COST ACTION TU1208

CIVIL ENGINEERING APPLICATIONS OF GROUND PENETRATING RADAR

Proceedings

First Action's General Meeting

Rome, 22nd – 24th July 2013

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- WG2: Dr. Christina Plati, National Technical University of Athens, EL
- WG3: Dr. Antonis Giannopoulos, University of Edinburgh, UK
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Preface
to the Proceedings of the First Action's General Meeting – COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar"

The First Action's General Meeting of COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar," is held in Rome, Italy, from the 22nd to the 24th of July, 2013. There are about 100 scientific participants attending this international event, from 19 European Countries.

Overall, the First Action's General Meeting includes the Action's Management Committee Meeting, the Steering Group Meeting, and the Meetings of the four Working Groups, composing the general pattern of the scientific program of the Action. Therefore, this event constitutes a valuable opportunity to meet the participants of the COST Action TU1208 as well as a prestigious forum for a promising discussion and a wide exchange of knowledge and experience related to the use of GPR in civil engineering problems.

The meeting is mainly devoted to address the state of the art, advancements, ongoing studies and open problems, in the fields of GPR technologies and methodologies, inspection strategies and practices, electromagnetic methods for the modelling of GPR scenarios, and numerical algorithms for the processing of GPR data. This event also aims at emphasizing the importance of the relations between the discussed scientific-technological issues and the social and economical concerns. A further objective of the meeting is to exchange and discuss preliminary ideas about the definition and coordination of test scenarios, representing both typical and unusual situations that may occur in civil engineering tasks, for an effective comparison between different advanced GPR equipment, inspection procedures, electromagnetic methods and data-processing algorithms.

It is a great honour to have Prof. David J. Daniels attending the meeting and giving a plenary talk on GPR design challenges. The purpose of this talk is to provide an overview of GPR system design issues, for the various modulation techniques, simultaneously suggesting what improvements in subsystems - such as antennas, receivers and transmitters - are needed to increase overall GPR performance.

We are honoured by the presence of Dr. Erica Utsi as well, presenting the EuroGPR activities and being available to discuss with the Action's participants ideas and proposals on possible joint initiatives between the EuroGPR Association and the COST Action TU1208.

We are also delighted to attend the plenary talk given by Prof. Antonis Giannopoulos, Chair of the Working Group 3, about the finite-difference time-domain method and the well-known GPR simulation tool GPRMAX, which he has developed in his career as a researcher. This talk includes an overview on the progress reached by the FDTD modelling over the last twenty years and provides instructions on possible developments to be pursued in the next future.

Furthermore, it is a great pleasure to have Dr. Immo Trinks, Chair of the Working Group 4, giving a plenary talk about large-scale archaeological prospection using GPR array systems, and presenting extraordinary results collected by his research team at the Roman town of Carnuntum, located about 30 km south-east of Vienna, in Austria. Between 2012 and 2015, the entire Carnuntum is being mapped in great detail using non-invasive prospection methods, as an excellent example of how high-resolution GPR measurements are of fundamental importance for the detection, mapping, documentation and investigation of the buried cultural heritage in three dimensions.

The Proceedings of the event include a special paper by Prof. David J. Daniels, resuming the plenary talk given during the meeting by the author. The characteristics of GPR systems are reviewed, with particular reference to the various modulation techniques. The issues related to the design of GPR antennas are considered and possible areas for further research and development are described. A brief discussion of signal processing is included and some new GPR applications are suggested.

The Proceedings of the First Action's General Meeting also collect three abstracts by Dr. Erica Utsi, Prof. Antonis Giannopoulos and Dr. Immo Trinks, summarizing their plenary talks.

The Working Group 1 (WG1) of COST Action TU1208 focuses on the design of innovative GPR equipment, on the building of prototypes, as well as on the testing and optimization of new systems. Besides the above-mentioned special paper by Prof. D. J. Daniels, this volume includes three papers developed by WG1 Members. The contribution by Dr. G. Manacorda, Chair of the WG1, Dr. A. Simi, and Dr. H. F. Scott, regards the state of the art and open issues in the field of the design, realization and optimization of radars devoted to the monitoring of critical transport infrastructures, to the survey of buildings, as well as to the sensing of underground utilities and voids. A further paper by Dr. R. Persico, Dr. N. Masini, Dr. M. Ciminale, and Dr. L. Matera, presents an innovative reconfigurable stepped frequency GPR and reports preliminary results obtained by using this system. The contribution by Dr. L. Gamma, Vice-Chair of WG1, focuses on testing, calibration and stability procedures/protocols for GPR equipment.

The Working Group 2 (WG2) of COST Action TU1208 deals with the GPR surveying of transport infrastructures and buildings, as well as on the sensing of underground utilities and voids. These Proceedings include four papers prepared by WG2 Members. A first paper, authored by Dr. J. Stryk and Dr. R. Matula, regards the state of the art and open issues in the field of the GPR inspection procedures for the surveying of pavements, bridges, and tunnels. The paper by Dr. C. Plati and Dr. X.

Derobert, Chair and Vice-Chair of WG2, respectively, makes the point on the use of GPR for the detection of underground utilities and voids. The contribution by Dr. L. Krysiński, gives a review of the methods related to the assessment of construction materials properties through the use of GPR techniques, discussing the research topics to be further developed and the main problems in this area. Finally, the manuscript by F. Tosti deals with the estimation, through GPR techniques, of the volumetric water content in structures, sub-structures, foundations and soil.
The Working Group 3 (WG3) of COST Action TU1208 is developing accurate and fast electromagnetic scattering methods for the characterization of relevant scenarios in GPR applications, as well as effective data-processing algorithms for the elaboration of GPR data collected during civil engineering surveys. Besides the above-mentioned abstract by Dr. A. Giannopoulos, this volume collects five papers written by WG3 Members. The paper by Dr. C. Ponti focuses on the state of the art and open issues in the development of full-wave methods for the solution of forward electromagnetic scattering problems by buried structures. A further paper by Prof. R. Solimene and Dr. A. Randazzo, instead, focuses on inverse electromagnetic scattering problems by buried structures. Next, the paper by Prof. S. Lambot concerns the development of intrinsic models for the description of near-field antenna effects, including antenna-medium coupling, for improved radar data processing using full-wave inversion. The paper by Dr. I. Catapano and Prof. E. Slob makes the point on shape-reconstruction and quantitative estimation of electromagnetic and physical properties from GPR data. Finally, the paper by Dr. N. Economou, Prof. A. Vafidis, and Dr. F. Benedetto, provides the reader with a deep understanding of the state of the art and open issues in the field of GPR data processing techniques.
The Working Group 4 (WG4) of COST Action TU1208 focuses on different applications of GPR and on other Non-Destructive Testing (NDT) techniques for civil engineering applications. Besides the above-mentioned abstract by Dr. I. Trinks, this volume includes four papers written by WG4 Members. The paper by F. Soldovieri is concerned with a review of the recent advances related to the use of GPR, and its integration with other NDT techniques, in the applicative domain of the archaeological prospecting and cultural heritage diagnostics and monitoring; the main scientific/technological challenges are identified and possible strategies to tackle them are devised with a particular interest to the role that the COST Action TU1208 could play. The paper by Dr. L. Crocco and Prof. V. Ferrara addresses a challenging and emerging field of application of GPR, namely the localization of buried or trapped people, possibly exploiting the detection of the Doppler frequency changes induced by their physiological movements as heart-beat and breathing; the main motivations for which the topic is worth to be considered in the framework of the COST Action TU1208 are

outlined and an overview of some relevant literature is provided. The paper by Dr. M. Solla focuses on the use of GPR combined with other NDT methods in the surveying of transport infrastructures: published works in roads and pavements, concrete and masonry structures, and tunnel testing, are resumed. In geotechnical and geological tasks, the efficiency of GPR is strongly dependent on the site conditions, mostly due to the limited in-depth penetration and target discrimination: the paper by Dr. K. Dimitriadis and Dr. V. Perez-Gracia resumes the state of the art in this field and discusses how future research has to be oriented in order to improve the application of GPR and other NDT techniques in geotechnical and geological applications.
We sincerely thank COST for funding the COST Action TU1208 and the First Action's General Meeting. We deeply thank "Roma Tre" University for hosting this event and for providing facilities. We are also grateful to IDS Ingegneria dei Sistemi SpA for covering the printing costs of this volume.

Lara Pajewski, Chair of the COST Action TU1208
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GPR DESIGN CHALLENGES

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Abstract

This paper describes some of the design challenges for Ground Penetrating Radar that still remain to be solved, as well as some of the issues that systems designers need to consider in developing new technology and techniques. Two applications are suggested for further development.

I. INTRODUCTION

In Section II this paper reviews the characteristics of Ground Penetrating Radar with particular reference to the various modulation techniques. In Section III some of the issues relating to the design of antennas are considered and possible areas for further research and development are reviewed. A brief discussion of signal processing is included in Section IV and some suggested areas of application for ground penetrating radar are described in Section V. One of the common themes associated with ground penetrating radar is the methodology of testing and verification and this is discussed in Section VI. The paper concludes in Section VII.

II. SYSTEM OVERVIEW

GPR is a technique based on the principles of RADAR (RAdio Detection And Ranging) to measure the location and size of targets buried in visually opaque material. The design and principles of GPR are described by Daniels [1], [2] and in the hands of an expert provides a safe and non-invasive method of performing speculative searches without the need for unnecessary disruption and excavation. GPR has significantly improved the efficiency and safety of the exploratory work that is fundamental to the construction and civil engineering industries, the police and forensic sectors, security/intelligence forces, geological hazards, mineral resource, ground water, environmental and archaeological surveys.

GPR relies for its operational effectiveness on successfully meeting the following requirements:

– efficient coupling of electromagnetic radiation into the ground;
– adequate penetration of the radiation through the ground having regard to target depth;

– obtaining from buried objects or other dielectric, conductive or magnetic discontinuities (contrasts) a sufficiently large scattered signal for detection at or above the ground surface or within or between boreholes, trenches or mine shafts;
– adequate bandwidth in the detected signal having regard to the desired resolution and noise levels;
– adequate wavelength and polarization of electric field compared to the size, shape and orientation (geometry) of the buried object for detection.

The physics and technology of GPR and its ability to detect buried targets are well understood and proven even though the underlying physics and engineering are not simple.

The various factors that need to be considered in the design of GPR systems are shown in Fig. 1.

Most GPRs for operate in a region where the wavelengths radiated are greater than, or in the same order of magnitude as the dimensions of the target. This is between the Rayleigh and Mie (or resonance) region of the target dimensions and is quite unlike conventional radar systems where the target dimensions are generally much larger than the wavelength of the incident radiation, i.e., the optical region. Planar interfaces may have cross track dimensions significantly greater than the wavelengths radiated but thin layers as in road construction, may be the same order of magnitude dimensionally as the wavelengths radiated.

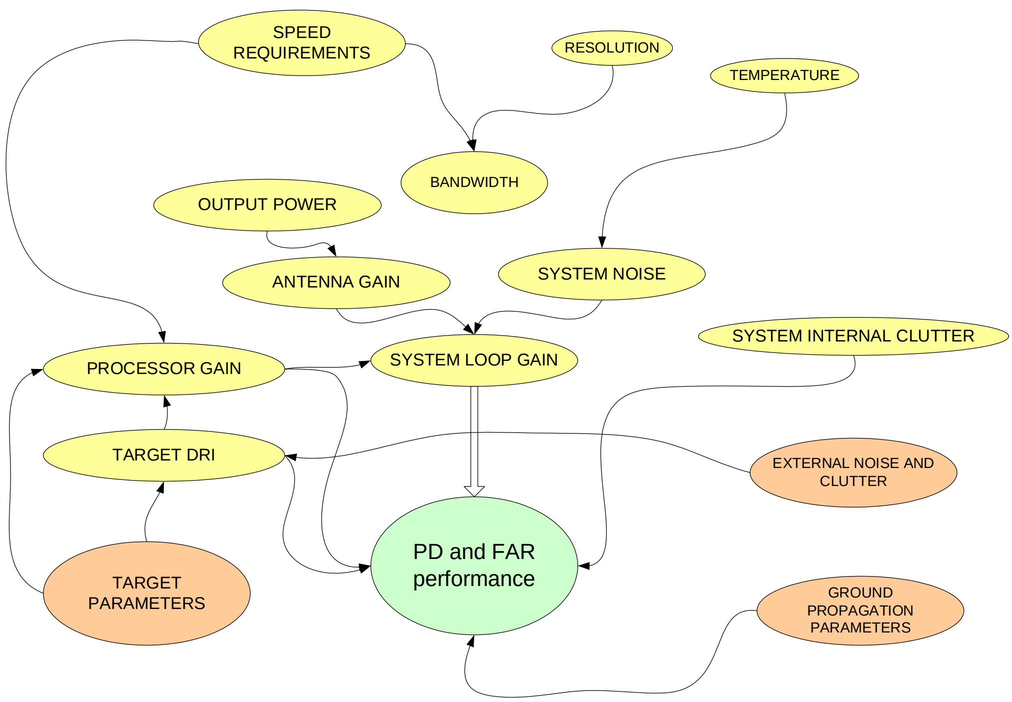

FIG. 1 – Considerations in the design of GPR systems.

GPR performance can be predicted with some accuracy given information on the characteristics of the soil or host material and target. A GPR will detect, within the limits of the physics of propagation, all changes in electromagnetic impedance in the material under investigation. Some of these changes will be associated with wanted targets, others may not be and the required signal from one investigation may be clutter to another. For example, one user may want to see rebar while another wants to see past the rebar to obtain the thickness of concrete. The radar has, in general, no way of discriminating specified targets unless very sophisticated recognition algorithms are used in the signal processing and much of the skill of the successful user comes from forming a conclusion from both the radar image and a knowledge of target characteristics and soil properties as well as external information.

GPR system loop dynamic range

GPR systems are regulated by national and international licensing organizations such as ETSI [Europe], FCC [USA], OFCOM [UK] etc with regard to the permitted radiated power levels and compliance with these regulations is mandatory.

In terms of the power they can transmit, typically a GPR transmits an average power less than a milliwatt [1.10^{-3} W] [3], [4]. In the UK the maximum permitted power levels [EIRP] for GPR over the frequency range 150 MHz to 4 GHz are as follows:

- Total radiated power: ≤250 microwatts
- Radiated spectral line power: ≤100 nanowatts
- Maximum leakage power from antenna shield: ≤10 nanowatts

The minimum signal that the receiver can detect lies between picowatts [1.10^{-12} W] and femtowatts [1.10^{-15} W] depending on its design. There are fundamental limitations to receiver sensitivity dictated by the thermal noise of the receiver, its bandwidth as well as environmental RF noise or clutter which set the limit to system loop sensitivity. The ratio of the mean transmitted power and the minimum detectable signal sets the overall system loop dynamic range of the measurement system and this lies in the region of 10^8 to 10^{12} or expressed in decibels 80 dB to 120 dB.

Physics of propagation

The strength of the received signal depends on the radar cross section of the target and the losses encountered by the radar signal as it propagates from the transmit antenna, couples into the ground, reflects from the target and returns to the receive antenna. The radar cross section of the target is defined by its physical size with respect to the wavelengths propagating in the dielectric material. If the target is very much smaller than the wavelength, it has a very small radar cross section and consequently becomes vanishingly small. Other factors affecting the signal level are related to the antenna efficiency in coupling energy into the ground, the losses in the material (which are usually expressed in dB per metre), and the way in which the transmitted signal spreads out from its radiating antenna. In terms of power and in free space and with respect to a point source radiator and target the signal decreases in inverse proportion to the square of the range (target depth or distance) and this is termed spreading loss. If the transmit and receive antennas have directionality and hence gain, the signal will be more concentrated in a particular direction and hence this may provide a modest compensation for the effect of spreading loss. Although it is possible to increase directionality by using coherent arrays of antennas, the improvement is marginal and is not directly proportional to the number of antennas in an array. It is not possible to improve directionality to the point where spreading loss is eliminated.

Attenuation, Resolution, Bandwidth and Frequency

Free space radar systems need only consider propagation phenomena through the atmosphere but waves propagating through other media experience attenuation of both the electric (*E*) or magnetic (*H*) fields. The graph in Fig. 2 shows the attenuation loss in dBs per metre plotted against frequency in Hz for a material with a relative dielectric constant of 9 and loss tangents of 0.005 to 0.1 respectively.

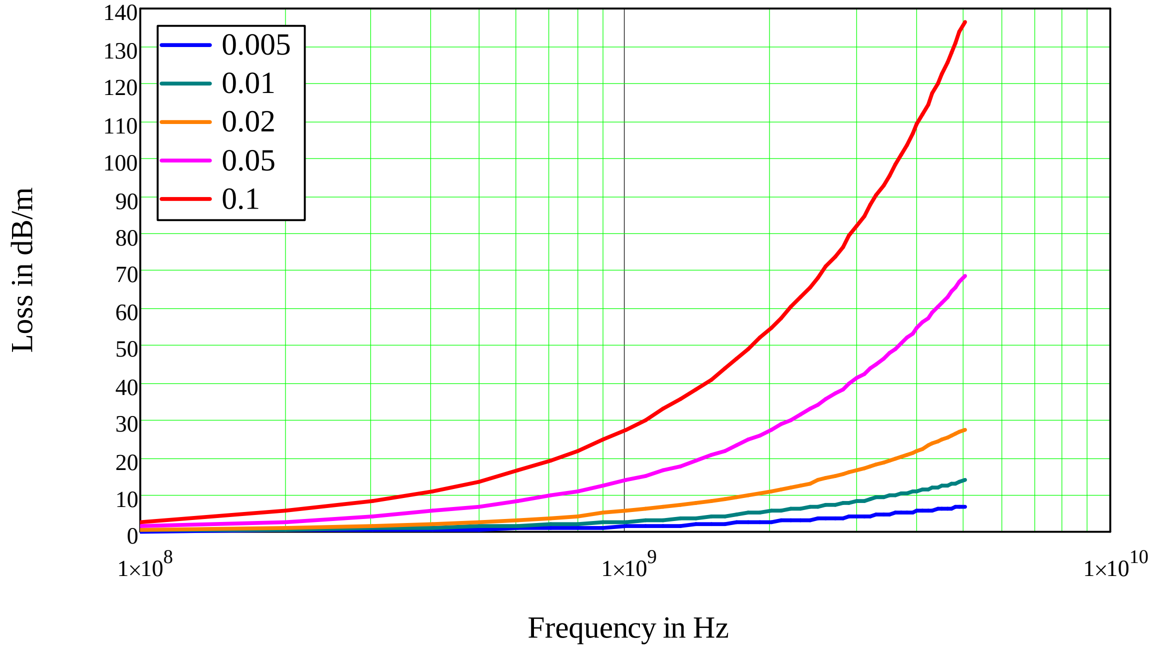

FIG. 2 – Material losses in dB per metre plotted against frequency in Hz for values of tanδ from 0.005 to 0.1

The impact of material attenuation on signal characteristics can be seen from the following simulation. A Ricker wavelet is the second differential of a Gaussian impulse and is typical of the radiated impulse from a GPR. Transmitting this through a lossy material is equivalent to passing through a low pass filter. The resulting effect on the time domain signal and the spectrum is shown in Fig. 3 and Fig. 4. The source wavelet is the transmitted waveform and the output the received waveform scaled by a factor of 2.94 and extended in time by 30%.

The effect on the spectrum is shown in Fig. 4 which shows the peak of the spectrum shifted to lower frequencies and the higher frequencies considerably reduced.

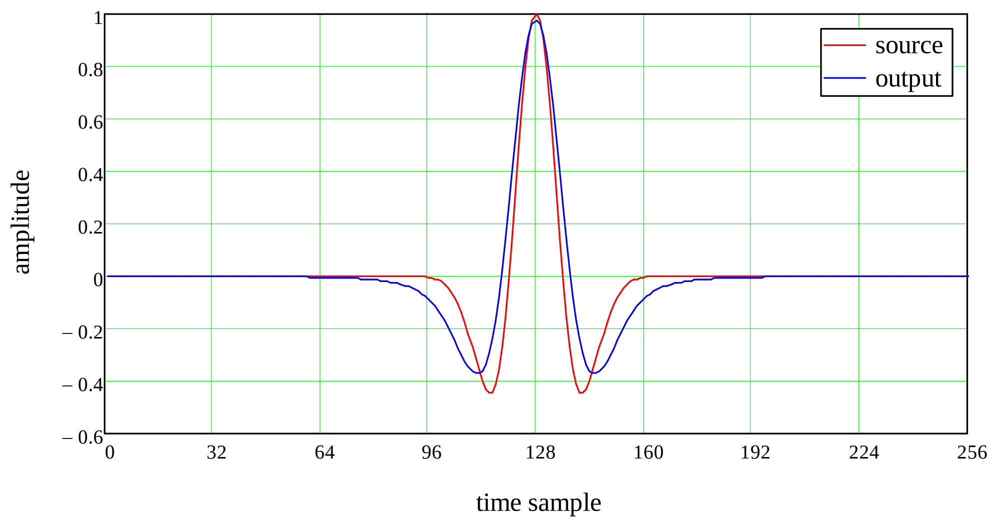

FIG. 3 – Effect of lossy ground on pulse amplitude and shape.

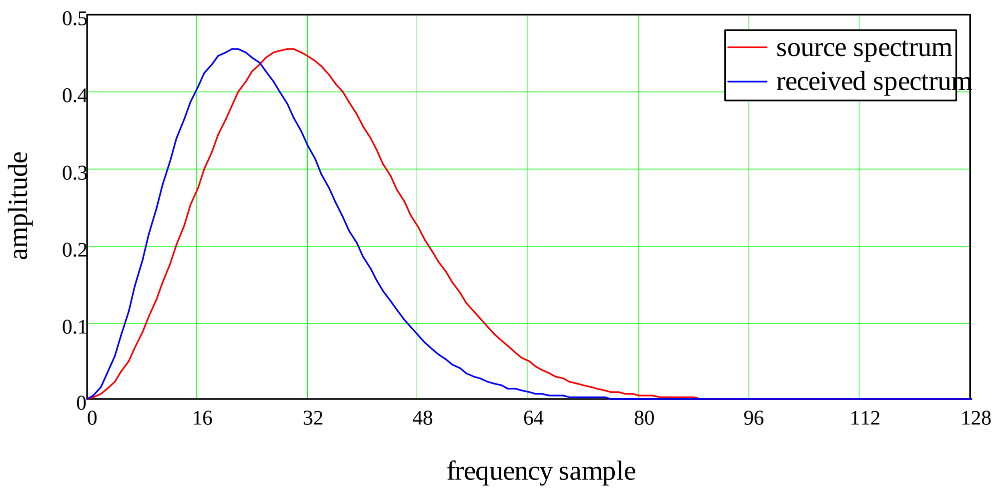

FIG. 4 – Spectrum of transmitted and received signals after passing through lossy ground.

The range resolution of GPR is generally set by the bandwidth of the received signal. When a number of features may be present, a signal having a larger bandwidth is required to be able to distinguish between the various targets and to show the detailed structure of a target. In this context it is the bandwidth of the received signal which is important, rather than that of the transmitted wavelet. The soil acts a low pass filter, which modifies the transmitted spectrum in accordance with the electrical properties of the propagating medium. There are some applications of GPR, such as road layer thickness measurement, where the feature of interest is a single interface. Under such circumstances, it is possible to determine the depth sufficiently accurately by measuring the elapsed time between the leading edge of the received wavelet provided the propagation velocity is accurately known. Although a greater depth resolution is achieved in wetter materials for a given transmitted bandwidth because of the reduced wavelength in high dielectric materials, earth materials with significant water content tend to have higher attenuation properties. This characteristic reduces the effective bandwidth, tending to balance out the change so that within certain bounds the resolution is approximately independent of loss within the propagating material. Where interfaces are spaced more closely than one half wavelength the reflected signal from one interface will become difficult to resolve with that from another. It should be noted that the normal Rayleigh criteria for range resolution is less appropriate for the case of a weak target adjacent to strong target and there is no accepted definition of resolution for the case of unequal size targets [3].

The plan resolution is defined by the characteristics of the antenna and the signal processing employed. In general, free space radar systems (apart from SAR), require a high gain antenna to achieve an acceptable plan resolution. This necessitates a sufficiently large aperture at the lowest frequency which is to be transmitted. To achieve small antenna dimensions and high gain therefore requires the use of a high carrier frequency, which may not penetrate the material to sufficient depth. When selecting equipment for a particular application it is necessary to compromise between plan resolution, size of antenna, the scope for signal processing and the ability to penetrate the material. Plan resolution improves as attenuation increases, provided that there is sufficient signal to discriminate under the prevailing clutter conditions.

Clutter

A major difficulty for operation of GPR systems is the presence of clutter within or on the surface of the material or in the side and back lobes of the antenna. Clutter is defined as unwanted reflections that occur within the effective bandwidth and search window of the radar and present as spatially coherent reflectors. Animal burrows, cracks in the ground are examples of features that will cause reflections. Careful definition and understanding are critically important in selecting and operating the best system and processing algorithms. Clutter can completely obscure the buried target and a proper understanding of its source and impact on the radar is essential. A key issue is the effect on the signal of variations in the topography of the ground surface caused by pothole or ruts. Methods of processing the radar signals that adjust the delay time to the front surface to “flatten it” will actually distort the radar signature of buried targets. Abrupt discontinuities can also cause multiple reflections, which become superimposed on later arriving reflected energy. Such “interference” will be extremely difficult to remove.

Comparison of modulation techniques

A useful comparison of the relative performance of modulation techniques has been carried out by Hamran [4] who showed that the intrinsic performance of different types of radar modulation schemes is related to the process by which the information in the reflected signal is sampled. Ideally all the information should be sampled in one process, whereas time domain and frequency domain systems employ a range of down sampling techniques that are sub optimal. Assuming that the system dynamic range [SDR] is fundamentally defined as the ratio between the peak radiated power from the transmitting antenna and the minimum detectable peak signal power entering the receiver antenna, Hamran showed that different radar system could be analysed by considering the average transmitted power and the receiver noise figure provided the receiver is matched to the transmitted waveform. Where this is not the case, a correction for mismatch loss needs to be introduced. Hamran’s comparison assumed identical radiated power spectral density, receiver integration times, antenna gains and receiver noise figures at T = 300K, noise figure F = 5, system gain of G = 10, and a signal to noise ratio of 25.

The limitations to the system performance are in Table 2.

