objects and compute radiation patterns of antennas, as well as the electromagnetic field scattered by targets.

For any wire-grid model, a fundamental question is the choice of the optimum wire radius and grid spacing. The most widely used criterion to fix the wire size is the so-called same-area rule [2], coming from empirical observation: the total surface area of the wires has to be equal to the surface area of the object being modelled. However, just few authors have investigated the validity of this criterion. Ludwig [3] studied the reliability of the rule by examining the canonical radiation problem of a transverse magnetic field by a circular cylinder fed with a uniform surface current, compared with a wire-grid model; he concluded that the same-area rule is optimum and that too thin wires are just as bad as too thick ones. Paknys [4] investigated the accuracy of the same-area rule for the modelling of a circular cylinder with a uniform current on it, continuing the study initiated in [3], or illuminated by a transverse magnetic monochromatic plane wave; he deduced that the same-area rule is optimal and that the field inside the cylinder is most sensitive to the wire radius than the field outside the object, so being a good error indicator. In [5], a circular cylinder was considered, embedded in a dielectric half-space and illuminated by a transverse magnetic monochromatic plane wave; the scattered near field was calculated by using the Cylindrical-Wave Approach and numerical results, obtained for different wire-grid models in the spectral domain, were compared with the exact solution. The Authors demonstrated that the well-known same-area criterion yields affordable results but is quite far from being the optimum: better results can be obtained with a wire radius shorter than what is suggested by the rule.

In utility detection, quality controls of reinforced concrete, and other civil-engineering applications, many sought targets are long and thin: in these cases, two-dimensional scattering methods can be employed for the electromagnetic modelling of scenarios. In the present work, the freeware tool GPRMAX2D [6], implementing the Finite-Difference Time-Domain method, is used to implement the wire-grid modelling of buried two-dimensional objects. The source is a line of current, with Ricker waveform. Results obtained in [5] are confirmed in the time domain and for different geometries. The highest accuracy is obtained by shortening the radius of about 10%. It seems that fewer (and larger) wires need minor shortening; however, more detailed investigations are required. We suggest to use at least 8 – 10 wires per wavelength if the field scattered by the structure has to be evaluated. The internal field is much more sensitive to the modelling configuration than the external one, and more wires should be employed when shielding effects are concerned.

We plan to conduct a more comprehensive analysis, in order to extract guidelines for wire sizing, to be validated on different shapes. We also look forward to verifying the possibility of using the wire-grid modelling method for the simulation of slotted objects.

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Electrical Resistivity Tomography and Ground Penetrating Radar for locating buried petrified wood sites: a case study in the natural monument of the Petrified Forest of Evros, Greece

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A geophysical survey was carried out in the Petrified Forest of Evros, the northernmost regional unit of Greece. This collection of petrified wood has an age of approximately 35 million years and it is the oldest in Greece (i.e. older than the well-known Petrified Forest of Lesvos island located in the North Aegean Sea and which is possibly the largest of the petrified forests worldwide). Protection, development and maintenance projects still need to be carried out at the area despite all fears regarding the forest's fate since many petrified logs remain exposed both in weather conditions – leading to erosion – and to the public. This survey was conducted as part of a more extensive framework regarding the development and protection of this natural monument. Geophysical surveying has been chosen as a non-destructive investigation method since the area of application is both a natural ecosystem and part of cultural heritage. Along with electrical resistivity tomography (ERT), ground penetrating radar (GPR) surveys have been carried out for investigating possible locations of buried fossilized tree trunks. The geoelectrical sections derived from ERT data in combination with the GPR profiles provided a broad view of the subsurface. Two and three dimensional subsurface geophysical images of the surveyed area have been constructed, pointing out probable locations of petrified logs. Regarding ERT, petrified trunks have been detected as high resistive bodies, while lower resistivity values were more related to the surrounding geological materials. GPR surveying has also indicated buried petrified log locations. As these two geophysical methods are affected in different ways by the subsurface conditions, the combined use of both techniques enhanced our ability to produce more reliable interpretations of the subsurface. After the completion of the geophysical investigations of this first stage, petrified trunks were revealed after a subsequent excavation at indicated locations. Moreover, we identified possible buried petrified targets at locations yet to be excavated.