TABLE I - DYNAMIC RANGE CHARACTERISTIC OF GPR MODULATION TECHNIQUES

Description	Modulation	Dynamic range Uncorrected	Dynamic range Corrected	Limitations
Basic radar	Flash sampler	121dB	121dB	
Time domain	Sequential sampling	88 dB	88 dB	1, 2
Frequency domain	Step frequency	85 dB	121 dB	1, 2, 3, 4
Frequency domain	FMCW	85 dB	121 dB	1, 2, 4, 5
Noise	Noise	121 dB	121 dB	1, 2, 6,
Noise	Pseudo Random Coded	105 dB	105 dB	1, 2, 6, 7

TABLE II - LIMITATIONS TO GPR MODULATION SCHEMES

Note	Description
1	Antenna coupling and ring down
2	RX noise figure
3	Duty cycle
4	Sample window side lobes
5	Sweep linearity
6	Cross correlation window side lobes
7	Cross correlation sequence

From this it can be seen that the frequency domain radar systems offer the greatest potential radar system loop dynamic range. However the most common limitation that all modulation schemes suffer from is the antenna coupling and ring down issue as well as receiver noise figure.

Time domain systems

The majority of time domain radar systems use impulses of radio frequency energy variously described as baseband, video, carrier-less, impulse, monocycle or polycyclic. The radar is controlled by a master clock, which after a suitable time delay triggers a pulse generator, which generates pulses, typically of amplitude within the range between 10 V to 200 V with a pulse width within the range between 200 ps to 50 ns at a pulse repetition interval of between several hundred microseconds to one microsecond or less, depending on the system design, which are applied to the transmit antenna. It is quite feasible to generate pulses of several hundred kV albeit at long repetition intervals. A portion of the transmit signal is usually tapped off to provide an input to the sampling control to ensure timing stability of the signals fed to the sampling head. The radiated pulses propagate and are reflected from the target and are received by the receive antenna.

The output from the receive antenna is applied either to a flash A/D converter or a sequential sampling receiver. If the pulses are sufficiently long duration (> 10 ns) and the radar repetition rate is slow (> 100 ms) a flash A/D converter can be used. Where the pulses are shorter < 10 ns and the radar repetition rate is faster (< 100 ms), then a sequential sampling receiver is used. Alternative methods of data acquisition are based on high-speed analogue to digital converters or the cross correlate receiver. There are several methods of acquiring the high bandwidth RF signals output from the receiver; direct Analogue to Digital conversion using high speed (flash) A-D converters, frequency selection followed by high speed A-D conversion, or sequential sampling.

The stability of the timing increment is very important and generally this should be 10% of the sampling increment, however practically stability in the order of 10 ps to 50 ps is achieved. The effect of timing instability is to cause a distortion, which is related to the rate of change of the RF waveform. Evidently, where the RF waveform is changing rapidly, jitter in the sampling circuits results in a very noisy reconstructed waveform. Where the rate of change of signal is slow, jitter is less noticeable. Normally control of the sampling converter is derived from a sample of the output from the pulse generator to ensure that variations in the timing of the latter are compensated automatically.

The key elements of this type of radar system are the impulse generator, the timing control circuits, the sampling detector and the peak hold and analogue to digital converter. The impulse generator is generally based on the technique of rapid discharge of the stored energy in a short transmission line. One method of achieving this is by means of a transistor operated in avalanche breakdown mode used as the fast switch and a very short length of transmission line. However the avalanche process is statistical by nature and is accompanied by jitter and step recovery diodes provide a much better jitter performance.

The high speed sampling approach conventionally used to display fast waveforms produces a low S/N ratio because the spectrum of the sampling pulse is a poor match for that of the received pulse. Being an essentially non-selective filter, it allows large amounts of noise energy to enter the receiver. Also, the sampling circuit tends to add milliamp level unbalanced currents as well as sampling pulse noise to its output. Although a quite acceptable trade off for usual laboratory purposes, this may be unacceptable for receivers with sensitivity in the microvolt range.

Frequency Domain systems – FMCW radar

An FMCW radar system transmits a swept carrier frequency by means of a voltage-controlled oscillator (VCO) over a chosen frequency range on a repetitive basis. The received signal is mixed with a sample of the transmitted waveform and results in a difference frequency which is related to the phase of the received signal hence its time delay and hence range of the target. The difference frequency or intermediate frequency (IF) must be derived from an I/Q mixer pair if the information equivalent to a time domain representation is required as a single ended mixer only provides the modulus of the time domain waveform.

In essence, the FMCW radar measures the phase of the IF signal which is directly related to target range. The frequency of the IF signal can be regarded as a measure of range. An inverse complex frequency-time transform is used to reproduce a time domain equivalent to the impulse radar, but most frequency domain radars display a signature as shown in Fig. 5. The effect of windowing the IF waveform is significant and the unwindowed case gives rise to the well-known sinc ($\sin(x)/x$) function. This limits the dynamic range of the receiver, whereas a windowed case can potentially achieve a better dynamic range albeit at the disadvantage of reduced resolution as shown in the lower part of the graph. It can be seen that the close in sidelobes are some -15 dB for the rectangular window and decrease to less than –40 dB for the Hamming window. This enables smaller targets close in range to a larger target to be detected.

FMCW radar systems are particularly sensitive to certain parameters; they requires a high degree of linearity of frequency sweep with time to avoid spectral widening of the IF and hence degradation of system resolution and practically a useful system should aim to keep all non-linearities less than 0.1% and ideally less than 0.01% [5].

Linearisation of the sweep was traditionally achieved by three well established methods; correction by means of an analogue correction for a known non-linearity, a digital look up table to correct the measured non-linearity and a dynamic correction technique using a delay line discriminator. The main difficulty with the first two methods is that the non-linearities are often temperature dependent, which then requires either temperature stabilization of a measurement of device temperature and a set of characteristics to cover the required temperature range. This is easier to achieve with a digital look-up table.

The oscillators that provide the sweep for an FMCW may be generated by a VCO which is driven by a voltage generated from a look up table that is pre-compensated for non linearities or alternatively a digital sweep generator produces a linear ramp signal using DDS techniques that is applied to a coarse tuning port of a high frequency tunable oscillator, such as a YIG tunable oscillator (YTO). A PLL has, as its inputs, an accurate linear swept frequency sinusoid from a DDS and a linear swept frequency output signal from the YTO to produce an error correction signal that is applied to a fine-tuning port of the high frequency tunable oscillator. The error correction signal compensates for any non-linearities introduced into the linear swept frequency output signal by the high frequency tunable oscillator.

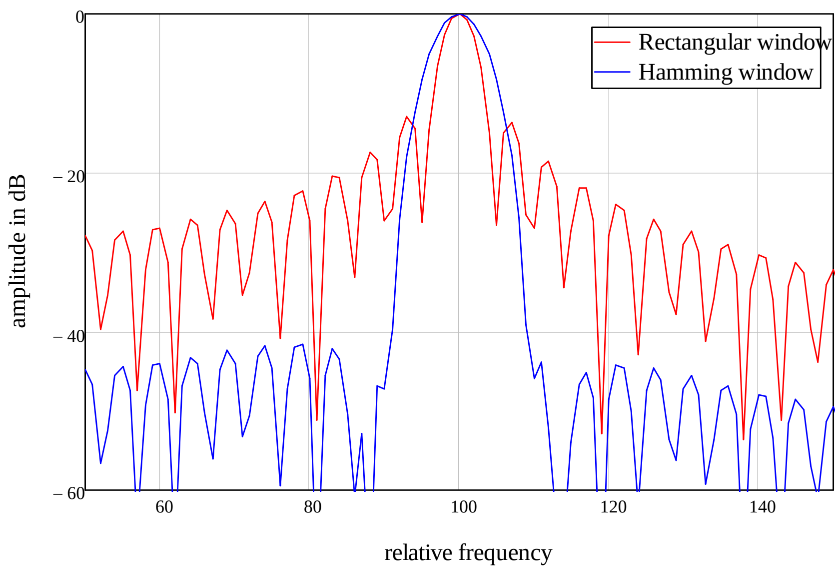

FIG. 5 – Effect of windowing on FMCW resolution and sensitivity.

Morgan et *al*. [6] compare the performance of a VCO and DDS and the effect on the range performance and concludes that DDS solutions offer better phase noise and better linearity, although spurious returns at multiple range are some 20 dB higher than the VCO solution.

The leakage that occurs between the transmitter and receiver antennas or via the circulator can have the unwanted effect of biasing the mixer into saturation and hence cause a reduction in system sensitivity and dynamic range. This problem can be partially solved by using an additional path to introduce a phase cancellation to reduce the leakage but this tends to be limited to narrower bandwidth systems. Another unwanted effect that for large targets the phase noise of the source then appears in adjacent range bins, completely saturating these and dominating any return echoes from smaller targets. In the worst case for close in targets this appears as radial lines on a PPI display and can increase the noise level over all the range bins at that angle on the display.

Other features of an FMCW radar system must also be considered. Changes in VSWR of the microwave components over the range of swept frequencies may cause "frequency pulling" of the transmit oscillator unless high levels of isolation are built in. Changes in VSWR can be caused by variations in antenna to sub reflector spacing or by changes in the characteristics of components such as the circulator or mixer. The amplitude-frequency transfer characteristics of all of the components in an FMCW radar system should be substantially flat. Ideally amplitude ripple levels should be less than ± 0.25 dB otherwise the radiated waveform will exhibit an amplitude modulation which will cause spectral spreading of the IF waveform with a resultant loss of solution and system performance.

The greater dynamic range of the FMCW radar is a significant advantage provided that the sweep linearity can be maintained and the spectral broadening and sidelobes of the IF envelope minimized.

Frequency Domain systems – Stepped frequency radar

SFCW radar radiates a sequence of frequencies in regular increments ranging over a defined bandwidth. Any repetitive pulsed signal can be transformed to a frequency domain representation, which consists of line spectra whose frequency spacing is related to the pulse repetition rate and envelope is related to the pulse shape. Hence, a repetitive impulsive waveform can be synthesized by transmitting individual frequencies whose amplitude and phase is accurately specified. The main advantages of the SFCW radar are its high dynamic range (> 100 dB) and low noise floor as well as the ability to avoid certain frequencies when transmitting, thus making compliance with licensing and interoperability requirements much easier than most other types of modulation.

The optimum step frequency signal for SFCW radar is described by Cherniakov [7] who proposed that the optimum received signal is one which results in an equal signal to noise ratio per spectral line taking into account the soil losses. In effect the transmitted spectrum is weighted to ensure that the SNR per spectral line is a constant. A further extension of this proposition is to iteratively modify the weighting of the transmitted spectrum at a limited number of spectral lines to maximize the energy/SNR cost function.

Compared with time domain radar systems, SFCW radar offers the potential advantages of greater dynamic range [Δ = 30 dB], increased mean output power [subject to license restrictions], spectral shaping and high configurability particularly in terms of bandwidth and spectral occupancy. Configurable spectral occupancy may well alleviate compatibility issues related to operation physically adjacent to other sources of EM radiation. Step frequency radar also offers the possibility of calibrated compensation of antenna response. Other modulations techniques such as COFDM, noise or pseudo random coded each have limitations and hardware challenges that do not make them immediately attractive. Even with an improved radar design it will still be necessary to develop antennas more suited for vehicle applications and with a rate of ring down better than the current design.

However, SFCW has a number of intrinsic design challenges which, if not addressed, potentially limit its suitability as a ground penetrating radar system. These are:

- speed of the transmission of the spectrum;
- settling time of the transmitted spectral lines;
- saturation of the receiver during the transmission of the spectral lines;
- intermodulation and higher order mixing products in the receiver mixer;
- system complexity;
- stability of system calibration;
- power consumption;
- signal processing.

Noise modulated systems

Noise modulated radar offers some very attractive possibilities to the designer of GPR systems. The radiated power is evenly spread throughout the spectrum and the receiver is less susceptible to interference. However until recently such systems were relatively rare. Developments over the last few years are changing that situation and more efforts are being put into the development of noise radar systems. The basic principle of operation of noise radar is that of a correlator. The radar transmits a noise or Pseudo Random Coded signal and the received signal is a time delayed version τ_S of the transmitted signal. In the receiver the transmitted signal is used via a variable delay τ_v to cross correlate the received signal. Some of the key design issues in terms of noise radar are the ambiguity function and the range sidelobe suppression. Dawood and Narayanan [8] consider the underlying issues in terms of optimizing the ambiguity function. They developed an ultra wideband (UWB) random noise radar system, which transmits an ultra wideband random noise (Gaussian) waveform with uniform power spectral density (PSD) in the 1-2 GHz frequency range. They showed that for a random noise radar a correlator matched to the transmit process is required and that for a UWB transmit random process, the compression or stretch due to the range rate on the envelope of the return process cannot be ignored.

The key issue for such correlator receivers becomes the sidelobe levels which can have the unfortunate effect of masking weak signals by the sidelobes of strong signals.

Spatially modulated systems

Single frequency methods of imaging are based on the technique of viewing the target from a number of physically different positions in an aperture over the target and recording the amplitude and phase of the received signal and then mathematically reconstructing an image of the target. The process may be either holographic, whereby the recorded field represents the scattered field at a plane or tomographic, whereby the recorded field is that of the transmitted field through the target at all angles of view.

The drawbacks to the process are that accurate positioning of the antenna elements is required and this usually involves mechanical positioning of either the transmitter and receiver elements or both. The accuracy of measurement in terms of amplitude and phase are key factors in the quality of the image reconstruction. This imposes a practical limitation on operational situations, but may be useful either where the position of the target can be controlled or the target can be viewed at all sides as in a tomographic image. Where the target has multiple layers of different velocities of propagation, as might be the case for a human, the solution of the forward propagating wave paths as a function of view angle is non-trivial.

The differences between optical holography and radar holography appear to lie in the way in which the wave field is recorded. In the case of the optical hologram the image plane comprises the forward scattered field as shown in Fig. 6. In the case of radar system the recorded field comprises the backscattered field and this may of course not be the same as the forward scattered field.

The effect of material attenuation is significant as the general effect is to apply a windowing function across the recording aperture thus limiting its useful size in relation to sharply focused images as shown in Fig. 7.

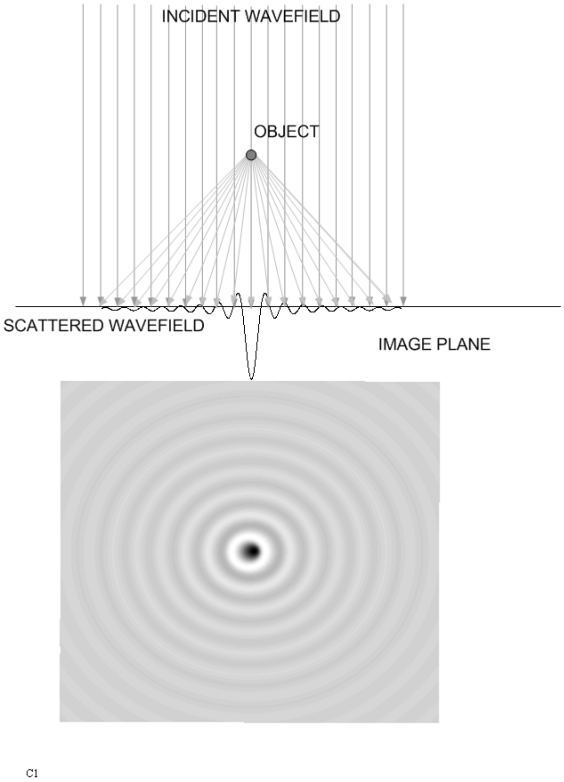

FIG. 6 – Holographic recording.

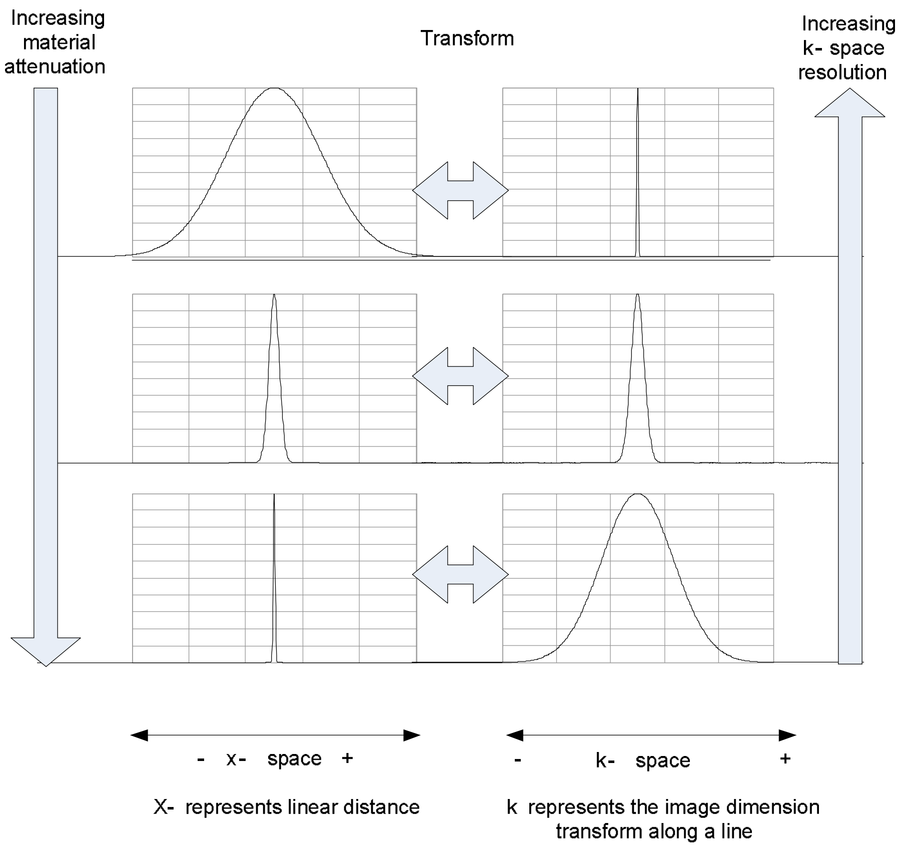

FIG. 7 – Effect of material attenuation on radar synthetic aperture image.

In addition, the effect of both material attenuation and relative permittivity on the antenna beamwidth should be considered. As the values of loss and relative permittivity increase the beamwidth of the antenna reduces and this degrades the gain of the synthetic aperture. In general, synthetic aperture methods are most useful in lower loss materials.

Reference [9] notes that holographic radar receives a signal amplitude that decreases with the range law and material attenuation hence penetration depth depends on the attenuation in the surveying medium, and the target reflectivity with the added complication that targets at short range will obscure targets at deeper range in the recorded images. This phenomena may be exploited as the ability to detect targets at very short ranges is far better than conventional GPR systems.

III. ANTENNA DESIGN CHALLENGES

Introduction

GPR antennas are generally operated in three distinct modes with respect to the ground surface.

A. Those operated close [< 10 cm] to the ground surface, usually with a zero angle of incidence could be termed "Proximal antennas".
B. Those operated 0.1-1m from the ground surface, usually with a zero angle of incidence could be termed "Close in antennas".
C. Those operated > 5m from the ground surface usually at a slant angle could be termed "Standoff antennas".

GPR is generally operated so that the antenna is very close to the ground surface such that the energy transfer is predominantly either in the induction or quasi-stationary radiation region (the near field). Some workers have reported detection by means of evanescent wave propagation and it may also be possible to exploit lateral waves. When the antenna is closely coupled into a dielectric the radiation characteristics of the antenna is affected to a considerable extent and the pattern in the dielectric is different to that in free space. The propagation path consists in general of a lossy, inhomogeneous dielectric, which, in addition to being occasionally anisotropic, exhibits a frequency dependent attenuation and hence acts as a low pass filter.

The upper frequency of operation of the antenna, and hence the GPR system, is therefore limited by the properties of the material. The need to obtain a high value of range resolution often requires the antenna to exhibit ultra-wide bandwidth, and in the case of impulsive radar systems, linear phase response.

The requirement for wide bandwidth and the limitation in upper frequency performance are mutually conflicting and hence a design compromise is adopted whereby antennas are designed to operate over some portion of the frequency range 10 MHz to 5 GHz depending on the resolution and range specified.

Stand-off GPR systems can be operated such that the energy transfer is in the far field region and this in turn brings challenges of energy transfer and above ground clutter rejection.

There are a number of requirements for frequency independent operation and these are as follows:

Excitation of the antenna from the region of the antenna from which high frequencies are radiated.

- A transmission region formed by the inactive part of the antenna between the feed point and the active region. This zone should produce negligible far field radiation.
- An active region from which the antenna radiates strongly because of an appropriate combination of current magnitude and phases.
- An inactive region created by means of reflection or absorption beyond the active region. It is essential that there is a rapid decay of currents beyond the active region. Efficient antennas achieve this by means of radiation in the active region whereas the less efficient use resistive loading techniques to achieve this characteristic.
- A geometry defined entirely by angles i.e., the biconical dipole, conical spiral, planar spiral maintain their performance over a frequency range defined entirely by their limiting dimensions, subject to an extended impulse response.

The two general types of antenna that are useful to the designer of GPR fall into two groups: non-dispersive antennas and dispersive antennas. Examples of non-dispersive antennas are the TEM Horn, the bicone, the bow-tie, the resistive, lumped element loaded antenna or the resistive, continuously loaded antenna. Examples of dispersive antennas that have been used in GPR are the Exponential spiral, the Archimedean spiral, the logarithmic planar antenna, the Vivaldi antenna and the exponential horn.

Element antennas such as monopoles, dipoles, conical antennas and bow-tie antennas have been widely used for GPR applications. Generally they are characterized by linear polarization, low directivity and relatively limited bandwidth, unless either end loading or distributed loading techniques are employed in which case bandwidth is increased at the expense of radiation efficiency.

Various arrangements of the element antenna have been used such as the parallel dipole and the crossed dipole, which is an arrangement that provides high isolation and detection of the cross-polar signal from linear reflectors.

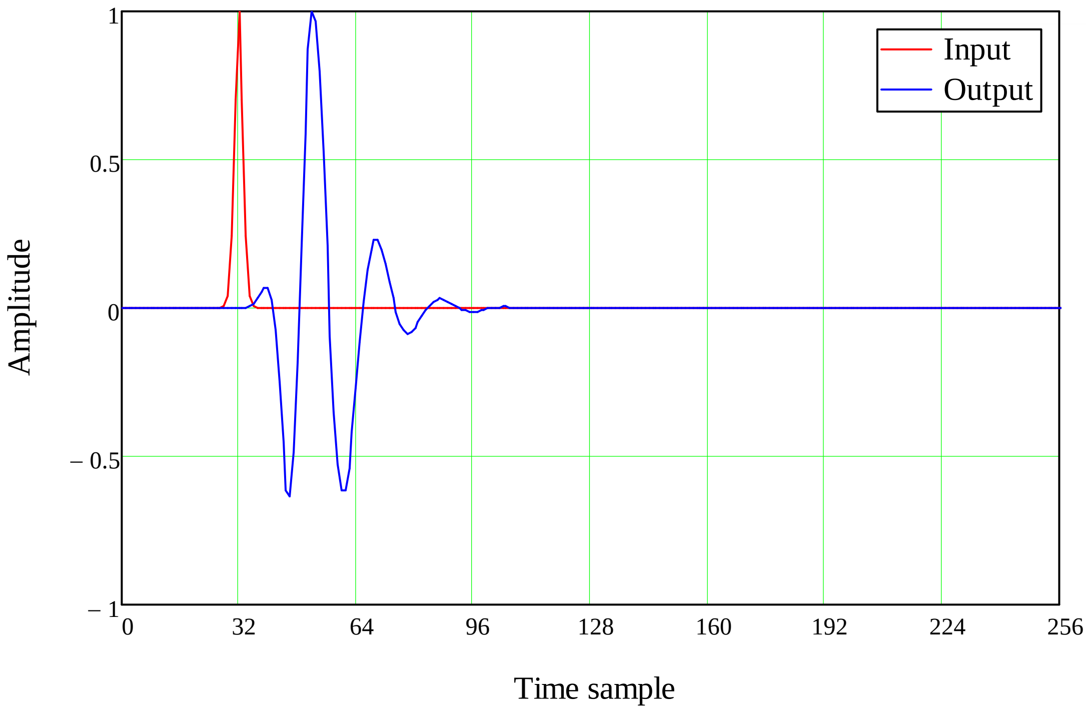

FIG. 8 – Impulse response of an antenna to an applied Gaussian input.

A typical antenna used in an impulse radar system would be required to operate over a frequency range of a minimum of an octave and ideally at least a decade, for example, 100 MHz - 1 GHz. All of the antennas used to date have a limited low frequency performance unless compensated and hence act as band pass filters, thus the current input to the antenna terminals is radiated as a differentiated version of the input function. In general it is reasonable to consider that the far field radiated electric field is proportional to the derivative of the antenna current.

The input voltage driving function to the terminals of the antenna in an impulse radar is typically a Gaussian pulse. The impulse response of the antenna is required to be short because it is important that the antenna does generate time sidelobes. These would obscure weaker targets that are close in range to the target of interest, hence both the resolution and detection performance of the radar can become degraded if the impulse response of the antenna is significantly extended. If the antenna is considered to be a bandpass filter then an examination of the impulse response illustrates the issue. In Fig. 8 the output response of a typical antenna is modelled using a 22 coefficient Hamming FIR filter and a 10th order IIR Butterworth filter with their respective low and high frequency cutoff values set to mimic a typical loaded dipole response. The impulse response plotted on a linear scale is typical of many GPR systems and at first sight looks acceptable , however if the impulse response is plotted on a dB scale as shown in Fig. 9 then the issue of time sidelobes becomes immediately obvious.

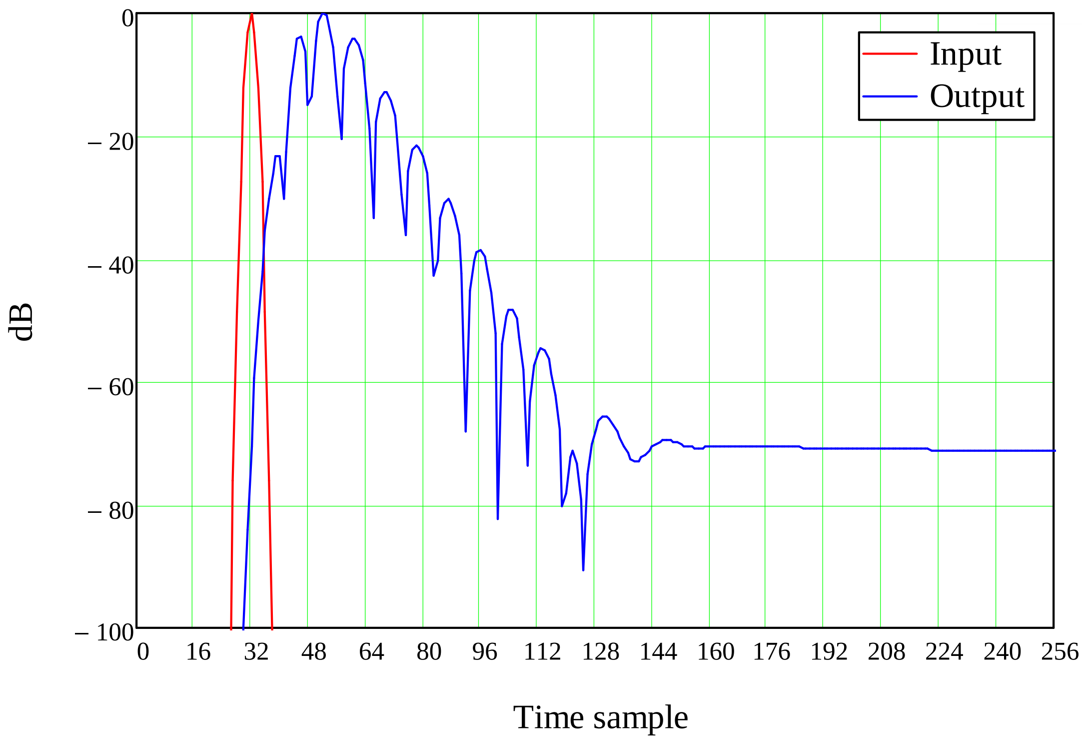

FIG. 9 – Impulse response of an antenna to an applied Gaussian input plotted in dB.

The energy stored in the antenna decays gradually and hence limits the detection of targets at greater range that are subject to attenuation and spreading loss. Hence the GPR has a limit to detection performance that is set by the slope of the time sidelobe rate of decay.

The requirement for portability for the operator means that it is normal to use electrically small antennas, which consequently result generally in a low gain and associated broad radiation patterns. Valle et *al*. [10] considered the theoretical and experimental directivity functions for antennas for ground penetrating radar. The classes of antennas that can be used are therefore limited, and the following factors have to be considered in the selection of a suitable design; large fractional bandwidth, low time sidelobes and in the case of separate transmit and receive antennas, low cross coupling levels. The interaction of the reactive field of the antenna with the dielectric material and its effect on antenna radiation pattern characteristics must also be considered.

Range or Time sidelobes

The observation about the time sidelobes is also relevant to frequency domain systems as unless the energy in the transmitted waveforms packet can be constrained in time or range the result is a radar that is unable to detect targets with a small radar cross section at longer ranges or time in the presence of a larger target such as the ground surface.

Most antennas have a rate of ringdown in the order of 10 dB per nanosecond, but if this could be increased to 20 dB per nanosecond the GPR detection performance would be usefully improved. This is therefore a topic worth further research and development and would radically improve GPR performance.

Coupling into the soil

Most antennas are designed to have a radiation impedance near to that of free space which has a characteristic impedance of 377 Ω. Many soils has a frequency dependent characteristic impedance which lies in the range of 50 to 200 Ω and the variability of the ground impedance is a source of variable loading and mismatch as well as a poor power transfer. For proximal operation could a low impedance aperture reduce the effect of ground loading and mismatch effects? While this was considered many years ago with *H* field antennas, perhaps further consideration could be given to methods of improving the efficiency of energy transfer. Assuming that the wideband performance can be maintained, are techniques such as focusing using 2 layer Double Negative materials with $\varepsilon < 0$, $\mu < 0$ as described by Engheta and Ziolkowski [11] worth investigating.

Multiple reflections between the antenna and the soil

When the antenna is some tens of centimeters above the ground there is a need to reduce the reflection seen by the reflected wave when it returns and meets the receive antenna. This situation is the cause of multiple reflections between the antenna aperture and the ground surface.

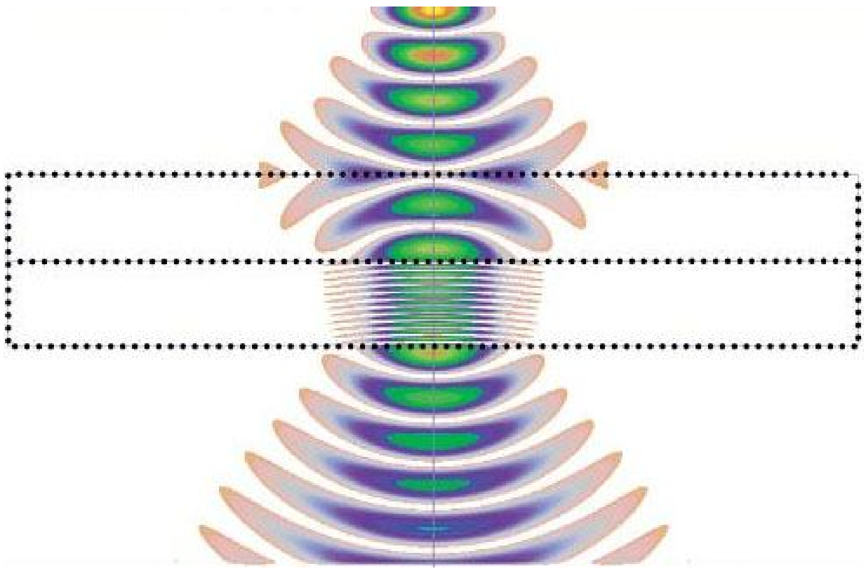

FIG. 10 – DNG slab lens with negative refractive index materials η = -1 and η = -6.

For standoff and close in operation could a high impedance aperture make the antennas apertures partially invisible to the incoming wave and hence reduce multiple reflections? Alternatively could novel absorbing screen techniques aid in reducing multiple reflections between the ground and the antenna?

Engheta proposed a thin absorbing screen [in contrast to a l/4 Salisbury screen] comprised of a metamaterial with high surface impedance [*R* = +1] based on a dielectric layer backed by a conductive ground plane on which is placed a thin resistive sheet as a means of reducing back reflections.

A further possibility in antenna design particularly for resistively loaded antennas in proximal operation is to adapt the resistive loading to the material impedance by changing the resistive loading of the antenna using MEM switches. This might improve GPR performance with respect to antenna ringdown and multiple reflections.

Optimization of antenna characteristics

In addition to the issues referred to in the previous sections, environmental clutter is also a limitation that is predominantly caused by lack of directivity and the associated back and sidelobe levels from most antennas. Therefore methods of minimizing back and sidelobes levels are a useful area of for further development. As an example consider a 3 mm long monopole antenna mounted on a 50 mm ground plane operating at 35 GHz as described by Sievenpiper et *al*. [12]. The use of a high impedance surface radically reduce the surface waves that radiate at the edges of the ground plane and provide a much better radiation pattern. The challenge is to achieve this improvement over a wide bandwidth and one of the issue with forbidden band approaches is the limitation this implies in terms of frequency. In addition to improvements in radiation performance the use of high impedance surfaces may also enable smaller antenna to be designed.

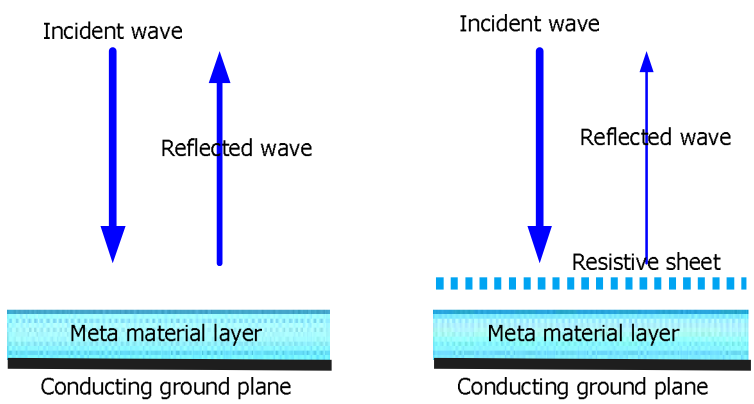

FIG. 11 – Minimisation of multiple reflections.

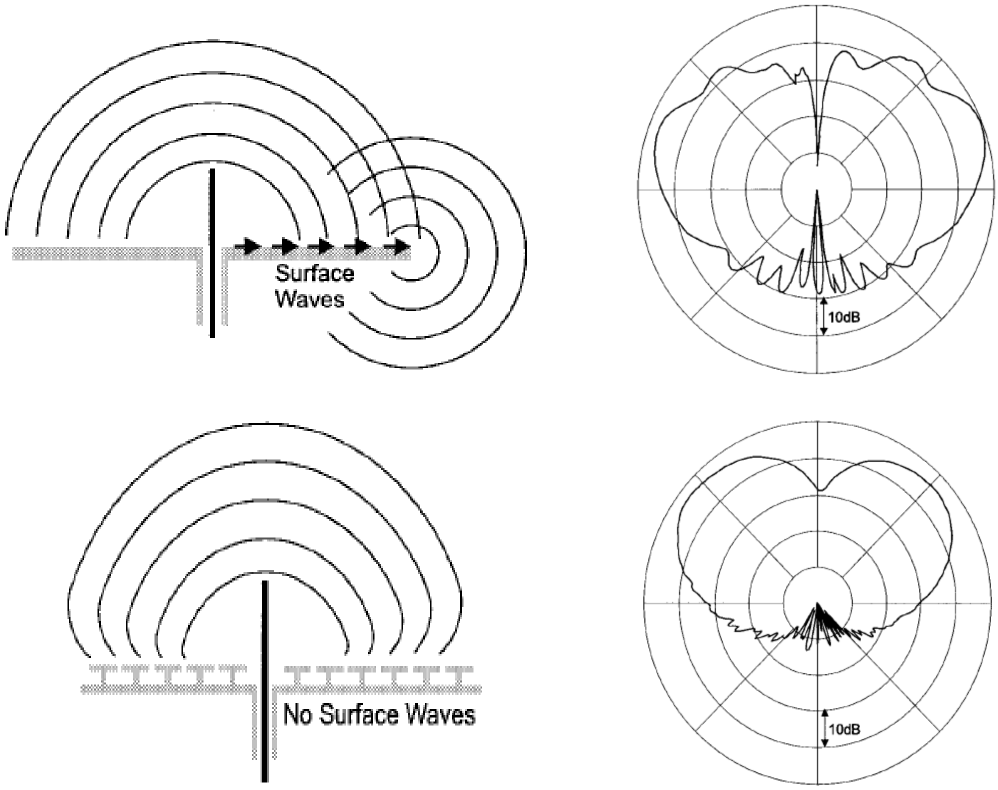

FIG. 12 – Reduction of antenna side and back lobe levels using high impedance surfaces

Single antenna versus dual antennas

The majority of GPR systems use two antennas, one for transmit and one for receive, because apart from a few applications, the very short time ranges provide a major challenge to the antenna and system designer. A single antenna is potentially more attractive because it reduces the size of the GPR and minimizes some of the deficiencies associated with dual antennas. However, in order to use a single antenna, certain design requirements need to be met. The receiver needs to be isolated from the transmit pulse and in a conventional radar this is achieved using a T/R switch. However for GPR the switching times need to be sub nanosecond if real time operation is required and the requirements for high isolation and low switching breakthrough are very demanding. Because of this situation very few GPRs use a single antenna with a T/R switch for short range applications. There is therefore an opportunity to develop such a component or an alternative way of operating with a single antenna. Alternatives to using a T/R switch are often found in the frequency domain where a circulator is used and in the time domain where a precision RF bridge/coupler is used to provide isolation between the receiver and the transmit signal/pulse by virtue of the high directivity of the precision RF bridge/coupler.

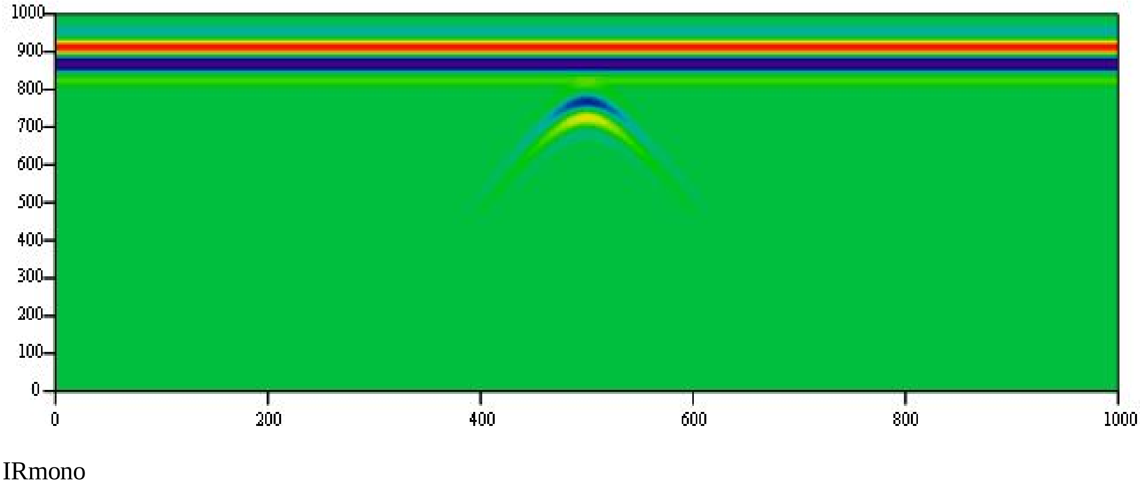

FIG. 13 – Simulation of single antenna GPR, target depth 100 mm, *x* scale 1000 mm, *y* scale 1000 mm.

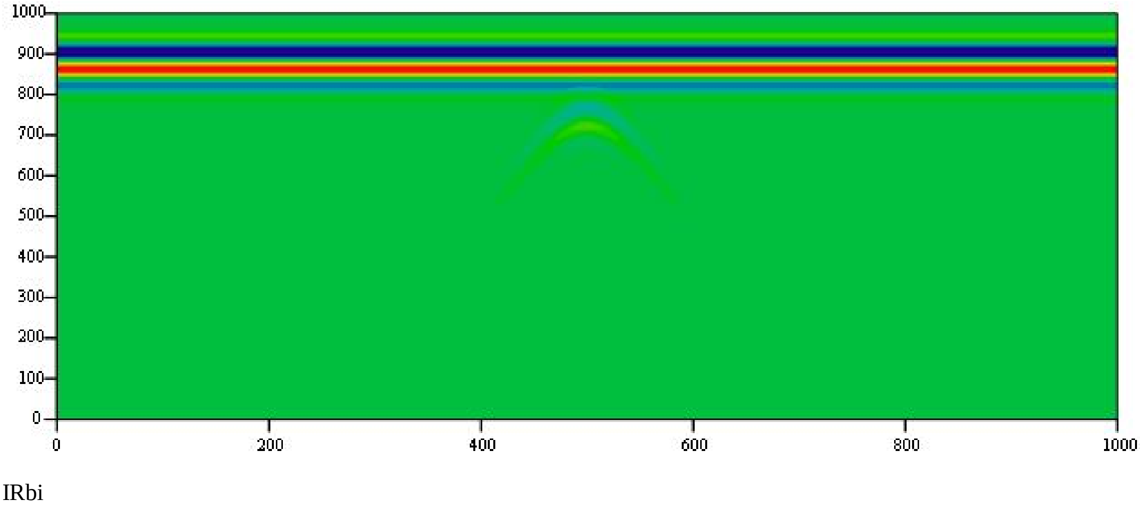

FIG. 14 – Simulation of dual antenna GPR, target depth 100 mm, *x* scale 1000 mm, *y* scale 1000 mm.

Simulations of a single antenna and dual antenna GPR using a point target are shown in Fig. 13 and Fig. 14.

The key differences between the two are as follows; the dual antenna GPR creates a hyperbolic spreading function which is narrower than the single antenna GPR by virtue of the separation between the elements. The amplitude of the received signal from the target is marginally greater by 10% in the case of the single antenna GPR although the auto scaling of the graphs has emphasized the visual difference. However the inherent isolation of the dual antenna GPR is much greater than the single antenna GPR and in order the achieve the same detection performance the single antenna GPR has to process the received A scan such that the internal reflections from the antenna and the reflection from the ground surface is reduced by at least -45 dB which the simulation includes. Some of this might be achieved by good matching of the antenna s11 parameter but a reduction of the reflection from the ground surface by at least -45 dB is demanding. It should also be noted that the single antenna configuration minimizes the duration of the energy associated with the reflection from the ground surface and antenna coupling in the dual antenna case due to the reduction of the associated time delays.

Array antennas

Vehicle based or airborne systems use much larger arrays of antennas to illuminate a swathe of the ground surface ahead of the platform and rely on the movement of the vehicle to create the down track data, which is single pass. Both the down track and cross track data may be processed using SAR techniques. Where the antenna elements are relatively close to the ground, the path losses encountered by off nadir elements may limit the SAR gain that can be achieved. As the array elements are generally fixed in position, changes in ground topography in both cross track and down track affect the path propagation and influence the type of signal processing that can be applied. This is illustrated in Fig. 7 and places an inherent limit on SAR performance for close in antenna array configurations. It may be worth considering a partial SAR process whereby only sub arrays are used.

IV. Signal Processing

Signal processing is primarily a means of reducing clutter. Fundamentally, the signal to clutter ratio of the radar data is the key to target detection. Most system noise in GPR systems can be reduced by averaging. GPR is heavily contaminated by clutter and reduction of this is a key objective.

The cost-benefit of implementation should be clearly demonstrated before superficially attractive but practically unsound methods are incorporated. Clearly, the wide range of targets, applications and situations encountered is likely to task even the most robust algorithm and the user should assess the real benefit of latest algorithm with some care.

The general objective of signal processing as applied to GPR is to present either an image that can readily be interpreted by the operator or to classify the target return with respect to a known test procedure or template.

The image of a buried target generated by a GPR radar will not, of course, correspond to its geometrical representation and this fact needs to be made clear to those considering the use of GPR but who are unfamiliar with the physics. The fundamental reasons for this are related to the ratio of the wavelength of the radiation and the physical dimensions of the target. In most cases for GPR the ratio is close to unity. This compares very differently with an optical image, which is obtained with wavelengths such that the ratio is considerably greater than unity.

In GPR applications, the effect of combinations of scattering planes, for example, the corner reflector, can cause “bright spots” in the image and variations in the velocity of propagation can cause dilation of the aspect ratio of the image. While many images can be focused to reduce the effect of antenna beam spreading, re-generation of a geometric model is a much more complex procedure and cost benefit of the exercise should be very carefully examined.

The main signal processing methods used in GPR are shown in Fig. 15, Fig. 16 and Fig. 17. Wavelet deconvolution or “spiking” may be an area of investigation worth further effort.

It is worth noting that practically most robust processing techniques are limited in the improvement they can achieve in other than very carefully controlled conditions.

V. APPLICATION CHALLENGES

Earthquake victims

GPR has been proposed for the detection of the victims of earthquakes. However the conditions resulting from earthquakes are almost the worst from the point of view of clutter for GPR.

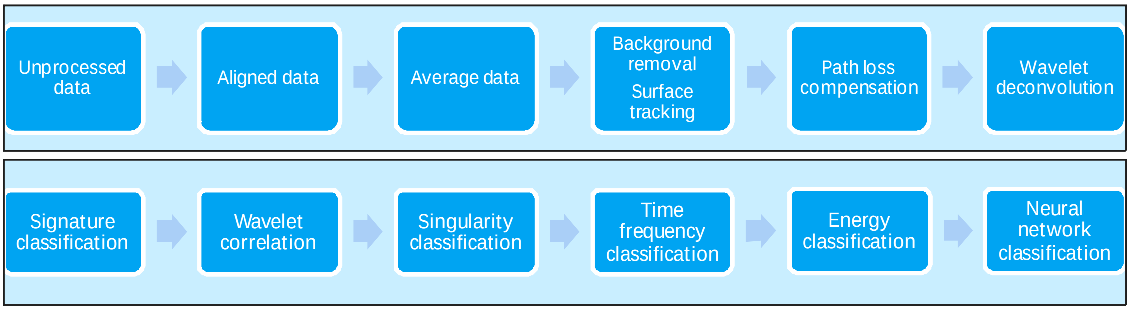

FIG. 15 – A-scan processing techniques.

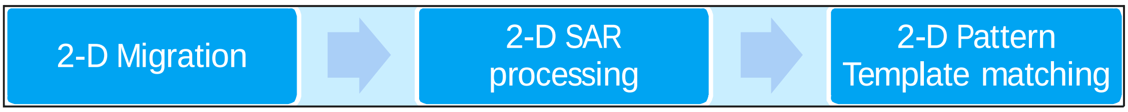

FIG. 16 – B-Scan processing techniques.

FIG. 17 – C-Scan processing techniques.

The remains of buildings are completely inhomogeneous, comprising multiple reflectors at different angles, voids and a topography of the front surface that limits the application of standard signal processing techniques. However Doppler radar systems have been extensively investigated for the detection of the victims of earthquakes as reported by Aggelopoulos et *al*. [13], Boric-Lubecke et *al*. [14], Chen et *al*. [15], Droitcour et *al*. [16], [17], Lohman et *al*. [18], Lubecke et *al*. [19], Lin [20]-[22], Park et *al*. [23], Xiao et *al*. [24] and Zhou et *al*. [25] who all describe various systems and experimental results. The velocities of typical human actions are 0.45 ms^{-1} for movement of the heart and 0.01ms^{-1} for breathing. At 1 GHz the Doppler frequency for human breathing is less than 0.1 Hz and this low frequency poses challenges for the design and operation of the radar in that it must remain very stable and noise free while measurements are being taken. In addition the signal generated by observers and detected in the back lobes of the antenna may be larger than that of the subject. Standard GPR is therefore not immediately suitable because its inherent high range resolution will encounter high levels of clutter, however if a GPR is able to process the Doppler information from targets, this will be means of drastically reducing the clutter levels and enable the detection of those victims who may still be alive.

Landmines

Landmines and improvised explosive devices [IEDs] are devices used to frustrate and slow down the maneuverability of military forces; their effect is also to deny civilians access to agricultural land and their means of livelihood. The injuries suffered by those maimed by these weapons are traumatic and in spite of the Ottawa Treaty their use and deployment continues. Generally these weapons are inexpensive to manufacture and emplace, and those deploying these weapons have an inherent economic and tactical advantage over those detecting and neutralizing them. The challenge in both military and civilian situations is to be able to detect and neutralize these weapons at an economic cost, and understand the networks that facilitate their deployment. Many of the landmines and IEDs encountered in affected countries are metallic mines, but some proportion of plastic or minimum metallic mines and IEDs can be found in a variety of countries and terrains and have proven to be highly effective at inhibiting the operation of conventional forces, because they are difficult to detect. GPR has been used very successfully for handheld applications for both humanitarian and military landmine and IED clearance [26]. In humanitarian applications, there is similar interest in use of robots for clearance of mine-affected land, although for now, mine clearance is still carried out by hand. Recent trials by HALO in Cambodia using a hand-held dual-sensor system (GPR and metal detector) have demonstrated that it is possible to achieve a 90% reduction in false identifications compared with a metal detector alone. This is a key benefit of GPR, since it increases the rate of clearance, which is allows more land to be put back to productive use or returned to the local inhabitants of mine affected areas. Although GPR for landmine technology is mature, it is capable of further development to enable continued classification of evolving targets and continued reduction of the size, weight and power of equipment.

One potential application lies in the use of GPR mounted on small UAV's for use in areas such as roads where vegetation does not significantly obscure the ground. GPR systems have been developed for standoff operation mounted on unmanned airborne or vehicle platforms but payload and navigation issues proved a limitation in the past. In the airborne case initial proving trials in a manned aircraft showed that pattern minefields in dry sandy conditions could be imaged from heights of several hundred meters at 400 knots, whereas for vehicle based applications the low grazing angles limit standoff range to some tens of meters for shallowly buried targets. Airborne GPR is already used for the survey of glaciers where quite compact and lightweight radars have been developed. Recent developments in miniature navigation and control systems offer the prospect of improved flight control and navigation. An example of a system for search and rescue applications is given by Erdos et *al*. [27] who successfully integrated sensors, navigation and communications sub systems into a commercially available RC aircraft. The challenge was to search an area 3 km by 4 km and deliver a 500 ml bottle of water close to the target and the project successfully completed the practice, qualification and tuning flight phase.

Such system capability may be appropriate for the GPR survey of roads for landmines provided both GPR sensors and accurate height keeping radar can be developed and integrated into robust flight platforms.

VI. GROUND TRUTH AND CONFIDENCE

Many publications relating to GPR provide limited statistical information relating to ground truth and target detection performance and a greater emphasis on this aspect of GPR would benefit the technique. In the case of an initial test of the GPR, the position and identity of buried targets should be hidden from the operator, so that clues are not inadvertently revealed by either ground sign or the test administrators. This is routinely done in the case of GPR for landmine detection and road condition assessment. In the case of geological features or roads, a robust method of assessing the performance of GPR against known phenomena must be a precursor to acceptance of performance claims. This would normally include the comparison of GPR results with those obtained by borehole data without the release of the latter information to the GPR operator or data analyst until after the GPR interpreted results and the borehole interpreted results are delivered to an independent third party for comparison (double-blind).

A well designed test will use a variety of stratagems to ensure the GPR operator cannot obtain visual clues from disturbed surfaces to infer the position of target(s) when data are processed. The GPR operator may wish to ascribe levels of confidence in classifying targets rather than a simple yes or no decision. Once the test data is available it should be analyzed in standard ways as described below.

Key parameters in assessing the performance of any detection system is its Probability of Detection (PD), the Probability of False Alarm (PFA) as well as the confidence that can be placed in the claimed PD and PFA. A standard method of describing the behavior of any process is based on an extension of basic statistical testing embodied in the term “receiver operating characteristic” [ROC] which originated from tests of the ability of World War II radar operators to determine whether a blip on the radar screen represented an object (signal), clutter or noise.

The ROC curve is another way of understanding the performance of a sensor and plots the true positive rate as a function of the true negative rate for different levels of sensitivity of the sensor. For example consider two populations, one due to true reports or detections and one due to false alarms, which are shown in Fig. 1 and labelled true and false respectively.

Their Gaussian population distributions have identical standard deviations, but different mean values. If a receiver detection threshold value were set to 5 then the majority of the true positive reports would be detected and a small proportion of true negative (false positive) reports would be included.