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Portuguese experience on the use of GPR

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Ground penetrating radar has been used for several decades in a wide range of applications, from pure research towards structural diagnostics and infrastructure survey. This method has proven to be very useful for fast and nondestructive quality check of structures, especially road pavements. Due to this fact, the use of this method is mandatory in a number of countries (United States, United Kingdom, Norway, etc.) before any digging operation or for the quality inspection of bituminous road beds, for example. In those countries, national guidelines exist to regulate the use of these equipments as well as rules and protocols to be followed by the professionals that provide those kinds of services.

In Portugal, despite the advanced level of the structural engineering and construction professionals, and the existence of complex structures, the use of ground penetrating radar has exhibited a rather low penetration rate, comparatively to other European countries. This situation is due in part to the fact that GPR services are still more expensive than a more traditional way, which generally does not have the same degree of precision or implies the destruction of a part of the inspected area, and also because of the nature of Portuguese professionals. There is also a lack of national rules to regulate the use of GPR, which is the responsibility of ANACOM, as well as a certain lack of knowledge from national and regional authorities in order to make it mandatory in particular applications, namely in the case of intervention in the underground and road infrastructure.

Despite this situation, GPR has been used in Portugal in recent years, although being mostly confined to the academic world. Thus, this communication presents several examples of the Portuguese experience on the use of GPR, which ranges from academic research towards structural and infrastructure inspection, to archaeological survey. This work is a contribution to COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar".

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GPR use and activities in the Czech Republic

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In the field of civil engineering applications in the Czech Republic, Ground Penetrating Radar (GPR) is used particularly for the diagnostics of roads and bridges.

There is no producer of GPR in the Czech Republic, sets of different producers are used, particularly Geophysical Survey Systems, Inc. (USA) and MALÅ GeoScience (Sweden). The measurement results are mostly processed by software Radan, Road Doctor Pro, ReflexW and RadEx.

The only technical specification in the Czech Republic is TP 233 issued by the Ministry of Transport, which describes the diagnostics of roads by GPR. Apart from a basic description of the method and a measurement system, it mentions possible applications. The only application where accuracy is mentioned is the locating of dowels and tie bars in concrete road pavements, which states that if calibration is performed, the expected depth accuracy is up to 1.0 cm.

The following R&D project is currently in progress:
New diagnostics methods as a supporting decision tool for maintenance and repair of road pavements - their contribution and ways of their usage (2012-2014)
The project aims to test possible non-destructive methods (particularly GPR and laser scanning), make recommendations when and how to use specific methods for individual applications and for changes in technical specifications.

The following R&D projects have been recently completed:
Position of dowels and tie bars in rigid pavements and importance of their correct placement to pavement performance and service life (2012-2013)
The project included an analysis of individual NDT methods used for the location of dowels and tie bars and for testing of their accuracy – GPR, MIT-scan and GPR in combination with a metal detector.

Multichannel ground penetrating radar as a tool for monitoring of road and bridge structures (2009-2011)
The project included detection of hollow spaces under non-reinforced concrete pavements, detection of excessive amount of water in road construction layers, and measuring of crack depths in road pavements.

The concrete structure diagnostics development through the use of WPR (Wall Penetrating Radar) scanner (2008-2010)
The project was focused on the development of WPR for non-destructive diagnostics of concrete structures, as an accurate and reliable device for diagnostic survey, even at less easily accessible places.

The results of road diagnostics by GPR are still not stored in the Road Database. In 2013, CDV designed a method how to perform assessment of the position of dowels and tie bars in concrete road pavements and the way how to register the measurement results of road layer thicknesses in the Road Database.