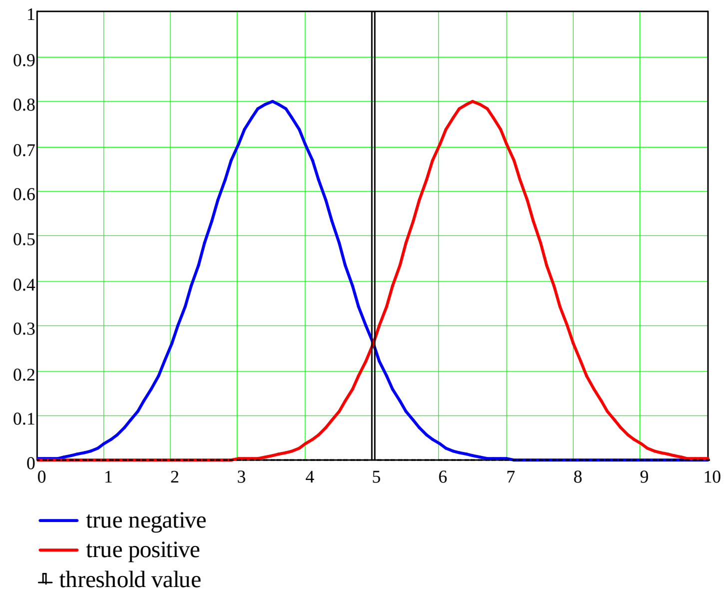

FIG. 18 – Distribution of true and false reports from a sample population.

This threshold can also be plotted as a pair of true positive/true negative reports or sometimes termed sensitivity/specificity parameters and this generates a receiver operating characteristic (ROC) curve. The ROC curve for Fig. 1 is shown in Fig. 2 and it can be seen that at a 0.95 true positive detection the false positive proportion is 0.1.

A test with perfect discrimination (no overlap in the two distributions) has a ROC plot that passes through the upper left corner (100% sensitivity, 100% specificity).

Therefore the closer the ROC plot is to the upper left corner, the higher the overall accuracy of the test.

The size of the sample must also be known in order to determine a confidence level in the result.

Elementary statistical sampling theory can be used to show that the confidence that can be placed in a test of a limited sample set is fundamentally related to the size of the sample set. If 10 tests are carried out on an equipment and even if all provide a positive report (a probability of detection of 100%), the statistical confidence in the claim is limited by the number in the set. At the 95% limit, the upper and lower confidence bounds can be derived from the Binomial Distribution and these are respectively 1 and 0.7.

In essence the smaller the data set, the less statistical confidence that can be ascribed to the results. At least 100 tests must be carried out to achieve a statistical confidence of 95% for a claimed Probability of Detection of 97%.

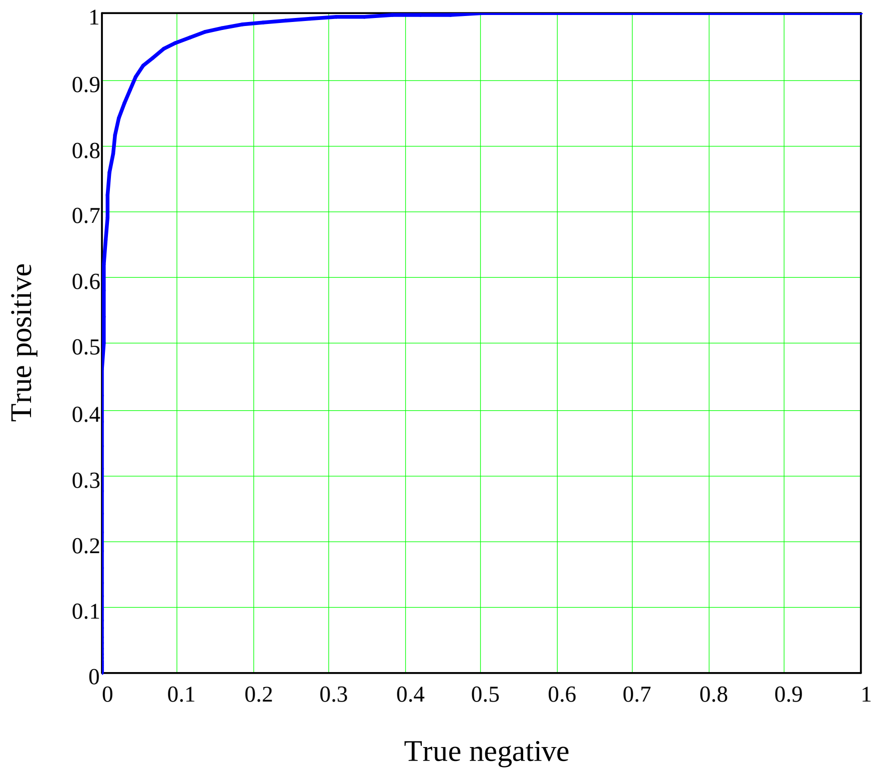

FIG. 19 – Receiver operating characteristic for distributions in Fig. 18.

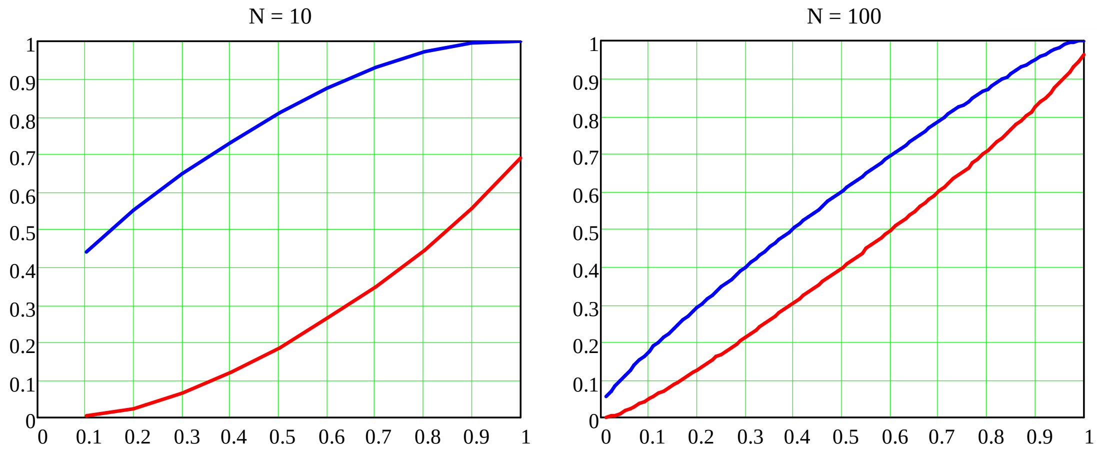

FIG. 20 – Confidence levels as a function of sample size.

VII. CONCLUSIONS

Although GPR technology is mature, it is capable of further development to enable continued classification of evolving targets and continued reduction of the size, weight and power of equipment.

New antenna designs and modulation techniques, will allow a greater breadth of capability and performance in the future. Indeed, recent developments in so-called meta-materials and advanced computer modelling techniques offer considerable promise in miniaturization of high efficiency antennas. Some areas for further development could be:

- optimization of system loop dynamic range;
- development of wideband components such as TR switches/precision couplers/bridges to enable single antenna operation;
- improvements in antenna rate of energy decay or ringdown to improve both resolution and detection performance;
- adaptive wideband antennas to optimize energy transfer to the material;
- wideband antennas with improved back and sidelobe performance;
- opportunities for higher rates or survey using UAV platforms;
- further development of UWB/Doppler GPR for the detection of victims of avalanches.

ACKNOWLEDGEMENT

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THE EUROPEAN GPR ASSOCIATION

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Abstract

The European GPR Association (EuroGPR) grew originally out of the UK based Impulse Radar Users Group, primarily in response to issues arising from using transmitting devices in a world where many types of transmitting devices were beginning to proliferate.

It became quickly apparent that the issues raised applied to all of Europe and, alongside It became quickly apparent that the issues raised the restrictions imposed by FCC regulation in the States, that a Europe-wide licensing regime was in the interest of all GPR users and manufacturers.

The Association was actively involved in developing the current licensing regulations and in contributing technical advice to European regulatory bodies such as ETSI and RSComm. It also developed and adapted its own Code of Practice which is now mandatory on all GPR users within Europe.

As use of GPR has grown, the activities of the organization have expanded as has the number, nationality and variety of members. The main aims of the organization are now to promote and support all legitimate use of the technology and to develop professionalism, training and standards in its use.

Current activities include the building of a substantial virtual library, development of training modules, liaison with other professional bodies and governmental organizations and the provision of technical advice to counteract misleading and inappropriate technological claims which might bring the technology into disrepute. Future aims include the formation of national Association groups capable of tackling local issues as well as responding to European co-operation.

GROUND PENETRATING RADAR MODELLING: THE STORY SO FAR

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Abstract

The ability to model the physical response of systems that we use to sense the environment, either manmade or natural, is fundamental in increasing our understanding about its condition and makeup and allows us to make important decisions in developing methodologies and approaches for its preservation, remediation, maintenance and exploration. Ground penetrating radar (GPR) is one of the most advanced tools that are often used – especially in engineering applications – to amass high resolution, albeit complex, information about a great range of opaque objects of interest and the shallow subsurface.

In our efforts to make sense of the complex information carried in the GPR data simulation of the underlying process of detection is a powerful tool in enhancing our understanding and often in guiding us to better interpretations. In the road to more quantitative GPR analyses that include automated imaging and data driven inversion approaches, efficient GPR simulation has a central role. As computer technologies accelerate and become widely available the next steps which, could include more practical use of GPR modelling, seem to be in sight.

This talk will try to provide a brief overview of GPR simulation and its progress over the last twenty years focusing on the development of GPRMAX, a free finite-difference time-domain tool that is used to simulate the GPR's response. It will present some examples of what it is possible with the availability of high performance computing and briefly cover some developments for increasing its capabilities. It aims to conclude with some ideas for the future and outline the directions for possible advances in this field.

ACKNOWLEDGEMENTS

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LARGE-SCALE ARCHAEOLOGICAL PROSPECTION OF THE ROMAN TOWN OF CARNUNTUM USING HIGH-RESOLUTION GROUND-PENETRATING RADAR MEASUREMENTS

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Abstract

Today the site of the Roman town of Carnuntum, located some 30 km south-east of Austria's capital Vienna, is to a large extent covered with agriculturally used fields, offering over some 10 square kilometres access to a unique cultural heritage landscape using non-invasive archaeological prospection methods. For the past 20 years Carnuntum has been the testing ground for high-resolution archaeological prospection methods developed by the Viennese research group Archeo Prospections® in collaboration with the University of Vienna, covering in total circa one square kilometre of survey area. Aside from large-scale manual magnetic prospection surveys conducted with highly sensitive Caesium magnetometers, earth resistance measurements as well as detailed ground-penetrating radar (GPR) measurements since 1997, the Forum of the civil town of Carnuntum, located in a horse paddock, has served in 2005 as test area for a detailed comparison of available single channel GPR systems. The establishment of the European Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology in Vienna in 2010 has provided the basis to extend the earlier fundamental research into Carnuntum using latest archaeological prospection technology and methodology, testing and applying remote sensing methods as well as novel high-resolution motorized prospection systems, such as several different multichannel GPR arrays and magnetometer systems for large-scale prospection. The systematic use of high-resolution GPR prospection in combination with remote sensing methods and magnetometry has amongst others resulted in the unique discovery of the school of gladiators of Carnuntum, first mapped with a single channel 900 MHz GPR system, and subsequently investigated in great detail using a multichannel 400 MHz array with only 8 cm crossline spacing. This discovery was a crucial factor in 2011 for gaining financial support permitting the area-wide prospection of the entire town of Carnutum in a 3-year prospection project. Between 2012 and 2015 the entire town of Carnuntum, comprising the civil town as well as the military camp and settlement are being mapped in great detail using non-invasive prospection methods. High-resolution GPR measurements are of fundamental importance for the detection, mapping, documentation and investigation of the buried cultural heritage in three dimensions.

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WORKING GROUP 1

Novel GPR instrumentation

PROJECT 1.1 "DESIGN, REALIZATION AND OPTIMIZATION OF INNOVATIVE GPR EQUIPMENT FOR THE MONITORING OF CRITICAL TRANSPORT INFRASTRUCTURES AND BUILDINGS, AND FOR THE SENSING OF UNDERGROUND UTILITIES AND VOIDS"
STATE OF THE ART AND OPEN ISSUES

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Abstract

The TU1208 Action focuses on the exchange of scientific-technical knowledge and experience of Ground Penetrating Radar (GPR) techniques in Civil Engineering. One of the main topics in the Action, therefore, concerns the design and optimisation of novel equipment to provide a step ahead with respect to the current technology. This paper reports on the state-of-the-art and on the possible developments that can be expected in the near future.

I. INTRODUCTION

The use of GPR in Civil Engineering is well known and there are several applications where it is currently utilised; they include the location of buried services, the detection voids or cavities, locating steel reinforcement in concrete, geotechnical foundation investigations, as well as archaeological, environmental and hydrogeological surveys. Continuous inspection of layers in road pavements and airport runways also requires an effective tool capable of providing quality control on engineering construction projects.

Requirements for these applications are different and each one imposes a particular set of constraints on the design of an effective GPR.

For example, the majority of buried plant is within 1.5 to 2 metres of the ground surface, but it may have a wide variation in its size, may be metallic or non-metallic, may be in close proximity to other plant and may be buried in a wide range of soil types, with implications for large differences in both the absorption and the velocity of propagation of electromagnetic waves, and consequent effects upon GPR performance.

For this application, the most important performance criterion is depth of penetration, with resolution (the ability to distinguish between closely space objects), whilst being important, is a secondary consideration.

On the contrary, survey of concrete or asphalt pavements requires very high resolution for accurately measuring the thickness of layers composing roadways or the runways; the same applies to the assessment of bridge decks where GPR signals can be analysed to detect potentially corroded areas.

Performance characteristics of GPRs are also often affected by ground conditions may that may vary rapidly within the area of a radar survey where, for example, variations in water content can be crucial and, particularly in urban areas, where there could be imported backfill of inconsistent quality.

Consequently, it can be sometime problematic to achieve both adequate penetration of the radar energy and good resolution, and some design compromises may have to be accepted.

In addition, a further issue concerns the interpretation of GPR data, which is not trivial in many situations; in this respect, the latest developments in GPR are oriented towards the design of equipment featuring real-time 3D high resolution images of surveyed areas.

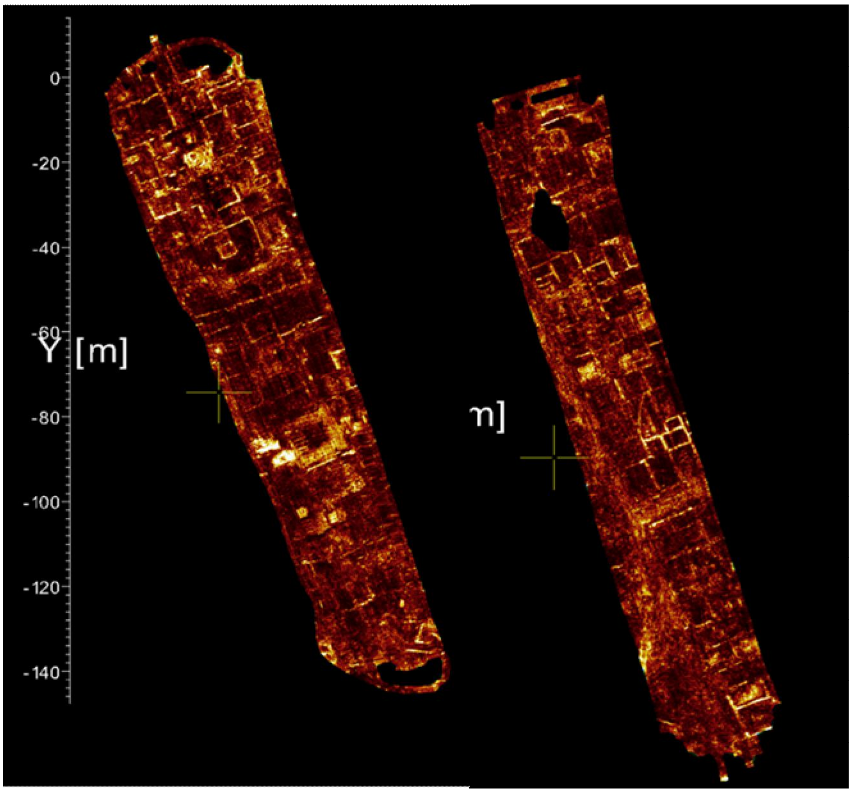

FIG. 1 – High resolution GPR image
of the archaeological site of Empúries (Spain).

An image like the one shown in Fig.1 is easily understandable even by a not skilled operator; however, this visualisation improvement can be effective only if the GPR performs well in terms of signal quality and detection range; in fact, if the received signal is too weak, as would be the case in wet, muddy ground, enhanced graphic software will solve neither the basic signal problem nor the detection performance.

Thus, the approach to be followed in the TU1208 Cost Action should address both the basic radar signal detection problem (which can be extremely challenging) and the aesthetics of the display.

II. TIME DOMAIN GPR

Ground Penetrating Radars are designed to probe up to a few metres into the ground through material that is, usually, non-homogenous and, unlike free-space, strongly absorbs radar signals. The frequency range that has been found to be useful for such an application lies within the limits of 100 MHz to 2 GHz.

Usually, the means of producing a transmit signal with the required frequency range is by an impulse generator based upon an avalanche transistor. A typical pulse obtained from such a device is shown below, together with its spectrum (note that the signal consists of just a single cycle with a period of, approximately, 10 nanoseconds, as shown in the diagram below). Although this is a cost-effective means of producing a signal with usable characteristics, the physical mechanism is a random process that may produce noise and jitter, thus limiting the inherent dynamic range of the system.

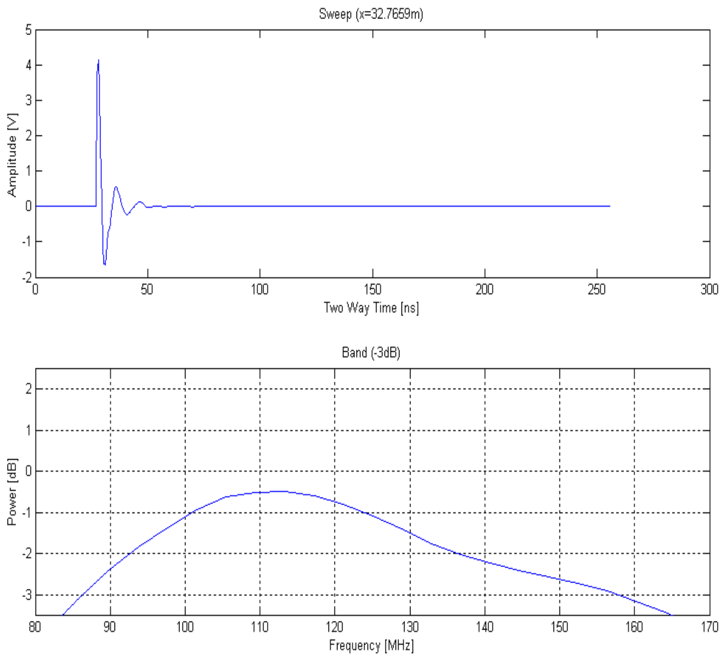

FIG. 2 – Impulse radar pulse and spectrum envelope.

The receivers for such systems are based upon the methods used in high frequency time domain sampling oscilloscopes which also have fundamental limits on their dynamic range, that rarely exceeds 70 dB.

The diagram below depicts a typical GPR system, consisting of an impulse source and receiver connected by transmission lines to transmit and receive antennas. The system is deployed close to the ground surface, and interactions occur between the radar and the ground and between its internal components. The major interaction paths are marked.

These interactions are extended in time and define what is known as the “Impulse Response” of the system. It is also known as the “Clutter Profile”. This is shown below in the next diagram as a decaying received signal - with respect to time and hence distance from the radar. Reflections from targets buried in the ground must be large enough for their peaks to be visible above the clutter profile. The system clutter profile is a critical system performance parameter and the radar must be designed to maximise its delay and to make it, as far as possible, independent of the electrical properties of the ground.

III. FREQUENCY DOMAIN GPR

Frequency domain radar systems have as long a history as their time domain counterparts. For some applications, the advantages of simple Continuous Wave (CW) systems is that they avoid the complication of modulation circuitry, have no minimum or maximum range as well as maximising power on the target.

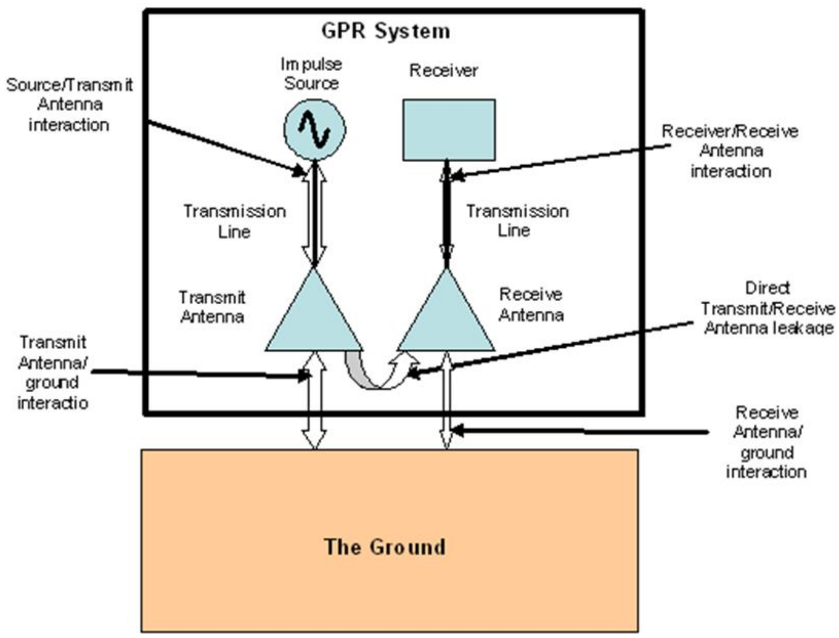

FIG. 3 – Impulse radar GPR scheme and major signal interaction paths.

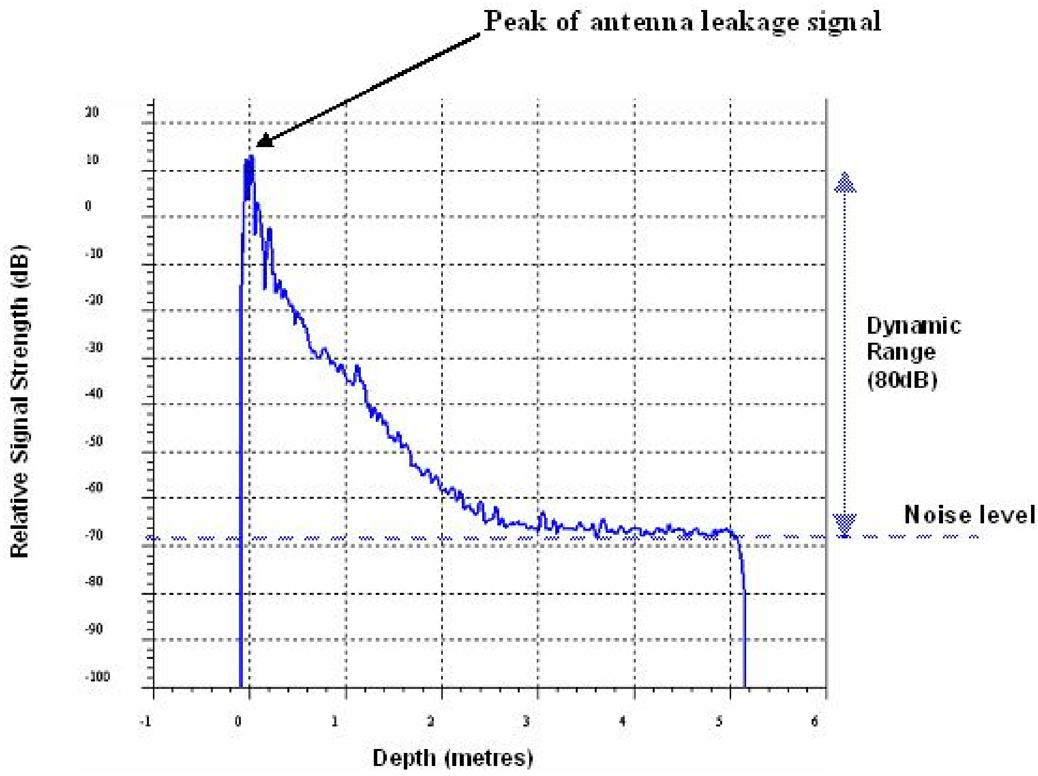

FIG. 4 – Consequent GPR clutter response.

However, because they depend upon the Doppler shift principle they also have the disadvantage of only being able to detect moving targets. The main use of such systems has been military, where they provide a means of determining the point of closest approach by guided weapons to their targets so that the warheads may be detonated at the correct time.

Being unable to detect targets unless they are moving and producing a Doppler shift clearly makes CW radars unsuitable for GPRs.

If, however, the source is able to produce a range of frequencies continuously varying with time, then it is possible to detect targets that do not move. Such radars are known as Swept Frequency Continuous Wave (SFCW). Usually the signal is generated by a source whose frequency can be controlled by the application of an external DC voltage.

In both the generation and reception of frequency domain signals, the technology is very different from that their time domain counterparts, and some aspects of the performance of such systems, particularly noise and dynamic range, are superior.

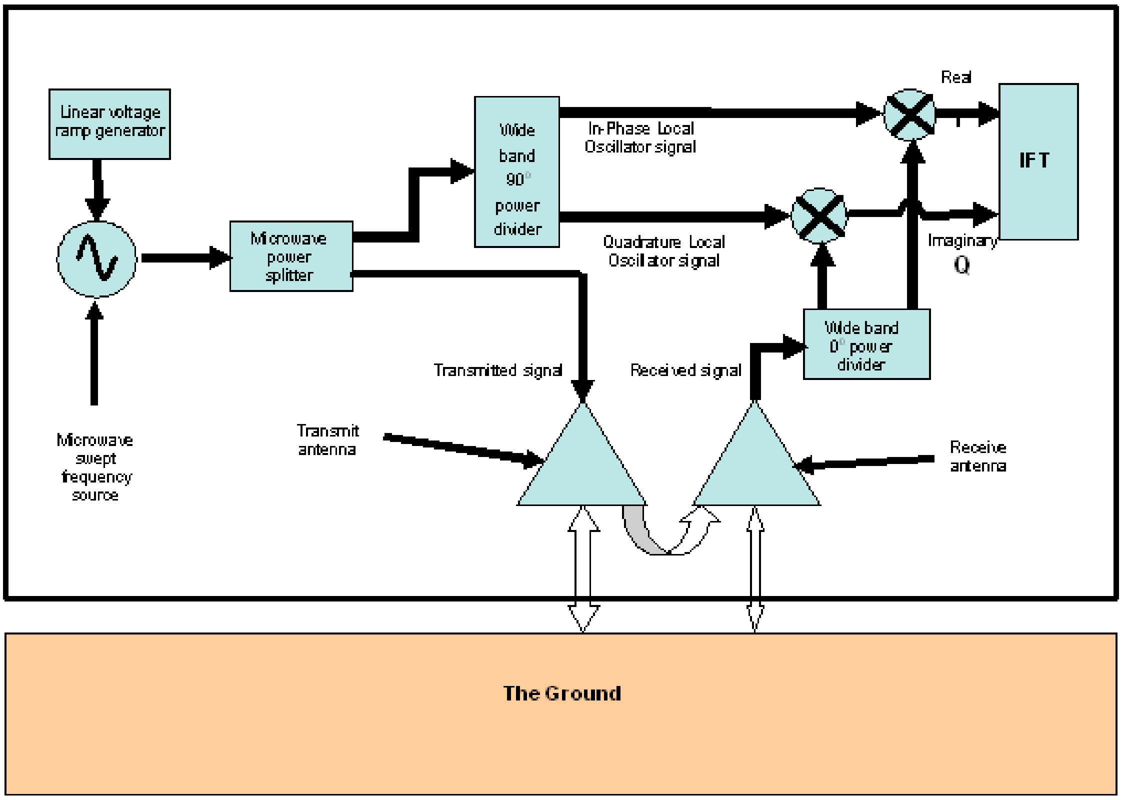

FIG. 5 – FMCW radar with I and Q outputs schematic diagram.

In fact, each measurement is made at a constant frequency and, hence, the output of the both the In-Phase and Quadrature mixers is a constant voltage.

Because both Local Oscillator signals are coherent with the received signal, the output of the mixers is proportional to the difference in phase between the transmitted and received signals, but the difference frequency cannot exist because there is no change in frequency.

In this sense, it is a CW radar and, technically, is termed a homodyne system.

By the application of a command, usually issued by a digital system, the frequency of the microwave source can be changed to a new value and, after allowing for the settling time, another CW measurement made where the mixer outputs are proportional to the phase difference between the transmit and receive signals at the new frequency.

As the microwave source is systematically “stepped”, in equal increments, through its complete frequency range, the DC voltages from both mixers are digitised and stored.

At the completion of the process, the record of the voltages of the mixers (which are proportional to change in phase of the received signals, with respect to the transmitted signal) may be displayed as a function of frequency of the transmitted signal. The result is indistinguishable from the difference frequency that would have been obtained from the continuously swept source.

The advantage gained from the extra complication of a stepped frequency source is that the transmitted CW signals are extremely stable and spectrally pure to a degree that cannot be obtained from a continuously swept source.

IV. Technology Development in TU1208 Working Group 1

The WG1 of the TU1208 focuses on the design, realization and testing of innovative GPR equipment dedicated for civil engineering applications.
The synergy with other WGs is a key aspect as it helps in deeply understanding the problems, merits and limits of currently available GPR equipment.

Even this activity is still at the early beginning, two main research axes can be already identified; these are

- the increase of the sensitivity (thus the dynamic range) of GPR systems, to enable the usability in a wider range of conditions;
- the development of antenna arrays to increase the amount and quality of data collected on-site. Sought enhancements shall concern the selection of the optimal working frequency and bandwidth, according to the characteristics of the targets of interest, as well as of the best waveform to be generated by the radar antennas.

In this subsection the concept of reconfigurable Ground Penetrating Radar for the increasing of dynamic range is introduced. The idea to reconfigure an electromagnetic system has been imported from the communication systems, where it can be of interest to have the possibility to switch among two or more different antenna beams (differently directed) and/or two or more different work bands, in order to face some possible propagation problem within one of the band, because e.g. of some fading or particular noise/interfering signals.

The idea to translate the reconfigurability within the context of the GPR systems dates back to 2008 [1]. The reconfigurability is meant as the possibility to change (or at least to switch) some parameters of the system vs. the frequency in a programmable way. This can help in equalize the answer of the system and extend the comprehensive exploitable band, meant both in terms of impedance and antenna pattern.

Moreover, if applied to a stepped frequency system the reconfigurability can be also exploited in order to prolong the integration time of the generated harmonics in a selective way, so to reject strong narrow band interferences and increase the dynamic range. An early prototype of stepped frequency system has been recently implemented, within the research project AITECH (http://www.aitechnet.com/ibam.html), by means of a collaborations between the Institute for Archaeological and Monumental Heritage

IBAM-CNR, the University of Florence and the Ingegneria dei Sistemi IDS corporation. The prototype is shown in Fig. 6. Some first results have been recently made available [2]: it has a large equivalent band that ranges from 50 to 1000 MHz through three couples of equivalent antennas, connected to the system switching on and off two series of switches. The switches allow an equivalent “cut” of the antennas, so making them suitable also for higher bands. Moreover, the system can prolong in a selective way the integration time of the harmonics and this can help to reject narrow band interferences and to increase the dynamic range. Finally, the power radiated at each frequency can be modulated, which can help in enlarging the band equivalent radiated pulse.

So, starting from those experimental results, it is possible to identify some main development lines regarding this kind of technology, for reaching the purpose of having a GPR that match the requirements for different applications, varying its properties as resolution (frequency and bandwidth) and dynamic range.

In the next subsection are introduced the main concepts regard massive GPR array. A single channel GPR as the one described in Section II produces several radar traces (amplitude towards depth) while moved on the surface.

The final result of the data collection is a single 2D profile called B-scan, where measured amplitude of the radar signal is reported along the depth and the length of the performed scan (Fig. 7).

FIG. 6 – Prototypal stepped frequency reconfigurable GPR, built within the AITECH project.

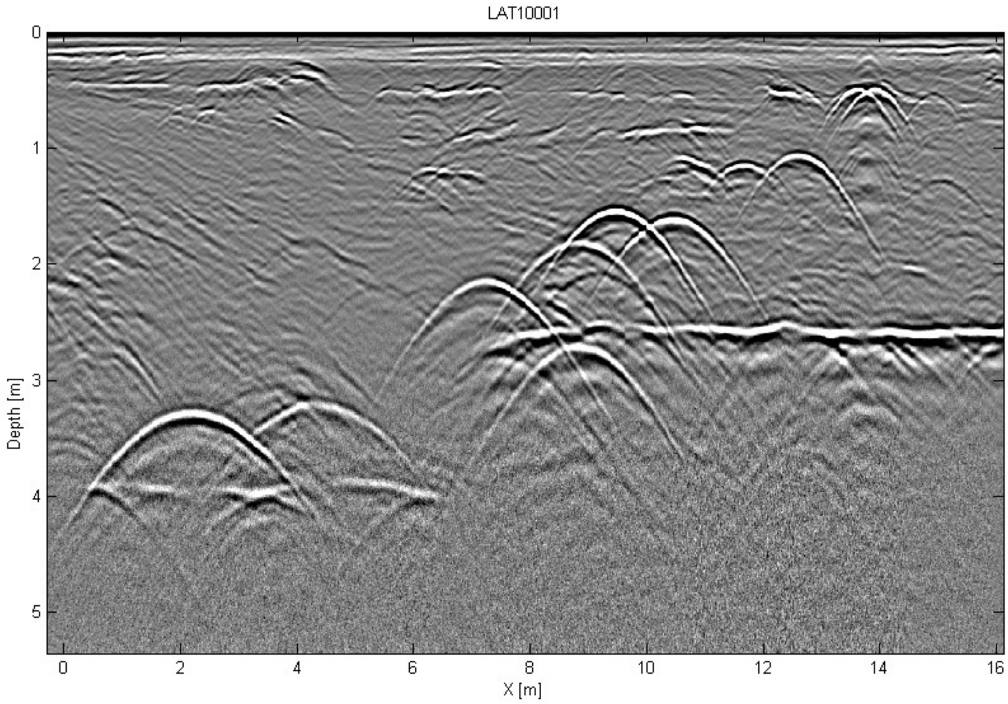

FIG. 7 – B-scan: radar amplitude map towards depth and length (measured with a 600 MHz GPR)

As assessed in the previous Section I, the latest developments in GPR are oriented towards the capability of obtaining real-time 3D high-resolution images of surveyed areas. So, this objective is achievable having a complete fine coverage of the surveyed area and collecting a 3D data volume, for example performing a lot of 2D profiles, one close to the others. Since this data collection procedure is really time consuming, several efforts have been addressed to realize a single GPR array that can produce a 3D data volume with just one scan. Fig.8 shows a 3D volume collected with a single GPR sensor, performing a lot of parallel scans.

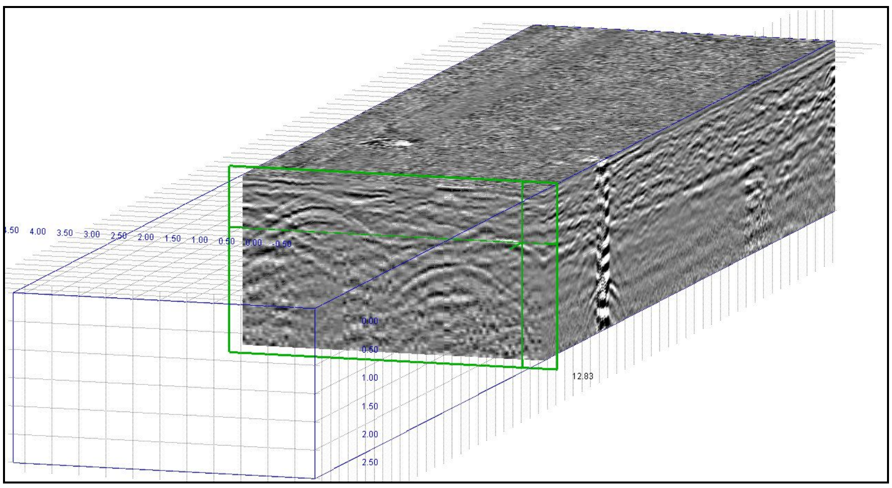

FIG. 8 – 3D data volume collected with a 200 MHz GPR system.

One of the main issues regarding GPR array design is the antennas spatial distribution; this aspect must compliance Nyquist sampling theorem, according the following Eq. (1) [3].

$$\Delta x \le \frac{\lambda_{\min}}{4\sin(\theta)} = \frac{c}{4\sin(\theta) f \sqrt{\varepsilon_r}} \tag{1}$$

In Eq. (1), Δx is the spatial separation between two GPR profiles, c is the speed of light in vacuum, θ is the half beam of the GPR antenna (that can be assumed to be 60°), f is the main working frequency, ε_r is the relative dielectric constant of the soil (maximum expected value is 15 while common value is 9).

This equation gives the closeness constraint of the GPR sensors inside the array. So, for GPR system commonly used for Civil Engineering application, which working frequency is within 200 MHz and 1000 MHz, this constraint means that maximum separation between profiles must be less than 14 cm for 200 MHz GPR system and 2.8 cm for 1000 MHz GPR system, considering a standard soil with relative dielectric constant equal to 9. Typically the specifications for the array design are more restrictive, the spacing between the sensors has to be less than the limit described above, considering that data collection should compliance the constraint even in soils with higher relative dielectric constant (up to 15).

Typical GPR antennas are planar dipoles, with a far from negligible width. One of the important aspects that must be taken in account in designing a GPR array is how to respect the requested specs, a way could be using more than one array with an offset, interleaving the profiles of one an array with the profiles of the others, in order to reduce overall profiles spacing.

Summarizing, in designing a GPR array, the first aspect that have to be approached is the definition of the working frequency, studying the application. Then, the minimal geometrical specifications are given by Eq. (1); in the design process the antenna technology and the number of required array have to be defined.

3D data volume collected by GPR arrays can be observed with dedicated software tools; a significant data representation is the C-scan, a slice of the 3D volume taken at constant depth [4].

In Fig. 9 a typical C-scan of a street is reported, taken at a depth of 0.5 m; the presence of some underground utilities is confirmed by those vertical traces on the planar view. Data were collected with 200 MHz single GPR radar system.

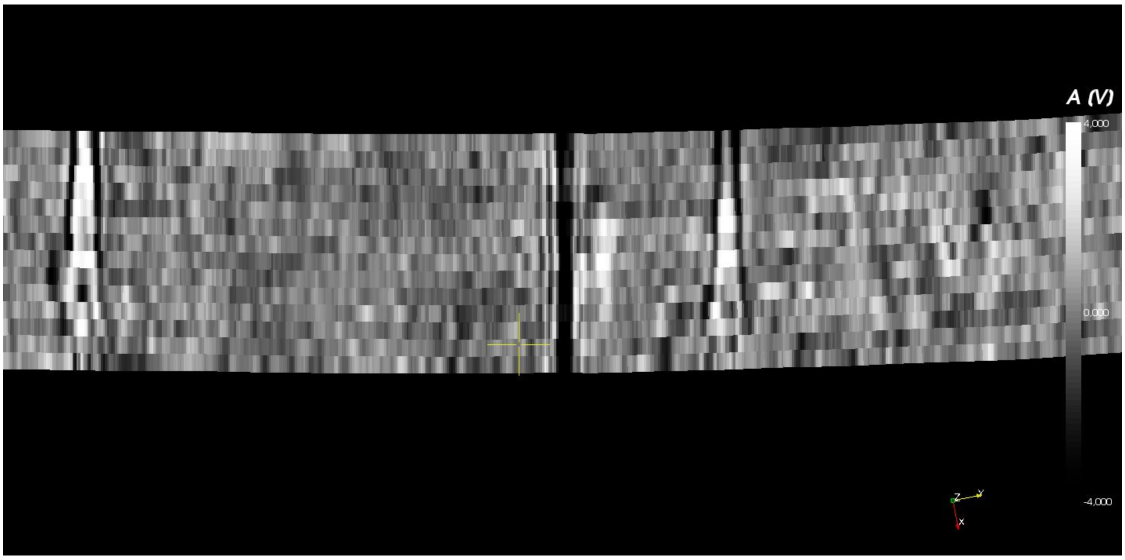

FIG. 9 – Typical C-scan of a street taken at a depth of 0.5 m.

V. CONCLUSION

This article describes actual GPR's architectures such the impulsive and the stepped frequency ones.

Two main research axes can be identified: the increase of the sensitivity (thus the dynamic range) of GPR systems, to improve the usability in a wider range of conditions; the development of antenna arrays to increase the amount and quality of data collected on-site, and the productivity.

Regarding the first line of research some steps forwards have been made even realizing a prototype of a reconfigurable stepped frequency GPR system, that features some benefits in terms of adaptivity to the environment and to the application, and in terms of increase of the dynamic range, better rejecting the noise and the interfering signals.

Sought enhancements shall concern the selection of the optimal working frequency and bandwidth, according to the characteristics of the targets of interest, as well as of the best waveform to be generated by the radar antennas.

Other important objectives in developing new GPR system are the increase of the productivity and the achievement of high performance in terms of detection capability and ease of data interpretation. Using a GPR array lets acquire a huge number of radar profiles densely spaced to reconstruct the entire 3D volume surveyed.

To assure a quick and correct data collection respecting Nyquist criteria, large and highly dense GPR arrays have to be designed. Some further step in this technology, which can be identified as a research line, regards the study of innovative GPR antenna technology and GPR sensors multiplexing.

ACKNOWLEDGEMENT

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PROJECT 1.2
"DEVELOPMENT AND DEFINITION OF ADVANCED TESTING, CALIBRATION AND STABILITY PROCEDURES AND PROTOCOLS, FOR GPR EQUIPMENT"
STATE OF THE ART AND OPEN ISSUES

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Abstract

This paper gives an overview about state of the art and open issues in calibration and stability procedures and protocols in use on common GPR equipment. More in depth we will resume in a single paper recent works (2012-2013) and propose possible enhancements or adoption in the standardization process.

I. INTRODUCTION

The specific topics are divided in three sections covering calibration procedures, stability procedures and protocols. Each of these sections summarizes the state of the art and highlights open issues as a basic material for discussion of develops and definition of such topics considering various types of GPR equipment.

II. CALIBRATION PROCEDURES

Calibration is an important process in the design and use of GPR equipment and different techniques may be applied for different implementations (polarimetric and full-polarimetric GPR, time-domain GPR and frequency-domain GPR). Polarimetric GPR requires accurate calibration of channel imbalance and crosstalk for both phase and amplitude terms. Current techniques for calibration of Polarimetric GPR data always ignore high-order terms to simplify equations. Reference [1], [2] explain a mathematical formulation to improve the accuracy of calibrating polarimetric GPR data. Such procedure effectively separates the crosstalk from the channel imbalance and radiometric calibration and removes the crosstalk errors caused by higher-order terms.

Reference [3] also covers a section about external calibration (i.e., finding the GPR transfer function), errors and the relative setup.

Comparisons between time-domain and frequency-domain GPR are presented for two different scenarios: above water layers and above sandy soil layer. A third scenario depicts antenna calibration above saline water.

III. Stability Procedures

Stability issues, as reported in [3], affect most time-domain (TD) and frequency-domain (FD) GPR. Measurements are usually carried out into free-space simulation in anechoic chambers. Some significant drift has been observed in TD-GPR due to not-in-sync pulse generator. This drift can affect the phase of the signal in the frequency domain in high frequency components.

Difference in stability between TD- and FD-GPR is reported to be because of the different type of antenna (bowtie, or biconical, for TD and horn for FD). Horn antenna is usually more directive than bowtie antenna. There seems to be a relation between stability and the measure after VNA calibration using high precision OSM (open, short, match) kit. Using a time-lapse measure lasting for 3 hours immediate after calibration reported an acceptable instability if performing radar measurements at least 18 minutes after calibration.

IV. Protocols

Reference [4] describes a dated proposal for standardized test and evaluation procedures. This work was inspired by the emergency of having multisensory mine detection systems describing issues to be addressed when drafting best practice documents. Test has been conducted on hand-held devices thus keeping vehicle-based solutions in mind.

V. Conclusion

Testing, calibration and stability procedures and protocols on the GPR equipment still need some definitions and the depiction of possible scenarios with different GPR implementations. A good starting point will be then the classification of device and technologies from different manufacturers and the possible use for each device. This means like a double-entry table for each topic having GPR equipment on rows and scenarios on columns.

Acknowledgement

The author acknowledges the COST Action TU1208 “Civil Engineering Applications of Ground Penetrating Radar”, supporting this work.

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PROJECT 1.3
RECONFIGURABLE STEPPED FREQUENCY GROUND PENETRATING RADAR: A PRELIMINARY EXPERIMENTAL TEST

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Abstract

In this paper some results achieved with an innovative reconfigurable stepped frequency ground penetrating radar (GPR) are shown. In particular, we focus on the case history of the church of St. John Baptist in Parabita (near Lecce, Southern Italy). The aim is to show that reconfigurable GPR systems can provide meaningful results, and constitute an issue worth studying in more depth.

I. INTRODUCTION

The reconfigurability is an issue being dealt with for several years now in the framework of wireless communication system, especially with regard to arrays of antennas [1],[2]. In that context, the reconfigurability is meant as the possibility to change the impedance and/or the radiation pattern of the antenna, so that the system can change the frequency work band and/or the direction of maximum transmission/reception of the signal.

More recently, the concept of the reconfigurability has been transferred into the framework of the Ground Penetrating Radar (GPR) prospecting. In particular, the GPR reconfigurability has been introduced as the possibility to change some parameter of the system vs the frequency so to enlarge the available band [3]. In particular, we might think to change the input reactance and resistance of the antennas by means of a bank of capacitors and inductors and by means of lambda fourth transformers [4]. The antenna impedance can be changed also by means of suitable cut to the arms of the antennas, performed by means of one or more series of switches placed along their length.

In particular, this equivalent “cut” of the arms allows to control also on the radiation pattern. In particular, unlike the case of communication devices, in the framework of GPR prospecting it is desirable to have a radiation pattern not much variable vs the frequency, and in particular with a unique broadside radiation beam [5]. Actually, when the arms of the antenna are cut by means of the switches, the detached parts of the arms play the role of passive (parasitic) elements, on which induced currents arise. However, simulation results achieved on “pixelled” antennas have shown that the effect of these parasitic elements are not expected to be dramatic [6], especially if the part of the antenna cut out is in its turn cut in several electrically small sub-parts, so that the currents induced on the passive elements result reduced.

In 2008, the research Project AITECH (www.ibam.aitechnet.html), led by the Institute for Archaeological and Monumental Heritage IBAM-CNR and financed by the Puglia Region, has given the chance, among other things, to implement a prototype of reconfigurable stepped frequency GPR system, that has been projected by IBAM-CNR, University of Florence and IDS S.p.A. The system has been conceived equipped with two bow tie antennas with two series of switches along their arms, so that (according to the qualitative scheme of Fig. 1) we have two “long antennas” if all the switches are set “on”, two “medium antennas” if the internal switches are set on and the external ones are set off, and two “short antennas” if all the switches are set off. Moreover, the system allows to prolong selectively the integration time of each radiated harmonic signal: in this way, it is possible to improve the rejection of narrow band interferences prolonging only slightly the comprehensive required measurement time.

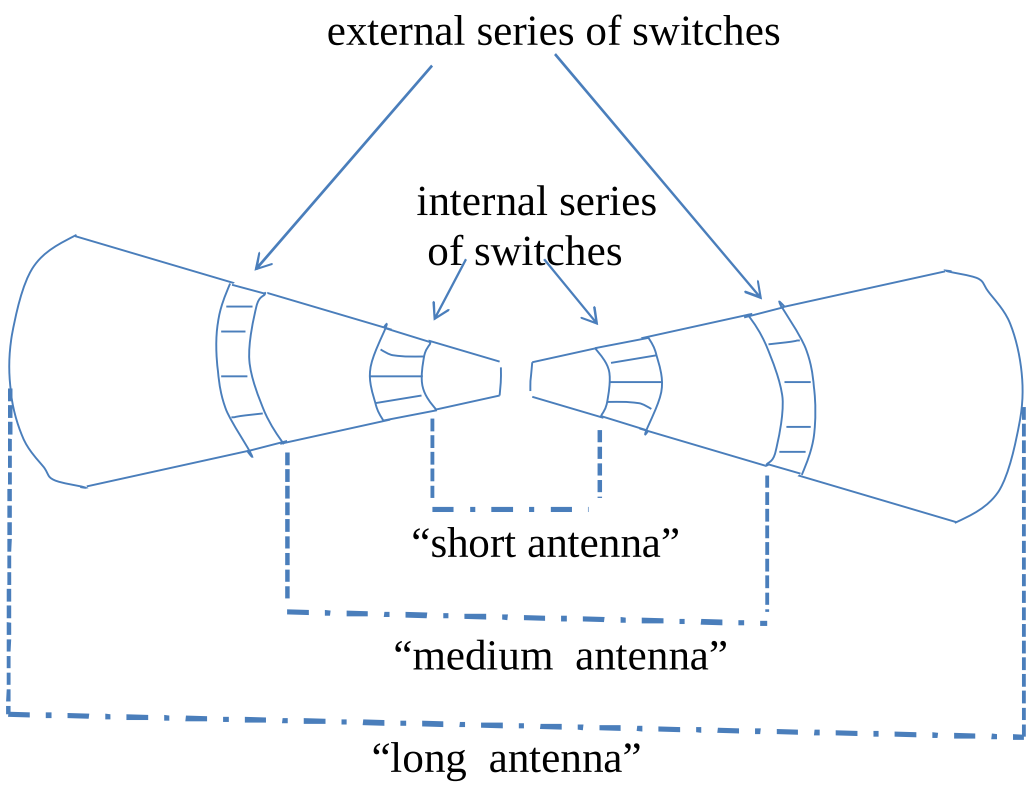

FIG. 1 – Scheme of the reconfigurable antennas.

The frequencies most affected by interferences can be inferred from the same GPR data, by examining, e.g., the variance of the in-phase and in-quadrature components through the samples gathered at any fixed frequency.

The system is already equipped with a code able to do this too. Finally, it is possible to modulate the transmitted power vs the frequency, so to equalize (partially) the shape of the equivalent received synthetic pulse. The comprehensive band spanned by the system ranges from 50 MHz to 1 GHz, but sub-bands can be optionally selected. For any spanned band, all the equivalent couples of antennas (long, medium and short) can be exploited, or two of them (namely the long and medium antennas or the medium and short antennas). After gathering the data, it is well advised to choose the most suitable bands for the processing of the data gathered with any equivalent couple of antenna looking at the amplitude spectrum of the data. The reconfigurable system has been recently tested in several sites, both indoor and outdoor, in comparison with a commercial system (at the moment we have made use of a Ris-Hi Mode pulsed system equipped with a double antennas at central frequencies 200 and 600 MHz). In particular, here we will show the results achieved in the church of St. John Baptist in Parabita (near Lecce, Southern Italy).

II. The Case History

The church of St. John Baptist, is a monument that has been enlarged more times during the centuries. Its first nucleus is of the 15th century, and the initial church was directed along the current transect. Then, it was enlarged toward the orthogonal direction a first time probably during the renaissance period (XVI century) and a second time during the 19th century, when the church reached its current size and shape. A restoration project is scheduled, and preliminary analyses have been performed by IBAM-CNR in order to provide some insight possibly helpful for the restoration works. In particular, the entire central nave plus the right hand side nave (looking from the altar to the current main entrance) have been prospected in order to check the presence of buried anomalies of archaeological interest and/or possibly related to the dynamic of the humidity within some of the lateral walls. The left hand side lateral could not fully prospected because indeed it is a quite narrow corridor, where it was not possible to move the trolley of the GPR. We took this chance to test the prototype and so the church has been prospected both with a commercial pulsed Ris Hi-Mode system equipped with a double antennas at 200 and 600 MHz and with the prototype of reconfigurable stepped frequency GPR system. In both cases, two orthogonal set of B-scans were gathered and the interline space between the scans was 40 cm. We tried to move the two systems along the same grid, compatibly with the fact that the size of the two systems is not exactly the same, as can be appreciated in Fig. 2.