The comparative measurements of devices used for the measurements of variable parameters of roads are performed according to technical specification of the Ministry of Transport TP 207: Accuracy Experiment. The specification deals with devices measuring surface properties and deflections of road pavements. GPR is not included there. In 2013, CDV designed a method how to perform this experiment for continual measurements of pavement layer thicknesses by GPR on reference road sections. The designed method is based on the first realized comparison measurement of pavement layer thicknesses at two-kilometre asphalt motorway section. 6 Czech companies participated in the comparative measurement.

Wider use of GPR method will allow to clarify measurement accuracy for individual applications. The performance of comparative measurements together with issuing of authorization for measurement will guarantee that the measurements on Czech road network are only performed by companies with required knowledge and experience.

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A review of ground penetrating radar research and practice in the United Kingdom

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Ground penetrating radar has been playing an important role for many years in assisting in the non-destructive evaluation of UK's built environment as well as being employed in more general shallow depth geophysical investigations. Ground penetrating radar, in the United Kingdom, has a long history of original work both in developing original research ideas on fundamental aspects of the technique, both in hardware and in software, and in exploring innovative ideas relating to the practical implementation of ground penetrating radar in a number of interesting projects. For example, the base of one of the biggest organisations that connects ground penetrating radar practitioners is in the United Kingdom. This paper will endeavour to review the current status of ground penetrating radar research - primarily carried out in UK Universities - and present some key areas and work that is carried out at a practical level - primarily by private enterprises. Although, the main effort is to concentrate on ground penetrating radar applications relating to civil engineering problems other related areas of ground penetrating radar application will also be reviewed. The aim is to create a current picture of ground penetrating radar use with a view to inform and potentially enhance the possibility of new developments and collaborations that could lead to the advancement of ground penetrating radar as a geophysical investigative method.

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Full-waveform inversion of GPR data for civil engineering applications

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Conventional GPR ray-based techniques are often limited in their capability to image complex structures due to the pertaining approximations. Due to the increased computational power, it is becoming more easy to use modeling and inversion tools that explicitly take into account the detailed electromagnetic wave propagation characteristics. In this way, new civil engineering application avenues are opening up that enable an improved high resolution imaging of quantitative medium properties. In this contribution, we show recent developments that enable the full-waveform inversion of off-ground, on-ground and crosshole GPR data. For a successful inversion, a proper start model must be used that generates synthetic data that overlaps the measured data with at least half a wavelength. In addition, the GPR system must be calibrated such that an effective wavelet is obtained that encompasses the complexity of the GPR source and receiver antennas. Simple geometries such as horizontal layers can be described with a limited number of model parameters, which enable the use of a combined global and local search using the Simplex search algorithm. This approach has been implemented for the full-waveform inversion of off-ground and on-ground GPR data measured over horizontally layered media. In this way, an accurate 3D frequency domain forward model of Maxwell's equation can be used where the integral representation of the electric field is numerically evaluated. The full-waveform inversion (FWI) for a large number of unknowns uses gradient-based optimization methods where a 3D to 2D conversion is used to apply this method to experimental data. Off-ground GPR data, measured over homogeneous concrete specimens, were inverted using the full-waveform inversion. In contrast to traditional ray-based techniques we were able to obtain quantitative values for the permittivity and conductivity and in this way distinguish between moisture and chloride effects. For increasing chloride content increasing frequency-dependent conductivity values were obtained. The off-ground full-waveform inversion was extended to invert for positive and negative gradients in conductivity and the conductivity gradient direction could be correctly identified. Experimental specimen containing gradients were generated by exposing a concrete slab to controlled wetting-drying cycles using a saline solution. Full-waveform inversion of the measured data correctly identified the conductivity gradient direction which was confirmed by destructive analysis. On-ground CMP GPR data measured over a concrete layer overlying a metal plate show interfering multiple reflections, which indicates that the structure acts as a waveguide. Calculation of the phase-velocity spectrum shows the presence of several higher order modes. Whereas the dispersion inversion returns the thickness and layer height, the full-waveform inversion was also able to estimate quantitative conductivity values. This abstract is a contribution to COST Action TU1208

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Comparison of pulse and SFCW GPR in time, frequency and wavelet domain

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Ground penetrating radar (GPR) systems operating in the time- or frequency domain are two fundamentally different concepts, pursuing the same objective: non-invasive characterization of the subsurface. The aim of this study is to compare the performance of these two GPR systems in the time, frequency and wavelet domain. The time domain GPR investigated is the Utilityscan DF. This is a ground coupled GPR with a digital dual-frequency antenna (300 and 800 MHz). The Geoscope GS3F and VX1213 antenna array from 3DRadar is the frequency domain GPR used in this comparison. It is an air coupled stepped frequency continuous wave (SFCW) GPR with a frequency bandwidth from 200 MHz to 3000 MHz. Using data from several test sites of various soil types, the data is evaluated in the time domain, the frequency domain and the wavelet domain. Each of these domains contains specific information regarding the data quality.
Presenting the data in the time domain, allows visualizing the subsurface reflections. This makes it visible how strong the data is affected by internal interference, ringing and other noise. To compensate for the attenuation of the signal in time, automatic gain control is applied. The maximum of this gain function indicates the time where the signal is attenuated completely and noise becomes more dominant, corresponding with the maximal penetration depth of the different GPR systems. In the frequency domain, the data allows to investigate which frequencies contain most valuable information and which ones are affected by noise. Finally, by performing a wavelet transformation the data is transformed to the time-frequency domain. Due to frequency dependent attenuation of electromagnetic signals in the soil, low frequencies will be more dominant in deeper layers, and high frequencies will not be present anymore. This is determining for the range resolution of the data throughout the traveltime of the signal.

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Electromagnetic modelling of Ground Penetrating Radar responses to complex targets

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This work deals with the electromagnetic modelling of composite structures for Ground Penetrating Radar (GPR) applications. It was developed within the Short-Term Scientific Mission ECOST-STSM-TU1208-211013-035660, funded by COST Action TU1208 “Civil Engineering Applications of Ground Penetrating Radar”.

The Authors define a set of test concrete structures, hereinafter called cells. The size of each cell is 60 x 100 x 18 cm and the content varies with growing complexity, from a simple cell with few rebars of different diameters embedded in concrete at increasing depths, to a final cell with a quite complicated pattern, including a layer of tendons between two overlying meshes of rebars. Other cells, of intermediate complexity, contain pvc ducts (air filled or hosting rebars), steel objects commonly used in civil engineering (as a pipe, an angle bar, a box section and an u-channel), as well as void and honeycombing defects. One of the cells has a steel mesh embedded in it, overlying two rebars placed diagonally across the comers of the structure. Two cells include a couple of rebars bent into a right angle and placed on top of each other, with a square/round circle lying at the base of the concrete slab. Inspiration for some of these cells is taken from the very interesting experimental work presented in Ref. [1].

For each cell, a subset of models with growing complexity is defined, starting from a simple representation of the cell and ending with a more realistic one. In particular, the model’s complexity increases from the geometrical point of view, as well as in terms of how the constitutive parameters of involved media and GPR antennas are described. Some cells can be simulated in both two and three dimensions; the concrete slab can be approximated as a finite-thickness layer having infinite extension on the transverse plane, thus neglecting how edges affect radargrams, or else its finite size can be fully taken into account. The permittivity of concrete can be defined through a constant real value, or else its frequency-dispersion properties can be taken into account by incorporating into the model Debye approximations. The electromagnetic source can be represented as a simple line of current (in the case of two-dimensional models), a Hertzian dipole, a bow tie antenna, or else, the realistic description of a commercial antenna can be included in the model [2].

Preliminary results for some of the proposed cells are presented, obtained by using GprMax [3], a freeware tool which solves Maxwell’s equations by using a second order in space and time Finite-Difference Time-Domain algorithm. B-Scans and A-Scans are calculated at 1.5 GHz, for the total electric field and for the field back-scattered by targets embedded in the cells.