FIG. 2 – The prototype, on the left hand side, and the commercial system on the right hand site.

In particular, the prototype is slightly larger because it works also at lower frequencies with respect to the pulsed one.

The most meaningful slice is shown in Fig. 3. In particular, in Fig. 3 is reported a depth slice at 95 cm (time-depth conversion has been done on the basis of the diffraction hyperbolas) and shows, among other minor “spots” two main anomalies, indicated with 1 and 2. Due to the size and the shape of these anomalies, we had thought of possible crypts or hypogeal rooms.

To understand more, an endoscopic survey has been performed too, and it resulted that there are two buried cavities on the anomalies 1 and 2.

In Fig. 3 also the endoscopic image achieved on cavity number 1 is shown. In particular, in that point the cavity start at the depth of 85 cm and shows a thickness of 95 cm. The images in Fig. 3 in particular, are the best ones achieved with both instruments, and compare the image achieved from the short antennas of the prototype with the antenna at 600 MHz of the pulsed system. As can be seen, the image achieved from the prototype seems more defined and the two cavities appear more marked.

During the restoration work, both cavities will be excavated. They might be hypogeum rooms partially filled up with end product, in which case they will be empted and reported to their original size. We have estimated, on the basis of the data, an order of 4-5 m^3 of material for cavity number 1 and an order of 16 m^3 for cavity number 2, that at any rate might continue also outside the perimeter 2, in which case we cannot evaluate its volume.

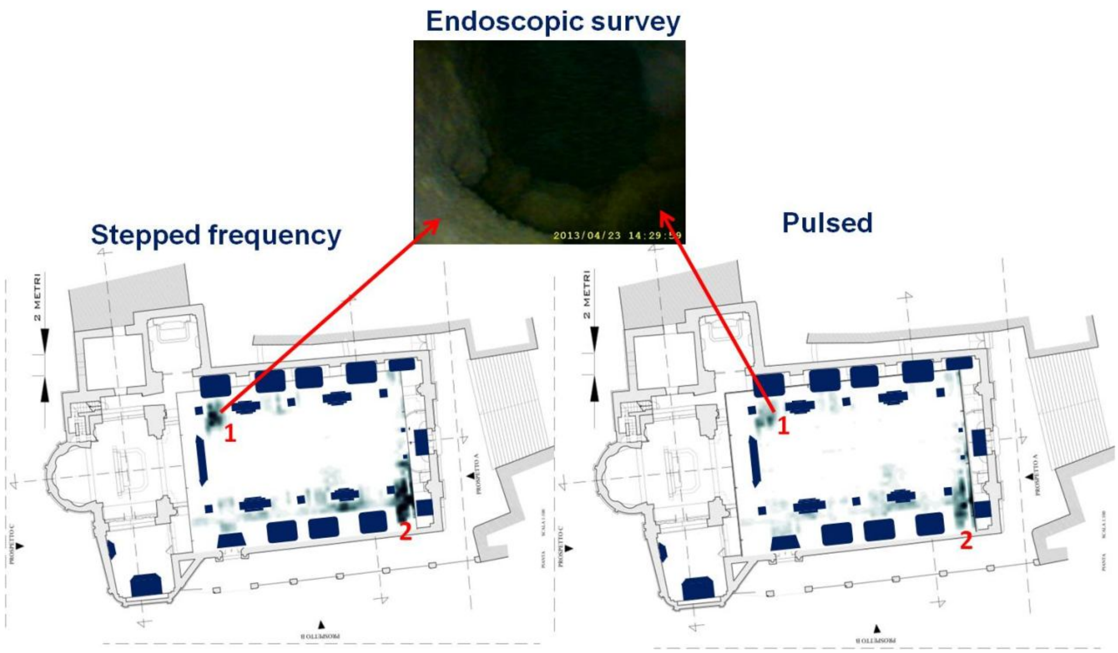

FIG. 3 – Depth slice at 95 cm achieved with the stepped frequency system (left hand side), depth slice at 95 cm achieved from the pulsed system (right hand side), and endoscopic survey (central image).

III. CONCLUSION

In this paper a brief resume of some results achieved from a reconfigurable stepped frequency system have been shown, compared with the results of a commercial pulsed system. The results are comparable and in the case at hand we dare say even better, and some (even if very partial) ground truth has confirmed the main result of the prospection. Beyond this one, some further case histories have been analyzed too, only partially published up to now. In the end, the prototype has some pros and also some cons, but it demonstrates that the reconfigurability is a strategy technically possible for the implementation of relatively compact multiband GPR systems.

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WORKING GROUP 2

GPR surveying of pavements, bridges, tunnels and buildings; underground utility and void sensing

PROJECT 2.1
"INNOVATIVE INSPECTION PROCEDURES FOR EFFECTIVE GPR SURVEYING OF CRITICAL TRANSPORT INFRASTRUCTURES (PAVEMENTS, BRIDGES AND TUNNELS)"
STATE OF THE ART AND OPEN ISSUES

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Abstract

This is an initial word to the project 2.1 of COST TU1208. This project concerns a diagnostics of transport infrastructure structures – pavements (line structures), bridges and tunnels. It includes individual applications which are currently in use in both in the implementation phase, and in the phase of research. Furthermore, it introduces issues which need to be dealt with, so that this NDT method could be applied in greater extent.

I. INTRODUCTION

Ground penetrating radar (GPR) has had a certain tradition in the field of diagnostics of transport infrastructure structures. Not only can it be used for one-off structure condition diagnostics, but it can also be used for a comparison of the development over a certain time period.

The following three chapters briefly describe the basic information on the diagnostics of pavements, bridges and tunnels by ground penetrating radar, while focusing on individual applications. The other two chapters describe the needs for more intensive application of this NDT method and open issues.

Retaining walls [1] and railway tracks [2] are ranked among other transport infrastructure structures which are diagnosed by ground penetrating radar but are not included here.

There are a large number of articles and research projects concerning these issues. Only the selected and the most state-of-the-art ones are included below. American reports from the programme SHRP 2 [3]–[5] and the results of a European project Mara Nord [6]–[8] are some of the complex ones.

The ground penetrating radar is usually not used as an acceptance test, but rather for the identification of weak and damaged parts of a structure, which occur within the course of its use. The ground penetrating radar is often combined with other methods (Project 4.3 of the Action). Some applications are a standard practice; others are still being verified within research projects.

II. Pavement Diagnostics

The measurements are performed on flexible (asphalt) as well as rigid (concrete) pavements, which both have their specific properties.

Road pavements are line structures; therefore, the accuracy of measurement location plays an important role. They are usually performed in the longitudinal direction under high speeds, so that traffic is not affected. In this case, the measurement is performed with the use of one or several horn antennas, or a field of antennas, respectively. 3D recording is performed under lower speeds. Some applications require a local measurement, which is performed with one or more dipole antennas. One of the first GPR applications in road engineering was to determine the thicknesses of road pavement layers. Nowadays, ground penetrating radar is used for pavement diagnostics at the project level, i.e., for the evaluation of shorter road segments. It is not used at the network level at the moment. Another extended application is the localization of the in-built reinforcement. These include dowels and tie bars in jointed unreinforced concrete pavement or rebar in continuously reinforced concrete pavement (CRCP).

The aim of other applications is the localization of hidden (under surface) distresses, a spots where loosing of connection between layers, layers and rebar, etc. occur. Individual applications of GPR pavement diagnostics are shown below, in the classification to common and research ones.

Common applications:

- thickness of asphalt pavement layers [9]–[12];
- thickness of concrete pavement layer (with or without dowels, tie-bars or rebar) [10], [12];
- thickness of unbound pavement layers [9], [12];
- position of reinforcement in concrete pavement [13];
- de-bonding and delamination of pavement layers [14];
- heterogeneity of pavement:
    - changing of pavement layer structure;
    - identification of caverns (e.g., under concrete slabs, as a result of floods) [15];
    - identification of frost heaves [9], [16], etc.

Research applications:

- condition of reinforcement in-build in concrete pavement (e.g., corrosion);
- depth of surface cracks [17];
- localisation of bottom-surface initiated cracks [17];
- pavement pumping prediction [18];
- heterogeneity of pavement (Project 2.4 and 2.5 of the action):
    - moisture content;
    - air voids content;
    - compaction;
    - segregation of aggregate.

III. Bridge Diagnostics

The ground penetrating radar diagnostics is usually focused on concrete bridges, or stone-masonry arch bridges, respectively [19]. It usually concerns the condition of the bridge deck, pavement, its connection to the bridge deck, but also other applications. An important role is played by the diagnostics of the location and condition of the reinforcement in a form of construction bars and prestressed or post-tensioned tendons (or their ducts). Individual applications are shown below, in the classification to common and research ones.

The measurement is usually performed when problems occur. The problems are found within a visual inspection–leaking, crack occurrence, etc.

Most commonly, dipole antennas are used. The measurement of the bridge deck is usually performed at low speeds in longitudinal as well as in transversal direction. If necessary, a 3D measurement is used. Regarding the diagnostics of girders and elements such as pillars, etc., the measurement of vertical areas is performed with a single antenna, often manually held.

The application at girders and vertical elements is performed with a manually led cart with a single dipole antenna.

The evaluation is usually conducted generally in the form of maps for different depths or in the form of cuts.

Common applications [20]–[23]:

- position of reinforcement in bridge deck (spacing);
- concrete cover of reinforcement in bridge deck;
- thickness of bridge deck;
- position of prestressed or post-tensioned tendons or tendon ducts [24];
- de-bonding and delamination of pavement layer;
- bridge deck deterioration (cracks, caverns, etc.).

Research applications:

- diameter of reinforcement in-build in concrete [25];
- condition of reinforcement in bridge deck (e.g., corrosion);
- evaluation of sealing course on bridge deck [26];
- moisture content;
- bridge girder diagnostics [27], etc.

IV. Tunnel Diagnostics

Regarding the ground penetrating radar diagnostics, the least documented area is the evaluation of condition of tunnels. The reasons is lower number of these structures and more difficult access for measurements, which nearly always depend on regular maintenance (tube cleaning, equipment check, etc.).

The main focus is on the determination of the thickness and condition of a tunnel wall, including the evaluation of reinforcement condition. Apart from this, hollow spaces between concrete and rock are evaluated.

The measurement is performed at the tunnel lining different slope areas at different heights with the use of special mounts built in the measuring vehicle, or with a manually held antenna. Horn or dipole antennas are used. The evaluation comes in the form of maps.

Common applications [28], [29]:

- position of reinforcement in tunnel wall;
- thickness of tunnel wall;
- homogeneity of tunnel wall.

Research applications:

- condition of reinforcement in tunnel wall;
- hollow spaces between concrete and rock;
- moisture content, etc.

V. Common Needs

The issues which need to be dealt with in order to improve the use of ground penetrating radar in practice are shown below. These issues need to be explained to the common users of this NDT method as well as to administrators of transport infrastructure structures, who order diagnostics by this method.

- optimum device setting for specific application–number of channels, antenna frequency, measurement speed, method of localization of the measurement spot, etc.;
- determination of measurement accuracy (in depth)–acceptance of this accuracy for basic applications, particularly for the determination of individual road pavement layer thicknesses and reinforcement location;
- raster optimization of the measurement–3D measurement versus line measurement (in two perpendicular directions);
- minimization of the number of drill holes for calibration needs–the use of methods CMP (Common Mid Point), WARR (Wide-Angle Reflection and Refraction) and others;
- the method how the measurement results should be fed into databases and road administrators’ systems (e.g. layer thickness).

VI. Open Issues

The issues mentioned in the previous chapter are being dealt with at a certain level. Apart from them, it is necessary to tackle others which need to be dealt with in future:

- automation when evaluating the measured data for specific applications;
- training of personnel for these applications in terms of measurement and evaluation;
- integration of this NDT method into European standards and technical specifications (In Europe, there is no equivalent to standards ASTM D4748-10 [30] and ASTM D6087-08 [31], which deals with the application of ground penetrating radar for roads and bridges; only in some European countries, there are technical specifications, e.g. DMRB 7.3.2 [32] in UK and B 10 Merkblatt [33] in Germany);
- performance of comparative tests of individual devices at national and international level (at least for pavement diagnostics, where similar tests are carried out for other devices measuring variable parameters);
- optimization of costs for individual GPR applications in road engineering and inclusion of prices in the issued price lists of rates.

VII. Conclusion

GPS is already in use at all three types of transport infrastructure structures (pavements, bridges and tunnels). A number of applications are standard procedures, but even for them there is still a room for improvement and there is still need to set stricter regulations. The application of this method either separately or in combination with other NDT methods is being tested. The results of this commencing COST action should support this effort.

Acknowledgement

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PROJECT 2.3
"INNOVATIVE INSPECTION PROCEDURES FOR EFFECTIVE GPR SENSING AND MAPPING OF UNDERGROUND UTILITIES AND VOIDS, WITH A FOCUS TO URBAN AREAS"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Ground Penetrating Radar (GPR) has proved its ability to act as a powerful geophysical non-destructive tool for subsurface investigations. The remarkable technological developments have increased, among others, the practice of GPR in sensing and mapping utilities and voids. In particular, GPR is effectively used to locate and map objects such as pipes, drums, tanks, cables and underground features or to detect subsurface voids related to subsidence and erosion of ground materials. Furthermore, deploying GPR methods prior to directional drilling prevents damage to existing utilities, thus resulting in cost effective installations. In that frame, this paper presents some studies showing the GPR performances and limitations, from single-channel systems to the potential of multi-channel 3D imaging and integrating systems.

I. INTRODUCTION

Transportation agencies need accurate methods for measuring the near-surface and subsurface conditions of their transportation facilities. Determining pavement thickness, detecting voids beneath pavements and measuring the moisture content in pavement layers are examples of subsurface pavement conditions for which data are necessary. One promising technology for addressing these issues is Ground Penetrating Radar (GPR) [1].

GPR is a non-invasive and non-destructive tool that has been successful in some transportation applications, such as profiling asphalt pavement thickness and detecting air filled voids. Furthermore it is used for a variety of applications, including: mapping underground utilities, profiling ice thickness, bathymetric (depth measurements) surveys of fresh water lakes, archaeological investigations, shallow bedrock profiling, measuring pavement thickness, measuring pavement base and subbase thickness, locating voids beneath pavements, detecting bridge deck delimitation, mapping soil stratigraphy and characterizing environmental contamination [1].

In France, some legal accidents in 2007 and 2008 have led to modify the regulation of work in the neighbourhood of utility networks which has been official since July 01, 2012, including one legislation, four decrees and a standard (NF S 70-003- Part1 to Part3) [2].

In one hand, the responsibility of the owners is increased while three levels define the accuracy of localisation of a utility, from class A when the uncertainty of positioning is below 40 cm, to class C when it is above (for this last case, complementary investigations being required). On the other hand, the SIG mapping of utility network has become the central subject of the territorial collectivities, which have to invest in geomatic science.

The first trials followed by two pilot cities have shown mitigated results. Indeed, three businesses are gathered: the knowledge of the utilities, the detection and geo-localisation techniques, but the professional community is not yet well prepared to such accuracy requirements. Indeed, training courses are under construction, supervised by the Ministry of Ecology, Sustainable Development and Energy, due to the fact that two certifications in 2017, for detection and geo-localisation, will be necessary for services companies.

In such frame, GPR imaging is one of the promising non-destructive methods that have offered new opportunities for mapping the subsurface structures of shallow earth in highly urbanized regions [3, 4]. The present paper refers to the procedures used for an effective GPR sensing and mapping of underground utilities and voids with a focus to urban areas.

II. MAPPING OF UNDERGROUND UTILITIES

The often-repeated infrastructural improvements in basic infrastructure facilities are road widening and relocation of utilities. If there are no proper care and systematic work approach observed, the road works may disrupt and cause damage to underground utilities. Hence, mapping of these underground utilities is necessary to avoid great loss and accidents [5].

Underground utility mapping is a process of identifying the position and labelling public utility mains which are located underground. These mains may include lines for telecommunication, electricity distribution, natural gas, water mains and wastewater pipes (Fig.1). In some location, major oil and pipe lines, national defence communication lines, mass transit, rail and road tunnels also compete for space underground [6].

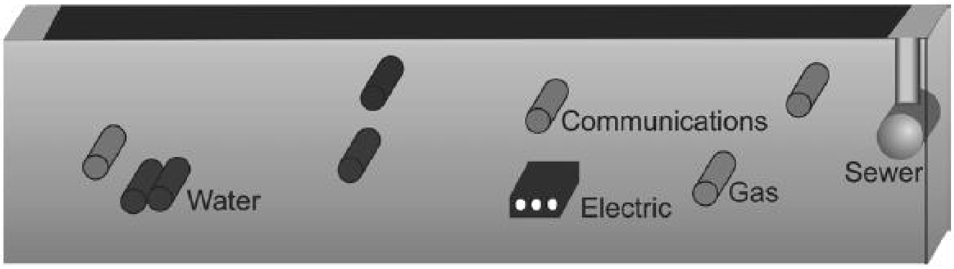


FIG. 1– Underground utilities [6].

Underground utility mapping refers to the detection, positioning and identification of buried pipes and cables beneath the ground, corresponding to three businesses. It deals with features mainly invisible to the naked eyes. While the determination of position can be obtained with conventional or modern survey equipment, the detection and identification of underground utilities require special tools and techniques [7].

GPR is commonly used to locate and map objects such as pipes, drums, tanks, cables and underground features or utilities. In application of utilities detection, radar data are used to detect the existence of underground utilities which mainly have different conductivity and dielectric properties from its surrounding.

Several studies have been carried out concerning the mapping of underground utilities from last 90's to now-a-days. In 2001 the GPR technique was used for the detection of a main water supply pipe in Stockholm, Sweden [8]. The presence of the pipe was well known, although the exact location was unknown. The survey was performed over a road in which several pipes and cables were buried. In order to locate the pipe a large number of short profiles (16 parallel profiles) were conducted perpendicular to the presumed strike of the pipe, using a 500 MHz shielded antenna. The data were loaded into a 3D visualization and processing software for analysis.

Another study was carried out in main campus of Universiti Sains Malaysia, Penang, specifically located at School of Social Sciences [5]. The aim of the study was to locate and map underground utilities or pipes that existed at the study area that could be used as a preliminary study for utilities mapping. Eight parallel ground penetrating radar survey lines were executed with total length of 8m and line spacing of 2m. In this case, a shielded antenna with frequency 250 MHz was used to detect and map utilities of the study area with suitable parameter setting. Anomalies were detected at depth < 2.5m at several survey lines that may be due to underground pipe, manhole trench, and underground cable that crosses the study area. Orientations of these utilities were successfully detected and well mapped.

In Kuala Lumpur, Malaysia, a GPR survey was performed using a 450 MHz antenna on a major road. The contractor needed to know where he could safely dig without hitting a utility while installing fiber optic communication cables. The survey was carried out in a few minutes, and locations of the utilities were marked on the pavement as the survey was being conducted. The fiber optic cable contractor quickly and safely trenched between sites of buried utilities [7].

Utility surveying was also performed at three sites in Hong Kong [9]. In this study three ground coupled centre frequency antennas - 100, 270 and 400 MHz were used. However, the use of 100 MHz antenna was abandoned because of lack of precise horizontal distance measurement without the usage of survey wheel. To ensure transect lines easily and to maintain a complete coverage of the targets a grid was used for the survey. It was achieved that the 400 MHz antenna was good at distinguishing underlying objects less than 2m, whereas 270 MHz one was 2m below.

Another utility-mapping was performed in two areas located in downtown São Paulo City, Brazil [10]. The main objective of this work was to locate subsoil utilities, such as, piping, galleries, electric cables etc., as well as concrete columns supporting the Roosevelt Road tunnel–viaduct complex in advances of the construction of the Line 4 subway (yellow) tunnel in São Paulo.

GPR measurements were performed using 200 MHz shielded antennas. Lines were surveyed along both the north-south and east-west directions in a polygonal area in order to achieve a pseudo 3D grid by 2D data interpolation. Interpretations of GPR results, combined with lithological information available from boreholes and trenches opened in the study areas provided important information for accurate location of shallow utilities in the subsurface. The study showed that the GPR method was a very important and useful step to precede excavation of São Paulo subway tunnels, providing the precise location of utilities in subsoil, as well as an estimate of their depths of occurrence. As a final point, based on these results, geotechnical work was safely carried out, and risks of dangerous accidents were avoided [10].

Through these few examples the benefit of performing several parallel profiles was clearly demonstrated. An object located in one profile only could easily be interpreted as a pipe, if interpretation were done in 2D only. By combining several profiles and load them into a 3D software, it’s easy to check whether the object is extending linearly or not. Thus this kind of interpretation improves the security of the investigation, at the cost of time. It is especially valuable when the site conditions are more difficult e.g. when many pipes and boulders are present. Moreover these researches showed that the ability of GPR to detect not only metallic objects, but also non-metallic objects (e.g. plastic, concrete ceramics or fiber optic cable), makes it a powerful tool to complement traditional methods in utility locating. This is of considerable importance, since an increasing fraction of buried pipes are non-metallic.

In the framework of a research program performed by the New York State Department of Transportation (NYSDOT) utility-mapping at two sites was successful in that GPR was able to (a) identify buried utility infrastructure both at previously known and unknown locations, (b) successfully cover the entire pavement intersection at both sites in relatively short period of time, and (c) achieve superior 3D image quality because of the multi-channel (array system) GPR/GPS capability that is not available in typical single-channel and even two-channel GPR systems [11].

The system used covers 5.12 feet with each instrument pass obtaining 14 channels of GPR data within each swath. Multiple parallel and transverse instrument passes were done at each site in order to obtain sufficient coverage to produce the 3D images. Post processing and interpretation were performed to generate the 3D images, maps and CAD drawings that were delivered for the project. These 3D images produced from specialized proprietary multiple antenna hardware and processing software, are much more illustrative and accurate than the vertical slice provided by a single antenna. For instance, the images can be rotated to achieve the optimal view of a critical utility crossing, and can be superimposed over pavement edges, curbs and other surface features for ease of identification. The system produces utility locations in X, Y and Z coordinates to within a few centimeters, usually within one or two centimeters. The results of this study illustrated the ability of multi-channel GPR technology to detect and map buried utilities, indicating the utility depths, orientations, and proximities to other surrounding infrastructure.

In addition, Road and Bridge Research Institute (Internal Project PW.S 531) have investigated the implementation of 3D Radar into practical use in road measurements in order to assess its real abilities in road diagnostics [12]. This radar model is a step-frequency system working in range 300MHz to 3GHz what correspond in practice to resolution of 700MHz impulse antenna. The antenna chamber contains 15 transmitter-receiver pairs allowing simultaneous data acquisition along 15 parallel profiles on road lane of width 2.4 m. The system has odometer and GPS antenna that allow excellent synchronisation of data sets collected in different measurement passages and next construction of horizontal slices of some wider area. Using real-time GPS equipment, one decimetre precision of data positioning and synchronisation is available. Thus the system has excellent possibilities in identification and localisation of utilities, combining proper software that developed by the producer, for such large data sets.

The identification of linear objects is based on wide review of horizontal slices, where thick linear objects have fine manifestations, with the possibility to visualise sets of horizontal slices and sets of vertical cross-sections. The effective penetration depth in road environments can be estimated to about 1 up to 1.5 m where some ground horizons were observed in rare cases. Thus the system has some possibilities of sub-base thickness estimation, and can give also fine evidence of media having complicate, strongly irregular, chaotic structure. The equipment is very noise resistive giving fine results in difficult electromagnetic environment where typical impulse antennae fall.

This system has also some disadvantages, from intense multiplications which occur in the case of strongly reflective horizons, inducing reverberations inside the antenna chamber and then difficulties in echogram interpretation. Moreover, the echograms have low resolution and clarity in comparison to corresponding impulse antennae. Nevertheless, the evolution of such array systems tends to propose accurate approach due to high density of measurement, with precise positioning, enabling similar resolution at lower frequencies than single antenna systems.

Among these experimental approaches estimating the performances of GPR systems, signal processing and imaging have been largely studied in numerous research laboratories. In the last few years, the ELEDIA Research Center (DISI - University of Trento, Italy) developed several techniques for real-time detection and classification of buried objects based on learning-by-examples (LBE), such as Support Vector Machines (SVM) [13][14]. A lot of work has been also addressed towards the development of inversion schemes based on the integration of both global and local search algorithms with multi-focusing strategies. As a significant example, the integration of the Inexact Newton Method (INM) with a computationally efficient multi-focusing scheme has been successfully validated in [15] when dealing with GPR measurements. A significant interest has been also addressed towards the application of innovative inversion procedures based on Bayesian Compressive Sensing (BCS) [16] and Interval Analysis [17] to the problem of subsurface prospecting. The localization of sparse metallic targets has been recently addressed in [18] by means of a new technique that models the targets through the local shape function (LSF) approach and solves the inversion problem in a BCS sense.

III. Detection of Voids

The development of voids beneath roadways can lead to major pavement failures. Voids typically develop because of subsidence and erosion of the base and subgrade materials. Void-related roadway problems have often developed near water supply pipes or drainpipes. Leaks, pipe breaks or dislocated joints allow fines to be carried away, resulting in local base or foundation erosion and the formation of weak areas, which eventually become voids. Voids continue to increase in size until the load carrying capacity of the roadway is compromised [19]. Voids can be either air or water filled.

Void detection beneath roadways using GPR is performed in many countries [19, 20]. For example the Texas Department of Transportation

(TxDOT) and Texas Transportation Institute (TTI) have successfully used the GPR technology to locate voids under roadway pavements [21]. The case-study presented here concerns the maintenance of a continuously reinforced concrete pavement (CRCP) section, which presented longitudinal cracks just after a patch repair. This has prompted district personnel to request an investigation to assess the safety of the structure and to determine if there were significant voids under the CRCP.

A 400 MHz ground-coupled antenna was used to survey and map the subsurface condition. GPR data was collected in the longitudinal direction parallel to the faulted joint and at selected transverse locations. A significant anomaly adjacent to the drainpipe was found which started directly under the CRCP. Based on the GPR image, the estimated size of the suspected void was significant (Fig. 2).

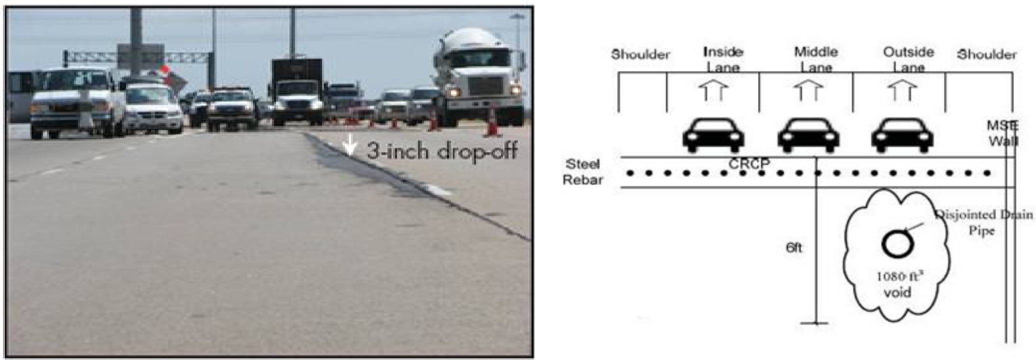
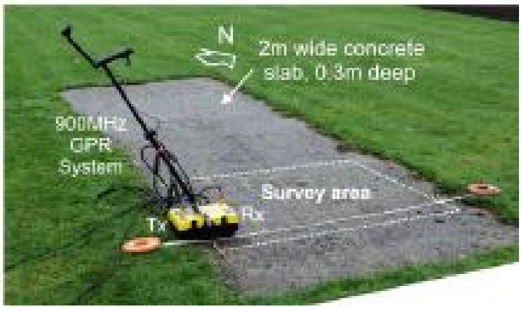


FIG. 2– Example of a drop-off of a continuously reinforced concrete pavement due to voids [19].

The GPR data indicated an anomaly over the transverse storm drain. This drain was separated and it was verified that this separation caused water to erode the area around the drain. Fortunately, the disjointed storm pipe was identified before severe roadway failure occurred.

In terms of concrete investigation, GPR has an excellent reputation for being able to image voids beneath concrete sections [22]. This kind of application was performed in United Kingdom where a test slab was used. The test slab forms part of the NSGG (Near-Surface Geophysics Group of the Geological Society) shallow geophysics test facility at the University of Leicester. The focus of this research was the practical detection of sub-metre scale voids located under steel reinforced concrete sections in realistic survey conditions (a capped, relict mine shaft or vent. Fig. 3 shows the general layout of the reinforced concrete test slab and images of data collection with the GPR.



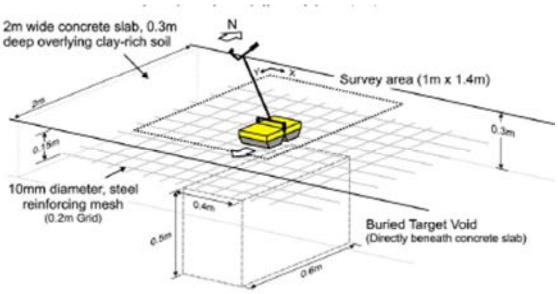


FIG. 3– Target void layout and data collection across the reinforced concrete test slab [13].

A GPR unit with 450 MHz and 900 MHz shielded antenna was used for all GPR surveys, in orthogonal grid, with each trace collected manually at defined intervals and processed using conventional methodologies. The results of these surveys have shown that the selection of antenna frequency is important and that care must be taken with the mode and configuration of the survey geometries.

In 2011, Mara Nord, an international cooperative project financed by Interreg IV A Nord, has been initiated among Finland, Sweden and Norway. In this project, one goal was to produce common guidelines for the use of GPR in asphalt air voids content measurement that could be used as a reference in procurement processes in all three countries [23]. In this framework, GPR technology was used to measure the dielectric value of the asphalt pavement, which was then used to calculate the air void content of the pavement. The method is suitable for measurement of air void content of new bituminous pavements only, regardless of the quality of the base course. It is suggested to be followed when doing survey design, data collection, analysis and reporting with a 2D GPR system prior to an asphalt air voids content measurement.

In pavement and top part of the pavement structure quality control surveys it is recommended that air coupled antennas be used especially when the interest is bituminous pavement and unbound base thickness and their quality. According to these guidelines, in normal cases, it is recommended that a 1GHz antenna be used in asphalt air voids content surveys, but if the amount of new asphalt is 60 kg/m^2 or less then it is recommended that a 2GHz antenna be used.

Concerning the number and location of survey lines Finland has required data collection only from the outer wheelpath and Swedish guidelines require the survey to be done from the outer wheelpath and between wheelpaths. Swedish guidelines can eliminate the effect of traffic compaction from the results. That is why these guidelines recommend that, if only one survey line is measured, it should be measured between the wheelpaths. However recent test results have shown that in addition to the two lines per lane it is also recommended that one line be measured along the pavement joint in lane centre [23].

When using air coupled antennas, after every survey session and before the GPR unit is switched off, a metal pulse reflection should be recorded. It is recommended that a metal reflection is also taken before the start of the measurement. Moreover, air voids content calculations using GPR technique requires calibration drill cores and at least 2 drill cores have to be taken and analyzed. The place of the drill cores should be selected first by measuring the whole road section and then by selecting places for the calibration cores from homogenous sections where dielectric value of the asphalt surface is close to the approximate average dielectric value of the new asphalt.

Several processing techniques, such as GA-based integrated strategy, have been proposed and assessed in [24] with unknown defects both in location and in size situated inside dielectric host mediums. Moreover, in [25] a new approach based on the integration between a multi-scaling procedure and the level-set-based optimization has been proposed, aimed at the reconstruction of the shape of multiple and disconnected homogeneous scatters. Such an approach can be clearly applied to the problem of void detection, as well as to the retrieval of metallic objects, by exploiting measurements collected from GPR systems.

IV. CONCLUSIONS

GPR has been used successfully with other technologies to identify and locate utilities—often previously unknown—prior to excavation, coring, or boring activities. Yet its full potential for augmenting subsurface utility-mapping has not been adequately researched, demonstrated, or determined. Part of this limitation has been due to the overwhelming use of single-channel GPR systems, as well as highly variable training and expertise in its use on an ad-hoc basis.

Over the past several years, significant technological progress has been made both in the hardware and software imaging systems dedicated to simplifying utility-detection, particularly multi-channel 3D imaging and mapping systems integrating GPR with complementary technologies and survey-grade GPS. These systems are capable of collecting larger areas of data more efficiently and more accurately demonstrating the results. It is expected that these collective technological changes will benefit the inspection procedures for effective GPR sensing and mapping of underground utilities and voids.

V. ACKNOWLEDGEMENT

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PROJECT 2.4
"INNOVATIVE PROCEDURES FOR EFFECTIVE GPR INSPECTION OF CONSTRUCTION MATERIALS AND STRUCTURES"
STATE OF THE ART AND OPEN ISSUES

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Abstract

The paper gives a review of methods related to assessment of construction materials properties by the use of GPR technique, focusing on recent research activity of Project 2.4 members in COST Action TU1208. The electromagnetic properties of the investigated media are interesting because they reflect another physical features of the materials (first of all their composition), giving possibility of non-invasive inspection of their condition. Moreover, the assessment of electromagnetic properties (e.g., wave velocity) is an inherent part of any GPR structural study necessary for correct depth recognition or amplitude interpretation. As a result of the review major directions of researches and some general problems of this methodological area were described.

I. INTRODUCTION

GPR measurements are deeply involved in considerations related to material properties of the media being scanned. In GPR measurements electromagnetic properties of the media are manifested extensively and these properties plays crucial role in further interpretations of measurements. Actually, any structural interpretation of the GPR results refers to wave velocity of the medium [1],[2]. On the other hand, the electromagnetic properties are closely related to other physical features of the investigated materials and mainly to their composition and small-scale structure (heterogeneous distribution of the components). Thus, the GPR measurements and results of their interpretation have usually interesting consequences in assessment of some material properties of the scanned medium. The relation between electromagnetic properties and compositional-structural properties of the medium usually needs investigations aimed to the specific category of materials representative for the given area of technology (e.g., concrete structures). This kind of experience formulates interpretation keys which allow successful interpreting the GPR results.

The problem of GPR inspection of material properties and structures has several levels and it links different types of research activity:

- methodologies of structural interpretations of GPR measurements directed on assessment of electromagnetic material properties (reflection amplitude determination, velocity analysis, travel time modelling, migration, hyperbola fitting, etc.);
- methodologies for direct investigation of the electromagnetic properties of the media;
- numerical simulations supporting the structural interpretations or laboratory measuring systems;
- investigations of the electromagnetic properties of specific categories of materials and their relation with other physical features.

II. ELECTROMAGNETIC PROPERTIES OF THE REAL MATERIALS

Most of phenomena observed in GPR practice can be described by the use of complex relative electric permittivity $\varepsilon_r^* = \varepsilon_r' + i \cdot \varepsilon_r''$, characterising interaction of the homogeneous medium with electromagnetic field. The presence of the imaginary part of permittivity $\varepsilon_r''(\omega)$ is responsible for wave absorption and it is closely related to frequency dependence of the real part $\varepsilon_r'(\omega)$, what describe Kramers-Kronig relations [3]. The electrical conductivity of the medium (e.g., salt water, porous rocks filled with electrolytes) is a phenomenon belonging to the category described by the imaginary part of permittivity, but absorption is not necessary associated with explicit conductivity (e.g., dry concrete, clay minerals) [3],[4]. The derivative electromagnetic properties used for material characterization - like wave velocity, reflection coefficients and plenty of quantities proper to numerous measuring systems - are determined by ε_r^* (and permeability μ_r^*)[1].

A special category of electromagnetic phenomena (reflection, refraction, diffraction etc.) is related to interaction of the GPR signal with inhomogeneous media and in some context these phenomena are called scattering. These effects are particularly interesting when the characteristic dimensions of permittivity anomalies are comparable to local wavelength of GPR signal to cause significant response (scattering), but they are not enough large for generation large scale manifestations on echogram which could be interpreted as a large-scale medium structure. Such situation is typical for real media and it has important practical consequences which can be illustrated by the following examples.

The continuous depth stratification is the first crucial example of the heterogeneity (Fig. 1). In the presented case the permittivity in concrete slab (sampled by drilling core) increases strongly inward, near the top surface. As a result the slab has significantly different permittivity values at the top and at the bottom.

[1] In the case of materials containing significant amount of ferromagnetic minerals the magnetic permeability μ_r^* can play important role [4] in formation of GPR response, but it is very rare exception among construction materials. Thus usually the relative permeability is assumed to be equal to one.

Moreover, in this case the reflection amplitude (peak-to-peak amplitude) measured at the top of the plate (where gradient occurs) is frequency-dependent (Fig. 2) despite the medium has not frequency-dependent permittivity. In the GPR image the stratification is manifested only as some deformation of the surface reflection.

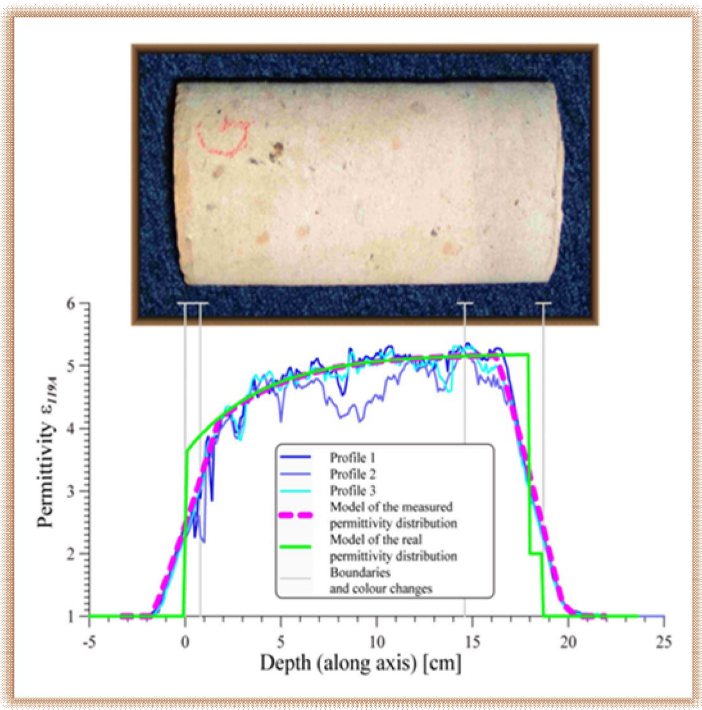

FIG. 1 – Characteristic features of the permittivity distribution in sandy concrete, after [31].

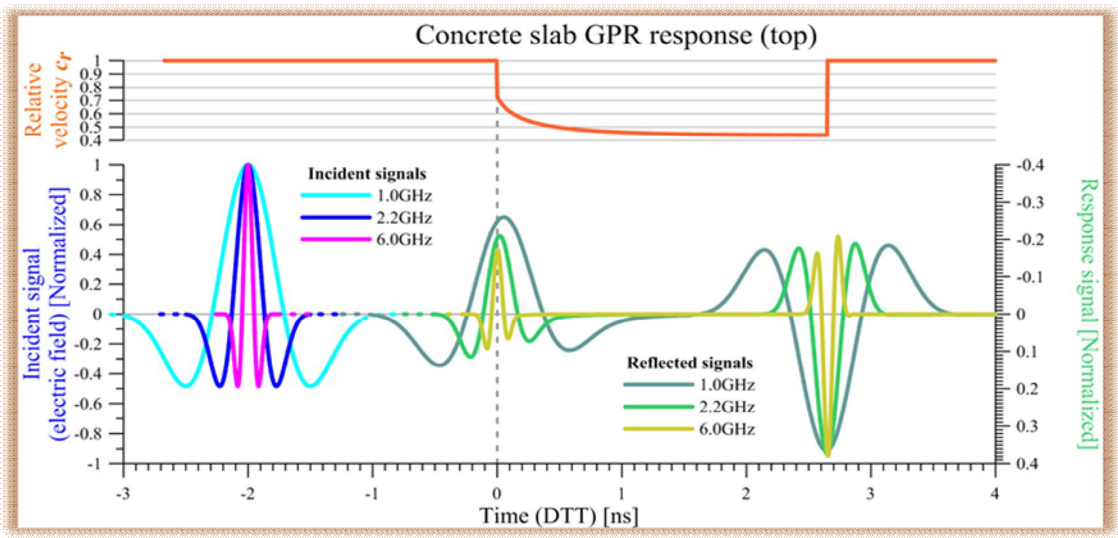

FIG. 2 – Numerical 1-D simulation of the GPR response (air-coupled configuration) of concrete slab having velocity stratification at the top. The shape and amplitude of the surface reflection (about zero time) visibly depends on the impulse frequency, despite the medium is non-dispersive was here.

The second important type of heterogeneity is related to media of granular structure like in stone-asphalt mixtures (Fig. 3). In the presented example smoothed permittivity observed in centimetre space scales, ranges from 6 to 8.

The distribution well illustrates the ‘problem of scaling’ in definition and determination physical properties (and their spatial distribution) of real media.

Any determination is dependent on resolution (smoothing scale) and results have large dispersion giving a measure of local inhomogeneity. Thus, the measurements dedicated to interdependence of parameters are very difficult.

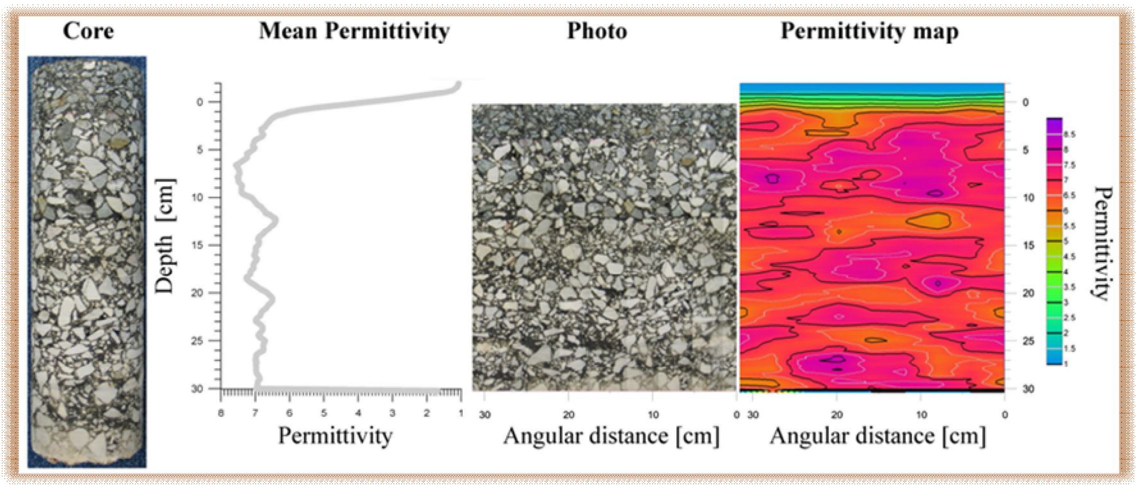

FIG. 3 – Map of the permittivity distribution on the lateral surface of the drilling core (from the right), panoramic photo of the lateral surface and the depth distribution of the level average permittivity and photo of the core [32].

Moreover, the electromagnetic properties are well determined numbers (material characteristics) for the homogeneous medium only. But for inhomogeneous media the primary meaning of these notions falls down and these terms are used in practice as some provisional characterisation of the medium in the frame of the given method. The granular media have also a special type of signal attenuation due to lateral scattering (non-dissipative attenuation). The absorption related to imaginary part of permittivity should be distinguished from wave attenuation related to scattering, but is usually difficult to make this distinction in GPR measurement practice.

III. MAJOR DIRECTIONS OF THE RESEARCHES

Among research efforts, several directions related to different material types can be distinguished. Despite different technical details, they have shared methodological background.

Soils and subgrades materials [5]–[14] have relatively long tradition of GPR investigations [5]. The field investigations are focused on determination of water content [6], [7], [11], [14] and composition (especially content of clay minerals [9], [10] responsible for important bearing properties of subbase [12], [13]). Among laboratory methods one can find determinations of frequency-dependent complex permittivity of soils [8] and specific methods for aggregate permittivity determination based on ‘frequency peak shift’ [9], [10].

The investigations of cement concrete [15]–[27] are focused on moisture content and composition manifested mostly in permittivity value, and on electrolytes (e.g. chlorides) content increasing the absorption. Among numerous approaches one can find analyses of the direct wave amplitude [15], [21], analyses of amplitude, relative attenuation and spectrum of the slab bottom reflection [16], [19], [27] and numerical modelling of the signal interaction with slab simulating the real geometry of the measuring system [17], [22]. These efforts allow for non-invasive determination of the slab permittivity and absorption in adequate [22] and efficient way [20] and some of them can be used in the field investigations [18]. Laboratory investigations of concrete properties focus on determination of complex permittivity as a function of frequency [23], [24], dependence of the permittivity on composition [25], [26] and considerations related to perspectives of complex permittivity determination on the base of refracted wave analysis [23]. The investigations of concrete properties have large practical industrial use (assessment of the concrete type, degree of degradation), as it is widely used construction material [personal communication from *Geofisica Consultores* (Spanish Geophysical Consulting)].

Investigations of asphalt mixtures [28]–[34] are focused on composition, estimations of void content [30], [34] and moisture content. Permittivity values are dominated by properties of the stone fraction of the mixture but compaction degree has also some significance. The laboratory determination of permittivity and its relation with composition is very difficult due to coarse grain structure of this material. Thus, the investigations of fundamental properties are rare [28], [29], [32], [33] and some predictive relations [4] are frequently used [30] instead of reliable estimations.

The strongly heterogeneous structure of asphalt mixture [32] and its interaction with high frequency GPR signal is a large area for future investigations.

For alternative determinations of permittivity and absorption some auxiliary non-GPR techniques are being used (capacimetry, resistivity measurements and imaging, TDR etc.).

It is worth to note that these alternative methods and comparative studies of different GPR approaches plays crucial role in development of the material testing techniques. The measuring systems have usually not elementary geometry influencing the results, and this influence cannot be well described by simple models. Comparative studies using reference materials and the same samples give possibility of the methods verification and allow estimating the influence of different types of material heterogeneity on results. Comparative studies help also to identify problems which are not visible in the frame of one approach.

IV. CONCLUSION

The review of the research efforts related to construction materials GPR testing shows large importance of comparative studies of the measuring methods. These comparisons are necessary for ability assessment and verification of these methods. This diagnostic discipline is an interesting and fruitful area for numerical modelling commenting on measuring procedures (with regarding the real geometry of the measuring systems). Investigations of heterogeneous materials structure and their GPR response constitute a large and relatively new research area.

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PROJECT 2.5
"DETERMINATION, BY USING GPR, OF THE VOLUMETRIC WATER CONTENT IN STRUCTURES, SUBSTRUCTURES, FOUNDATIONS AND SOIL"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Volumetric water content assessment in structures, substructures, soils, and subsurface in general is a crucial issue in a wide range of applications. The main disadvantages of subsurface moisture sensing techniques are usually related both to the lack of cost-effectiveness of the measurements, and to unsuitable support scales with respect to the extension of the surfaces to be covered and to the dimensions of the target to detect. In this regard, ground-penetrating radar (GPR) is an increasingly used non-destructive tool specifically suited for characterization and imaging. Several GPR techniques have been developed for different applications. In the case of moisture evaluation in concrete, the detection is important for the diagnosis of concrete structures at early stages of deterioration: water penetrating into the concrete pore networks contributes to the transfer of degrading and corrosive agents such as chloride. Concerning the particular case of identifying soil surface water content, two GPR approaches are commonly used, namely the ground-wave method and the reflection method; further, a different approach to shallow soil water content estimation is based on the analyses of the surface reflections of an off-ground system. This can be performed by using traditional off-ground methods or by using inverse modeling of an off-ground monostatic GPR system.

I. INTRODUCTION

Volumetric water content (VWC) dynamics in structures, substructures, soils, and subsurface in general is a key component in many fields of application such as agriculture, construction, geotechnical stability analyses, hydrological, and other environmental studies. Usually, water content measurements techniques at the field scale are invasive as well as time-consuming methods, e.g., gravimetric sampling or time-domain reflectometry (TDR) [1].

In that respect, ground-penetrating radar (GPR) is an increasingly used near-surface remote sensing tool specifically suited for characterization and imaging. Many efforts have been devoted to the use of GPR since the 1960s, particularly in archeology and civil engineering for detecting buried objects or investigating subsurface structures [2]–[4]. Several GPR techniques addressed to moisture sensing have been developed for different applications [5], [6] and materials: concrete structures [7], natural soils [8] as well as hot-mix asphalt layers [9] require specific approaches and model assumptions to reliably estimate the subsurface volumetric water content. In this paper, an overview of the most diffused techniques in VWC sensing is presented, also providing some insights for further developments of the researches.

II. VOLUMETRIC WATER CONTENT IN CONCRETE STRUCTURES

The detection of moisture is important for the diagnosis of concrete structures at early stages of deterioration as it determines most of the physicochemical pathologies, such as steel reinforcement corrosion, alkali-aggregate reaction, and freezing-and-thawing cycles. In that respect, Sbartaï *et al.* [10] observed that the risk of damage is strictly related to the degree of saturation or the moisture content in concrete. In this context, the use of traditional methods (e.g., electrical resistivity measurement or half-cell potential test) for assessing the condition of structures, is time-costly and requires lane closures for the sounding of bridge decks, with regard to the particular case of road inspections.

On the contrary, GPR is a powerful technique to characterize concrete moisture, as it can effectively investigate large surfaces in a relatively short time period. Many experimental studies have been carried out in the past for assessing the effect of concrete moisture variation [11]–[13] under controlled water content conditions. Further researches by Klysz and Balayssac [14] showed that the direct wave velocity and its variation of amplitude are linearly linked to the volumetric water content of the concrete, independently of its porosity. Both attenuation and velocity are sensitive to moisture and they can be used for a twofold purpose: VWC and salt content estimation. In this regard, many efforts have been also devoted to the determination of chloride contents in concrete, directly exposing structures reinforcement to corrosion [15]. Sbartaï *et al.* [16] tested the efficiency of the neural approach for predicting water and chloride contents of concrete by inversion of radar measurements. The results show that artificial neural networks may be implemented to model the experimental relationship between water and chloride contents of concrete and radar signal features, e.g., amplitudes of direct and reflected waves and propagation delays. Good prediction accuracy and a high capacity of generalization were obtained both for water (absolute error ≈ 2%) and chloride contents (absolute error < 0.5 kg/m^3).

More recently, Ihamouten *et al.* [17] studied the validity of the various intermethod coupling by characterizing four concrete mixtures at different water contents. Such approach is based on a coupling between the results of the wave–field transforms (transformations from time–displacement plans to temporal-frequency–spatial-frequency plans) and those of the *Q*-estimation methods. Promising results were obtained: the characterization of the hydric status of various concrete mixtures was possible by taking into account both the real and imaginary parts of permittivity over a large GPR bandwidth.

III. VOLUMETRIC WATER CONTENT IN UNSATURATED SOILS

Over the past decades, ground-penetrating radar has been a widespread instrument in the areas of unsaturated zone hydrology and water resources. Amongst the various applications, it has been used to identify soil stratigraphy [2], to assess subsurface hydraulic parameter [18], to locate water tables [19], and to measure soil water content [20]–[22]. Many petrophysical relationships exist to evaluate subsurface moisture [23], [24]. Further, it is well-known that the amount of water in soil pore spaces influences the complex permittivity of soils as the solid matrix permittivity is usually low over a wide range of frequencies [25]. Therefore, soil moisture content can be effectively evaluated by using high-frequency electromagnetic (EM) techniques.

Nowadays a gap between small-(< 0.01 m^2) and large-(> 100 m^2) scale measurements is still encountered. In fact, small-scale (e.g., capacitive sensors and TDR) and large-scale measurements (e.g., airborne and space-borne passive microwave radiometry and active radar systems [26]) are commonly used to characterize shallow subsurface soil water content. On the other hand, a few amount of instruments is suited for intermediate-scale (0.01-100 m^2) characterization of shallow subsurface soil properties.