A detailed description of the structures, together with the relevant numerical results obtained to date, are available for the scientific community on the website of COST Action TU1208, www.GPRadar.eu. Research groups working on the development of electromagnetic forward- and inverse-scattering techniques, as well as on imaging methods, might test and compare the accuracy and applicability of their approaches on the proposed set of scenarios. The aim of this initiative is not that of identifying the best methods, but more properly to indicate the range of reliability of each approach, highlighting its advantages and drawbacks. In the future, the realisation of the proposed concrete cells and the acquisition of GPR experimental data would allow a very effective benchmark for forward and inverse scattering methods.

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A GPR system for the high-resolution inspection of walls and structures

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Nowadays GPR systems are used in a broad range of applications, including the non-destructive inspection of man-made concrete structures such as pillars and bridge decks.

Concrete inspection involves several aspects including: location of reinforced bars in walls and floors, concrete condition assessment, concrete cover detection, etc. These surveys are very demanding as far as the system is concerned, because of the strict requirements in terms of resolution and accuracy.

Specifically, a key GPR application concerns the condition assessment of a structure that has undergone rehabilitation (e.g. for the removal of architectural barriers or new openings); in this case, the current practice requires to re-check the stability of the entire structure that includes the identification of the number of rebars in reinforced concrete beams location of pre-tensioned cables and early detection of corrosion. This can be done by verification holes (coring) that is costly and intrusive practice or by using a pachometer, but this tool has a limited field of investigation (up to 7-8 cm from the surface). GPR can instead be a useful investigative tool especially when the surface of the beam is not accessible because it is covered by screed or floor.

The need of detecting rebars with diameter in the millimeter range as well as the identification of small cavities and cracks, require the development of GPR antennas featuring linear phase and constant polarization, and capable to radiate a very short pulse (i.e. with a duration in the order of few hundreds of picosecond) with no ring-down in order to achieve a high range resolution. A novel 3 GHz center frequency antenna has been recently developed and tested; it has been found capable of providing a very clear image of the concrete internal structure that helps in locating targets and enables an early detection of damages, thus providing a fast and efficient maintenance of the structure itself.

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Ground Penetrating Radar Technologies in Ukraine

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Transient electromagnetic fields are of great interest in Ukraine. The following topics are studied by research teams, with high-level achievements all over the world: (i) Ultra-Wide Band/Short-pulse radar techniques (IRE and LLC "Transient Technologies", for more information please visit http://applied.ire.kharkov.ua/radar%20systems_their%20components%20and%20relevant%20technologies_e.html and http://viy.ua); (ii) Ground Penetrating Radar (GPR) with stepped frequency sounding signals (IRE); (iii) Continuous-Wave (CW) radar with phase-shift keying signals (IRE); and (iv) Radio-wave interference investigation (Scientific and Technical Centre of The Subsurface Investigation, http://geophysics.ua).

GPR applications are mainly in search works, for example GPR is often used to search for treasures. It is also used to identify leaks and diffusion of petroleum in soil, in storage areas, as well as for fault location of pipelines. Furthermore, GPR is used for the localization of underground utilities and for diagnostics of the technical state of hydro dams. Deeper GPR probing was performed to identify landslides in Crimea. Rescue radar with CW signal was designed in IRE to search for living people trapped under the rubble of collapsed buildings. The fourth version of this radar has been recently created, showing higher stability and noise immunity. Radio-wave interference investigation allows studying the soil down to tens of meters. It is possible to identify areas with increased conductivity (moisture) of the soil.

LLC "Transient Technologies" is currently working with Shevchenko Kyiv University on a cooperation program in which the construction of a test site is one of the planned tasks. In the framework of this program, a GPR with a 300 MHz antenna was handed to the geological Faculty of the University. Employees of "Transient Technologies" held introductory lectures with a practical demonstration for students majoring in geophysics.

The authors participated to GPR projects on the delineation of a diamond deposit in Karelia, on the localisation of unauthorized penetrations in product pipelines, and others. Since 2007, in close cooperation with researchers from V. N. Karazin Kharkiv National University (www.univer.kharkov.ua/en) and Kharkiv National Automobile and Highway University (www.khadi.kharkov.ua), we have been developing a GPR to monitor road conditions. The main objective is the creation of an equipment suitable to determine the strength characteristics of pavements. A GPR allowing to measure thicknesses of asphalt pavement layers with an accuracy better than 3 mm has already been created; it was transferred to services responsible for maintaining roads in good condition.

Specific standards and guidelines for the use of GPR has not been adopted in Ukraine, yet. GPRs are rarely used by public services. Nevertheless, recently the Ukrainian government has funded several projects on GPR technologies.

Ukrainians seek to maintain old and to establish new relationships with colleagues around the world. We were partners of the Ultrawideband Radar Working Group, which developed the standard "IEEE P1672 TM Ultrawideband Radar Definitions." LLC "Transient Technologies" has cooperation agreements with more than a dozen of GPR companies all over the world. A group of scientists from IRE is working in cooperation with researchers from Italy, Holland, Turkey, Brazil, Russia and Ukraine on the project of FP-7-PEOPLE-2010-IRSES no 269157 "Active and Passive Microwaves for Security and Subsurface Imaging" (for more details, please visit www.irea.cnr.it/en/index.php?option=com_k2&view=item&id=342:progetto-amiss&Itemid=165).

In recent years, many representative companies have appeared, offering GPRs of foreign production on the market of Ukraine.

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Expanding Minds – Assessing Competence

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The twin technologies of Ground Penetrating Radar (GPR) & Wall Probing Radar (WPR) enable the detection of buried material, either below ground or within built structures and are based on long standing scientific principles that are well understood at academic level. As a result of its lead in the development of firm standards for manufacturing and product supply; Europe has become a world focal point for GPR/WPR technology and commercial exploitation has flourished to such an extent that GPR/WPR is now used throughout Europe across diverse markets from civil engineering & construction, to traffic management, town planning and the maintenance of utilities. Other applications provide more societal benefit e.g. assisting forensic investigations; aiding health & safety and the reduction of workplace injuries; supporting environmental improvements by replacing intrusive works with non intrusive procedures; supporting heritage preservation through archaeological surveys; identifying water leakage from potable water distribution systems; the preservation of life through humanitarian/demining services and the search for new sources of water in drought areas.

For all these areas of endeavour however, the only vocational training available in the use of GPR/WPR is provided by manufacturers or suppliers in respect of the use of specific equipment; the focus being functional aspects of that specific equipment or, to the provision of specific services by the service providers to their own staff; the focus being the commercially deliverable aspects. In both instances this training has no recourse to common terminology, agreed physical principles, accepted parameters or technical limitations. This has led to wide ranging variations in the knowledge, skill and ability of operators and the issue of copious guidance documents for general and specific uses, from a wide variety of sources.

The lack of these common frames of reference means there is no solid basis for building recognised good practice and with no access to a relevant, common recognised assessment process there can be no common transferable skills. The only recognised qualifications available being academic ones, which are not generally applied or particularly relevant in a commercial environment. The industry is therefore unable to offer appealing career paths and employment opportunities in line with today's accepted practices.

This proposal is made to meet the immediate need for this situation to change; act as the catalyst for co-operation between all affected sectors of industry and commerce in COST countries, to develop a unified professional standards and training framework applicable to all areas of the technology's application. Thus ensuring vital services may always be delivered by: Professional companies; employing competent, trained staff; working to recognised and unified European standards. Interaction with members of Cost Action TU1208 and inclusion of the creation of a formalised training programme within Cost Action TU1208 in support of this is strongly welcomed.

EuroGPR is a not for profit Eurocentric organisation drawing its membership from a wide variety of manufacturers, service providers, institutions and non government organisations. It has strong links to existing standards institutions within Europe and worldwide links within industry and academia. It provides a neutral centre from which to set European wide standards towards which other interested parties may migrate without bias.

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2D and 3D GPR imaging of structural ceilings in historic and existing constructions

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GPR applications in civil engineering are to date quite diversified. With respect to civil constructions and monumental buildings, detection of voids, cavities, layering in structural elements, variation of geometry, of moisture content, of materials, areas of decay, defects, cracks have been reported in timber, concrete and masonry elements. Nonetheless, many more fields of investigation remain unexplored. This contribution gives an account of a variety of examples of structural ceilings investigation by GPR radar in reflection mode, either as 2D or 3D data acquisition and visualisation.

Ceilings have a pre-eminent role in buildings as they contribute to a good structural behaviour of the construction. Primarily, the following functions can be listed for ceilings: a) they carry vertical dead and live loads on floors and distribute such loads to the vertical walls; b) they oppose to external horizontal forces such as wind loads and earthquakes helping to transfer such forces from the loaded element to the other walls; c) they contribute to create the box skeleton and behaviour of a building, connecting the different load bearing walls and reducing the slenderness and flexural instability of such walls.

Therefore, knowing how ceilings are made in specific buildings is of paramount importance for architects and structural engineers. According to the type of building and age of construction, ceilings may present very different solutions and materials. Moreover, in existing constructions, ceilings may have been substituted, modified or strengthened due to material decay or to change of use of the building. These alterations may often go unrecorded in technical documentation or technical drawings may be unavailable. In many cases, the position, orientation and number of the load carrying elements in ceilings may be hidden or not be in sight, due for example to the presence of false ceilings or to technical plants. GPR radar can constitute a very useful tool for investigating with rapidity and high resolution, thin as well as very thick ceilings, in a non-destructive manner.

Ceilings may be made up as masonry vaults or timber/metal/concrete beams and elements laid down in one or two directions or, again, can be made as a combination of the above. A number of cases are here presented reporting on typical features to be recognised in radargrams in order to distinguish the material and possible shape of the relevant objects with the aim of providing a first small catalogue useful to the radar user and to professionals.

This abstract is of interest for COST Action TU1208.

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Improvement of the energetic properties of the GPR

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The necessary condition for the expansion of the impulse Ground Penetrating Radar (GPR) applications is to improve the GPR energy performance for the detection of signals on the background of noise. Digital signal processing techniques allow suppressing the noise largely, but they work only when the GPR is able to register the reflected signals.

The majority of the modern GPRs use sampling receivers. They allow recording signals of a very short duration. However, very large energy losses are inherent to this method.
To improve the signal to noise ratio it is possible to increase the power of the probing signal and to de- crease the noise level of the receiver.

In GPR, the transmitting and receiving antennas are usually electrodynamically coupled because they are situated quite close to each other. The sensitive input circuit of the receiver does not allow the excess of the signal amplitude typically more than 1 V. Thus, the increase of the intensity of the probing signal is possible only up to a certain level. To overcome this limitation, it was proposed to design an antenna in such a way that the coupling between the transmitting and receiving sections was absent or minimal. A special method that provided the decoupling below -64 dB was invented (theoretically the isolation is absolute and frequency independent).

In order to register as short as possible signals, researchers strive to make sample duration of the sampling converter as short as possible. However, the shorter the sample duration, the smaller the energy of the signal that can be received and the larger the noise.

Due to the dispersive absorption of electromagnetic waves in the ground, the high-frequency part of the signal spectrum is attenuated faster than the low-frequency part. It makes no sense to expect the arrival of very short pulses from deep reflectors. Thus, it is possible to increase the duration of the samples at reception of the signals from the deep objects. The authors proposed to increase the duration of the samples with the distance. In this way, a smoothing of the noise and an increase of the recorded energy at each subsequent sampling were achieved.

The next opportunity to improve the signal to noise ratio is the coherent accumulation of the signal that can be carried out both in digital and analog forms. Due to the fast ADC, it became possible to accumulate a large number of signals in an acceptable survey period.

In practice, the amount of accumulated signals is limited by jitter. Thus, to achieve accumulation and reception of signals without distortion the authors have suggested and implemented GPR improvements allowing to get the instability of sampling below 3.5 ps.

Owing to increase of the pulse-repetition frequency up to 1 MHz and data transmission via Ethernet, it was also possible to provide a fast GPR survey.

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COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar": first-year activities and results

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This work aims at presenting the first-year activities and results of COST (European COoperation in Science and Technology) Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar". This Action was launched in April 2013 and will last four years. The principal aim of COST Action TU1208 is to exchange and increase scientific-technical knowledge and experience of GPR techniques in civil engineering, whilst simultaneously promoting throughout Europe the effective use of this safe and non-destructive technique in the monitoring of infrastructures and structures. Moreover, the Action is oriented to the following specific objectives and expected deliverables: (i) coordinating European scientists to highlight problems, merits and limits of current GPR systems; (ii) developing innovative protocols and guidelines, which will be published in a handbook and constitute a basis for European standards, for an effective GPR application in civil- engineering tasks; safety, economic and financial criteria will be integrated within the protocols; (iii) integrating competences for the improvement and merging of electromagnetic scattering techniques and of data- processing techniques; this will lead to a novel freeware tool for the localization of buried objects, shape-reconstruction and estimation of geophysical parameters useful for civil engineering needs; (iv) networking for the design, realization and optimization of innovative GPR equipment; (v) comparing GPR with different NDT techniques, such as ultrasonic, radiographic, liquid-penetrant, magnetic-particle, acoustic-emission and eddy-current testing; (vi) comparing GPR technology and methodology used in civil engineering with those used in other fields; (vii) promotion of a more widespread, advanced and efficient use of GPR in civil engineering; and (viii) organization of a high-level modular training program for GPR European users.

Four Working Groups (WGs) carry out the research activities. The first WG focuses on the design of innovative GPR equipment, on the building of prototypes and on the testing and optimisation of new systems. The second WG focuses on the GPR surveying of pavement, bridges, tunnels and buildings, as well as on the sensing of underground utilities and voids. The third WG deals with the development of electromagnetic forward and inverse scattering methods, for the characterization of GPR scenarios, as well as with data- processing algorithms for the elaboration of the data collected during GPR surveys. The fourth WG works on the use of GPR in fields different from the civil engineering, as well as on the integration of GPR with other non-destructive testing techniques. Each WG includes several Projects.

COST Action TU1208 is active through a range of networking tools: meetings, workshops, conferences, training schools, short-term scientific missions, dissemination activities. During the first year of activities, a First General Meeting was organized in Rome, in July 2013, a second meeting took place in Nantes, in February 2014, and the Second General Meeting is being held jointly with the 2014 EGU General Assembly. A training school on "Microwave Imaging and Diagnostics: Theory, Techniques, and Applications", held in March 2014, was co-organised with the European School of Antennas. Four Short-Term Scientific Missions were funded, allowing young researchers to spend a period of time in an institution abroad, in order to carry out a research project contributing to the scientific objectives of the Action. The Action's activities were disseminated in international conferences [1]-[4], as well as in further workshops and meetings. Two volumes were published [5]-[6], and several scientific papers on peer-reviewed journals. A Springer book presenting the state of the art on civil engineering applications of Ground Penetrating Radar is being prepared and is going to be published in summer 2014.

A COST Action is a wide bottom-up interdisciplinary science and technology network, open to researchers from universities, public and private research institutions, as well as to NGOs, industry and SMEs. At present, About 100 Institutions from 24 COST Member Countries (Austria, Belgium, Croatia, Czech Republic, Denmark,

Estonia, Finland, France, Germany, Greece, Italy, Latvia, Malta, Macedonia, The Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Switzerland, Turkey, United Kingdom) have already joined the Action, together with an Institution from Armenia (Near Neighbour Country, NNC). Beyond European borders, six Institutions from U.S.A., one from Rwanda and one from Australia have joined the Action. Further applications from two NNCs (Egypt and Ukraine) and International Partner Countries (Hong Kong and Japan) are under examination.

COST Action TU1208 is still open to the participation of new parties and it is possible to include, in the scientific work plan, new perspectives and activities. Scientists and scientific institutions willing to join COST Action TU1208 are encouraged to contact the Chair of the Action and to follow the procedure described at http://www.cost.eu/participate/join_action.

For more information on COST Action TU1208, please visit www.GPRadar.eu.

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