Amongst the latter, GPR has proved to be the most promising technique for accurately soil moisture sensing [27]–[33]. In this regard, two GPR approaches are commonly used, namely the ground-wave method and the reflection method. Concerning the first one, surface VWC can be derived from the ground-wave propagation velocity [34]. The ground wave is the signal that travels directly from the source to the receiving antenna through the soil surface. It can be recognized in data collected using a multi-offset GPR acquisition configuration and its velocity can be determined from the slope of the linear relationship between the antenna separation and the ground-wave travel times. The main drawbacks of multi-offset GPR measurements include: 1) the method is time-consuming; and 2) a large horizontal distance of averaging for soil permittivity. The second approach is the surface reflection coefficient method, which uses off-ground radar configurations [35], [36]. The soil surface dielectric permittivity is derived from the Fresnel reflection coefficient, which is determined from the ratio between the amplitude of the reflection at the soil surface and the one obtained for a calibrating perfect electric conductor (PEC). However, this method still remains mostly unused nowadays for real-time mapping applications, mainly due to the requirement for such calibration [36]. In that respect, Lambot *et al.* [37] used an inverse modeling of an off-ground monostatic GPR system with the possibility of a full wave inversion of the radar signal, which takes into account the antenna effects and does not require an antenna height-specific calibration above a perfect electric conductor (e.g., a metal plate). Conversely, this approach includes the relatively time-consuming wave field inversion and uncertainties in antenna calibration that may cause possible errors.

Concerning further insights, one of the major open issues is in determining hydraulic soil properties in a changing water content profile from time-lapse monitoring measurements [38].

IV. CONCLUSION

In this review paper the issue of VWC sensing, by using GPR, has been analyzed for different materials according to various fields of application mostly focusing in the civil engineering area.

Theoretical and empirical approaches have been briefly reviewed showing different requirements on the basis of the surveyed material according to the medium properties. Some recent advances together with some unexplored topics outline promising research scenarios to deepen in the next future through the development of reliable models for volumetric water content assessment.

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WORKING GROUP 3

EM methods for near-field scattering problems by buried structures; data processing techniques

PROJECT 3.1
"DEVELOPMENT OF NEW METHODS FOR THE SOLUTION OF FORWARD ELECTROMAGNETIC SCATTERING PROBLEMS BY BURIED STRUCTURES"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Methods developed to solve forward electromagnetic scattering by buried objects are useful tools for interpreting data from Ground Penetrating Radar responses. Time-domain methods, as Finite-Difference Time Domain or space-time integral equations, are well established tools in the modeling impulse Ground Penetrating Radar systems. Integral equation methods, when solved with Method of Moments discretization, lead to dense linear system. Therefore, the implementation of novel approaches approximating the integral equation via series expansions with lower computational complexity is called for. Analytical techniques have the advantage to be accurate and fast, as the geometry of the scattering problem is taken into account by an expansion of the fields in terms of suitable basis functions.

I. INTRODUCTION

The development of methods for the solution of the forward scattering by buried objects has a wide interest in the field of Ground Penetrating Radar (GPR) [1]. In this context, the modeling of forward scattering is useful in the interpretation of data collected in the GPR surveys, in the testing of new data processing techniques, and in general to improve the understanding on the complex interaction between the electromagnetic field radiated by the radar antenna and the buried targets.

The physical and geometrical parameters implemented in the forward solvers must be capable to represent the scattering scenario in a manner which is as realistic as possible.

Some of the main issues are the accurate modeling of target geometry, a suitable representation of the source field radiated by the radar antenna, and the simulation of losses both in the embedding media. Two-dimensional problems may be considered in many cases, when the buried object have transverse cross-section which is small compared to the longitudinal size.

The use of time-domain techniques, especially Finite-Difference Time-Domain (FDTD) method [2]–[4], is well-established to investigate and numerically simulate GPR responses. In many scattering problems, an approach of wire modeling of the target may be used, in either time-[5], [6] or frequency-domain [7]. Another well-established method is based on integral equations; a novel approach of solution, alternative to Method of Moments (MoM) discretization, is proposed in [8], [9]. The development of analytical techniques extends the classical problem of scattering by a cylinder in free space, in the presence of one or more planar or rough discontinuities. Such techniques have to cope with the difficult task of handling different geometries, which can be fulfilled by means of plane-wave spectrum expansion of the involved functions relevant to the scattered fields [10]–[12].

In these paper, a review on the main established techniques and recent advancements, carried out by the participants of the Cost Action TU1208, for the modeling of forward scattering by buried objects is presented. Section II is dedicated to time-domain methods. A novel integral equation method is described in Section III. In Section IV, analytical approaches for two- and three-dimensional scattering problems are reported.

II. TIME-DOMAIN APPROACHES

Time-domain techniques are well suited in the frame of GPR applications, dealing with the scattering by a pulsed signal.

Among the possible approaches, FDTD method is a well-established one. A free of charge FDTD software tool developed to simulate GPR responses is GprMax, developed by Giannopoulos [2]. Both two-dimensional (GprMax2D) and three-dimensional (GprMax3D) models can be analyzed with this FDTD software. GprMax2D is mainly used for GPR "signature" simulations, whereas GprMax3D is used for a more realistic modeling of GPR problems, especially when comparisons with measured GPR data must be performed.

A fundamental issue in the modeling of GPR problems is the simulation of open boundaries, whereas FDTD takes into account of a finite simulation space, where all the source and output points, as well as the significant targets, are included. In [2], Absorbing Boundary Conditions (ABCs), applied at a sufficient distance from the source and the targets, and capable to simulate an unbounded geometry, are used to limit the computational space.

The main limitations in the FDTD method are in the staircase approximation of curved interfaces, and in the conditionally stable nature of the FDTD. The condition of stability, known as CFL, states that the three spatial variables Δx, Δy, and Δz, and the temporal discretization step Δt cannot be assigned independently. Therefore, when a small spatial step is used for an adequate modeling of the objects in the computation domain, the allowable discretization time-step used in the FDTD time-advancement is small as well. Moreover, the choice of small spatial steps in the simulation of structures of fine geometry in a large computation domain results in high computer memory requirements and long execution times. A solution to this problem has been proposed by Diamanti and Giannopoulos in [3], where subgrids with small spatial steps are introduced in a coarser FDTD grid.

The implementation of the subgrids is particularly useful to model parts of the computation domain with finer detail, or when regions with high dielectric constants supporting waves propagating at very short wavelengths are included in the computational mesh. An example of subgriding scheme has been also presented in [4], applied to simulate GPR responses from delaminations in brick masonry arches.

In many subsurface sensing applications, especially communication, power cables and geophysical investigations, thin wires can be used for the modeling of buried targets. In the literature, the electromagnetic field coupling to an arbitrary configuration of buried thin wires is solved with two main approaches: transmission line (TL) and wire antenna theory. TL approach [7], developed in the frequency domain, is based on telegrapher's equation. It may lead to a satisfactory approximation for long straight conductors with electrically small cross sections but it is not valid for finite length wires, wires of arbitrary shape and high frequency excitations.

For a more rigorous solution, applicable to finite-length buried wires of arbitrary shape, antenna wire methods can be used [5]–[6]. Solution is carried out in the time-domain, evaluating the transient current excited on a thin wire buried in a lossy half-space, in case of an electromagnetic pulse excitation. This formulation deals with space-time integral or integro-differential equation, of Hallen or Pocklington type, solved via the Galerkin–Bubnov scheme of the indirect boundary element.

III. FULL-WAVE INTEGRAL EQUATION APPROACHES

Integral equation approaches are widely used to model scattering phenomena. The equation is typically solved in a discretized way, making use of MoM. Anyway, MoM solution generally leads to a dense linear system, that turns out to be more and more costly the more complex is the scenario to be modeled.

The main drawbacks peculiar of MoM discretization can be overcome with the Contrast Source-Extended Born (CS-EB) method. It is an alternative full-wave integral equation approach proposed by Isernia et *al*. [8] for free space scattering problems, and extended by Crocco et *al*. [9] to the analysis of two-dimensional subsurface scattering problems. In the CS-EB method a rewriting of the traditional integral equation of two-dimensional scattering problems in terms of the so-called Contrast-Source equation is performed, exploiting the properties of Green's function in lossy media. Then, the obtained equation is linearized via series expansions, in a way very similar to the EB approximation. In this new approach, forward scattering problems can be conveniently solved by means of very simple series expansions, which allow a lower computational complexity and memory storage with respect to other iterative schemes.

The scenario analyzed by the CS-EB in [9] considers two half-spaces separated by a planar interface, and one or more targets are buried in the lower medium. A multistatic/multiview configuration is used, with N_T time-harmonic TM-polarized line sources located along a rectilinear domain Γ_T at a distance y_T from the interface, and N_R elementary probes displaced along the rectilinear domain Γ_R at distance y_R (see Fig. 1 in [9]).

The CS-EB model can be applied both to forward and inverse scattering problems. In case of direct scattering, the CS-EB model turned out to be particularly advantageous in the simulation of losses in the embedding medium and/or in the target.

IV. Analytical approaches

Analytical approaches for the solution of forward electromagnetic scattering by buried objects must be able to simultaneously copy with different geometries, i.e., one or more planar boundaries and the shape relevant to the buried scatterers.

An analytical approach solving a wide class of scattering problems is the Cylindrical Wave Approach (CWA), proposed by Frezza et *al*. [10]. In this pioneering on CWA, the problem of plane-wave scattering by perfectly-conducting (PEC) circular cross-section cylinders buried in a semi-infinite medium is solved. The total field in each medium is decomposed into field contributions, produced by the interaction between the incident field with the interface and the cylinder. They are distinguished in plane-wave fields and scattered field contributions, belonging to the latter group the field scattered by the buried targets in the lower medium, and the scattered-reflected and scattered-transmitted fields dealing with the interaction between the scattered field and the interface. The fundamentals of the technique are the use of cylindrical waves as basis functions of the scattered fields, and of plane-wave spectrum of a cylindrical wave to solve reflection and transmissions of such waves by a planar interface.

An accurate integration algorithm has been developed for the numerical solution of the spectral integrals relevant to the cylindrical waves used as basis function of the scattered fields. The resulting numerical code implementing the CWA theory is fast and accurate, leading to results both in near- and far-field regions.

The rigorous CWA formulation has paved the way to a successful extension of the method to more complex scenarios of scattering by buried objects, dealing with layered media, rough surfaces, or the excitation from a line-source.

In the above mentioned problems, checks based on the Same Area Rule (with PEC scatterers) and Same Volume Rule (with dielectric scatterers) have highlighted the possibility to simulate cylinders with arbitrary cross-section, through suitable arrangements of smaller cylinders.

A fundamental improvement to the CWA has been given with the development of a solution for cylindrical waves in a dissipative medium [11], which has been implemented in the case of scatterers buried below a flat interface in a semi-infinite medium.

On the side of three-dimensional scattering problems, a recent work has been published on the scattering of an elliptically polarized plane wave by a sphere buried in a dielectric half-space [12]. The electric field components of the incident and the scattered monochromatic plane waves have been expanded in series of vectorial spherical harmonics. A generalization of the method to the case of a short pulse scattered by a buried sphere has been presented, taking into account the dispersive properties of the involved media.

V. Conclusion

In this review paper the main approaches to the forward solution of scattering by buried objects have been recalled. In the presented works, a strong effort is devoted to implement accurate electromagnetic tools for the modeling of general scattering scenarios, with a particular interest in the field of GPR applications.

Among the possible techniques, FDTD turns out to be the most versatile for the simulation of complex problems, in terms of background and target geometry, and source modeling. Its main limitations are in the execution times and memory requirements relevant to high computational domains, and in the staircase approximation of curved scatterers. With targets of canonical shape, analytical and integral equation approaches may lead to a faster as well as accurate solution. An example is the wire antenna method, efficient in the simulation of buried pipes or power cables. The integral equation approach solved with the CS-BE method is an advantageous method in the simulation of targets buried in a lossy soil, as its formulation exploits of the properties of the Green's function in a dissipative medium.

Possible developments of this technique may be the extension to three-dimensional problems and non-homogeneous embedding media. In the CWA, an open issue is the development of the cylindrical-wave solution in dissipative media for a wider class of scattering scenarios, i.e., the problems of targets embedded in layered media, in the rough surface case, and with the line source excitation. For this particular source field, a further important advancement in the CWA would be offered by the development of a solution with a pulsed field. This novel time-domain approach may be particularly useful in modeling of targets with curved boundary, which is one the major limitations in FDTD technique.

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PROJECT 3.2
"DEVELOPMENT OF NEW METHODS FOR THE SOLUTION OF INVERSE ELECTROMAGNETIC SCATTERING PROBLEMS BY BURIED STRUCTURES"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Ground Penetrating Radar (GPR) is a non-destructive imaging technique able to provide high-resolution images of subsurface. From a theoretical point of view, it requires to solve an inverse problem, where a set of parameters describing the underground scenario must be retrieved starting from samples of the measured electromagnetic field. In this paper, the state of the art of recent inversion approaches is reported.

I. INTRODUCTION

The problem of imaging buried targets (subsurface imaging) has been the subject of a great deal of research as it finds application in a very large number of research fields (see [1]–[10], for example). In order to succeed in subsurface imaging a number of requirements must be complied with and traded off. These include hardware definition, that should allow for relatively small systems (for portability), ultra-wide operating bandwidth, low levels of the direct coupling between TX/RX antennas, antenna characterization in complex media, numerical modeling, effective forwards solvers and data processing algorithms [11]–[18]. Concerning data processing, since targets are buried within an extremely complicated scene (usually inhomogeneous with media that can be lossy and dispersive), before imaging clutter suppression, medium estimation and antenna deconvolution are generally needed.

In this contribution we focus only on the imaging procedure. In particular, a quick overview of different methods of subsurface imaging is provided within the framework of the electromagnetic scattering equations. First, the very popular migration algorithms are recalled (Section II). Furthermore, in Section III, the scattering equations are briefly introduced. It is shown that the subsurface imaging is a special case of inverse scattering problem. Accordingly, it is a non-linear and ill-posed problem. Despite of that, we start by presenting imaging algorithms based on simplified linearized scattering models and establish a connection with the migration ones. Then a discussion on non-linear inversion methods follows in Section IV. Section V is devoted to the description of a more recent class of imaging algorithms, the so called "qualitative" methods such as linear sampling, MUSIC. etc. Concluding remarks end the paper.

II. MIGRATION

Migration algorithms basically achieve imaging by re-focalizing diffraction hyperbolic patterns appearing in the data (B-scan). From the pioneering work of Hagendoorn [19] a number of different implementations followed. A non-exhaustive list includes the Wave Interference Migration [20], the A-scan-driven and the pixel driven approaches [21], the Diffraction Summation [20], the Range Migration [22], the Synthetic Aperture Focusing Technique [21], the F-K Migration [23] and the Kirchhoff integral equation [24]. The relationship between these different migration schemes has been recently discussed in [25].

The mathematical rationale of migration is provided by the homogeneous wave equation in conjunction with the so-called "exploding source model". However, this mathematical model internally contains an implicit contradiction: while the field is back-propagated as a solution of a homogeneous wave equation the exploding source assumes it being radiated by a localized source. The extrapolated field can be also interpreted as a Rayleigh-Sommerfeld hologram that coincides with the so-called Generalized Holography [26] (when data are collected over an infinite line). This connection is import because it establishes, in rigorous way, through the Porter-Bojarski integral equation, the relationship between the migrated field and the secondary sources.

III. LINEAR INVERSE SCATTERING APPROACHES

The scattering phenomenon can be described in terms of the Lippmann-Schwinger system of equations [27]

$$\begin{aligned} E &= E_{inc} + A_{STATE}(\chi, E) \\ E_S &= A_{DATA}(\chi, E) \end{aligned} \tag{1}$$

where E_{inc}, E_S and E are the incident, the scattered and the total fields, respectively, A_{STATE} and A_{DATA} are integral operators accounting for propagation through the relevant Green's functions. Finally, χ is the target contrast function. The reconstruction problem thus consists of inverting the system of equations (1) for the contrast function once E_S has been collected. This entails solving a non-linear inverse problem. The problem can be drastically simplified by invoking some approximate models (i.e., Born, Rytov [27], Extended Born [17], Kirchhoff [28], etc.) so that the scattering phenomenon may be modeled through a linear operator. However, the problem still remains ill-posed. To cope with this drawback, inversion can be achieved by some regularized scheme. Basically, regularization consists of replacing an ill-posed problem by a parameter dependent family of well-posed neighboring problems so that to establish a compromise between accuracy and stability [29], that is

$$\chi = A_\epsilon^\alpha E_S \tag{2}$$

where A_ϵ^α is the regularized inverse, α is the so-called regularization parameter, and ϵ the noise level. In particular, as $\epsilon \to 0$ also $\alpha \to 0$ and the regularized reconstruction tends to the generalized inverse. A large number of regularization methods have been devised. Very popular are the variational Tikhonov method and the iterative Landweber procedure [30]. Other methods are based on metric or statistic information criteria [31]. However, it can be easily show that all of them result in a filtering of the singular spectrum of the linearized scattering operator. It is clear that, apart the computational convenience that can dictate the regularization algorithm to adopt, the key question is the choice of the regularization parameter. This choice must be done by accounting for the noise level, the mathematical features of the operator to be inverted and the available a priori information about the unknown.

Different methods exist to select the regularization parameter. Such methods can explicitly exploit the knowledge of the noise level, (such as the Morozov discrepancy principle) or not (such as the generalized cross validation) [32]. Finally, it can be easily realized that migration substantially, corresponds to achieve inversion by means of the adjoint of the linearized scattering operator. This allows to obtain stable reconstructions, however as pointed out in [25], it is not a regularization scheme in the sense of Tikhonov and hence an intrinsic limit on the achievable resolution exists [33].

IV. NON-LINEAR INVERSE SCATTERING APPROACHES

Linear inversion schemes are computationally effective and flexible. However, they generally allow to retrieve only targets' geometric features. In order to obtain "quantitative" reconstructions the non-linearity of problem must be tackled.

A first step towards this direction is to consider high order Born models [34], [35]. However, in general the full-nonlinearity must be addressed.

Nonlinear inversion procedures can be coarsely divided in two main classes: stochastic and deterministic methods.

As to the first class, the inversion of the scattering equations is recast as an optimization problem [36], [37] and solved by using stochastic minimization algorithms, such as genetic or swarm optimization algorithms. In these methods, a set of trial solution is iteratively modified (according to some stochastic rule) until the minimum of a predefined cost function is obtained. The main advantage of these approaches is that they are in principle able to find the global minimum of the problem, thus reducing the possibility of obtaining false solutions [38].

The cost function is usually defined as the difference between the measured data and the field computed by means of the assumed propagation model, that is

$$f(\chi, E) = w_D \|E_S - A_{DATA}(\chi, E)\|_2^2 + w_S \|E - E_{inc} - A_{STATE}(\chi, E)\|_2^2 \tag{3}$$

where w_D and w_S are weights used to adjust the data and state contributions. In order the avoid considering the internal electric field as an unknown of the optimization problem, the two scattering equations can also be combined together in order to obtain a single non-linear operator $A_{NL}(\chi)$ [39]. Moreover, since one of the main drawbacks of stochastic approaches is the high amount of computational resources needed to perform the inversion, often only a limited subset of parameters describing the underground scenario is reconstructed (e.g., the position, size and dielectric properties of buried targets [40] or the coefficients of a parametric curve describing the shape of the object [41]).

Deterministic approaches, on the contrary, start from an initial solution (usually an empty investigation area if no a-priori information is available) and iteratively modify the solution according to some deterministic rule. The main drawback of such class of approaches is however that they can be trapped in local minima, corresponding to false solutions. An example of this type of approaches is the distorted-Born iterative method [42], in which the problem is solved by iteratively constructing a linearized problems by means of the distorted-Born approximation (at every step it is necessary to solve a direct problem for updating the Green's function); the linear problem is then solved by using a conjugate gradient method.

In [43] an inversion method based on an inner-outer scheme is used; the outer loop is a Gauss-Newton linearization scheme, whereas in the inner loop the obtained linearized problem is solved in a regularized sense by means of a truncated Landweber method. The contrast source inversion (CSI) method can also be applied. The key advantage of CSI is that it does not require to solve a full direct problem at every step.

Different forms of the scattering equations, such as the Contract Sources–Extended Born one [44], have also been derived in order to obtain improved reconstruction accuracy.

V. PROJECTION METHOD AND OTHER INVERSION APPROACHES

A further class of imaging methods are the so-called qualitative methods.

Such methods are non-iterative and require no approximate scattering models. They aim at recovering the support of the scatterers by adopting some indicator functions which assume very different values depending on whether they are evaluated inside or outside the scatterer domains. Moreover, they do not require the a priori knowledge of the nature of the scatterers. The linear sampling, the factorization and the point-source methods are examples of such a type of algorithms [45]. These algorithms need data to be collected under a multiview/multistatic configuration and their performance can strongly decrease for aspect limited measurements and for reduced number of acquisition [46], [47]. By contrast, they are computationally as effective as linear methods and work in time-harmonic regime. This allows to disregard soil dispersive effects and soil characterization over a large bandwidth. Also the time-reversal-music method is worth mentioning [48], [49].

Other approaches have been proposed, too.

In [50], [51], the position of a target is detected by estimating the scattered field directions of arrival through subarrays processing followed by a statistical filtering and a triangularization technique. In [52] an artificial neural network, trained with a hybrid optimization algorithm that is a combination of intelligent global harmony search and Levenberg–Marquardt algorithms, is used to mimic the electromagnetic tomography system.

Real-time detection and classification of multiple scatterers below the air-soil interface has also been investigated by using learning-by-examples (LBE) techniques, such as Support Vector Machines (SVM) [53].

A further class of data processing algorithms fall within the framework of the sparse minimization borrowed from compressive sensing literature.

This class of approaches are particularly suited for scatterers that project over a low dimensional "dictionary". In these cases, imaging can be cast as the inversion of an underdetermined matrix by adopting minimization in L^1 functional spaces [54]. Inversion procedures based on Bayesian Compressive Sampling (BCS) have been presented [55]. These techniques are able to provide satisfactory reconstructions in correspondence with single and multiple sparse scatterers, showing a remarkable robustness to noise and computational efficiency. However, the regularization parameters must be selected properly [56].

VI. Conclusions

In this paper, an overview of some recent methods for subsurface imaging has been presented. Such approaches have been assuming an ever growing importance, thanks to ability of providing quantitative information about buried targets. However, due to the non-linearity and ill-posedness of the underlying inverse scattering problem, theoretical and implementation issues can still occurs, leading to the need of further enhancing present approaches and exploring new solution paradigms.

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PROJECT 3.3
"DEVELOPMENT OF INTRINSIC MODELS FOR DESCRIBING NEAR-FIELD ANTENNA EFFECTS, INCLUDING ANTENNA-MEDIUM COUPLING, FOR IMPROVED RADAR DATA PROCESSING USING FULL-WAVE INVERSION"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Proper description of antenna effects on ground-penetrating radar (GPR) data generally relies on numerical methods such as the Method of Moments (MoM) or Finite-Difference Time Domain (FDTD) modeling approaches. Yet, numerical methods are computationally expansive and accurate reproduction of real measurements has remained a challenge for many years. Recently, intrinsic modeling approaches, through which radar antennas are effectively described using their fundamental features, have demonstrated great promise for near-field radar antenna modeling. Although such approaches are not suited for designing radar antennas, they are particularly powerful for fast and accurate modeling, which is a prerequisite when full-wave inversion is applied, e.g., for estimating medium electrical properties. These approaches are also of great interest for filtering out antenna effects from measured radar data for improved subsurface imaging.

I. INTRODUCTION

Ground-penetrating radar (GPR) for nondestructive imaging and characterization of the subsurface has been subject to intensive research for many years [1]–[4]. A major shortcoming in current knowledge is the modeling of the radar signal, which is necessary for quantitative reconstruction using full-wave inversion. Existing techniques usually rely strongly on simplifying assumptions regarding electromagnetic wave propagation phenomena, and in particular, neglect antenna effects, which include frequency-dependent radiation pattern, gain, phase delay, mutual coupling, and coupling with the medium of interest. GPR antennas determine the frequency-dependent fields that are transmitted into the subsurface and affect as well the backscattered fields that are measured. In this paper, a general overview of antenna modeling methods is presented and insights are provided for future lines of research.

II. NUMERICAL METHODS

Radar antennas can be modeled using numerical approaches, such as the finite-difference time-domain (FDTD) method [5]–[8], the finite element method (FEM) [9], [10], or the method of moments (MoM) [11], [12]. Yet, numerical approaches need significant computing resources to reproduce 3-D models and suffer from inherent differences between the real and conceptualized antenna models due to the discretization and sensitivity to small differences between the model and the reality: the computational domain needs to be modeled in detail [13]. For instance, Warren and Giannopoulos [6] used a 3-D FDTD approach through which the different parts of transmitting and receiving bowtie antennas were reproduced in the discretized model.

Although relatively good modeling results were obtained for data collected over different emulsions, still significant modeling errors could be observed. These issues can be addressed through the implementation of subgrids into the conventional FDTD mesh to simultaneously account for antenna details and economize on computational resources [14]. Pantoja *et al.* [15] extended a MoM in the time domain for the transient analysis of thin-wire antennas located over a lossy half-space. Numerical analyses showed good results for near-field cases, but where the antenna was not too close to a half-space medium.

III. EFFECTIVE OR INTRINSIC METHODS

More efficient techniques are based on electric field integral equation (EFIE) formulations [16]–[22], through which, for the particular case of antennas, a set of infinitesimal electric dipoles and field points is used. The parameterization of these dipoles to properly describe real antenna radiation patterns is, however, not straightforward [17], [23]. In addition, such formulations do not directly account for wave propagation between the source or field points and the radar transmission line reference plane, i.e., where the field is actually measured, and hence, antenna-medium interactions and mutual coupling are not directly accounted for. For instance, Gentili and Spagnolini [24] modeled a GPR horn antenna at some distance over a 3-D layered medium using an array of frequency-independent source dipoles and a feeding line characteristic impedance. Yet, with this approach the multiple reflections between the antenna terminal section and the medium were not accounted for. Slob and Fokkema [25] used a thin-wire approximation to study the effects of two antennas placed close together on the Earth's surface, and in particular, investigate the coupling between the antennas. They observed that the coupling is not negligible for GPR applications. The influence of the half-space medium on antenna behavior is strong but limited to a fraction of the wavelength in depth.

For the particular case of far-field GPR with applications to planar layered media, Lambot *et al.* [26] proposed a closed-form, frequency-domain, radar equation that simultaneously accounts for: 1) all antenna effects through frequency-dependent global reflection and transmission coefficients and 2) wave propagation in layered media through 3-D Green's functions. This intrinsic antenna-medium model relies on the assumption that the spatial distribution of the backscattered field locally tends to a plane wave over the antenna aperture, which is asymptotically valid in far-field conditions. The model has demonstrated an unprecedented accuracy for describing radar data and retrieving medium electrical properties, including frequency dependence, in a series of hydrogeophysical and engineering applications [26]–[29]. In addition, the validity of that model being theoretically independent of frequency and antenna type, the approach also applies to electromagnetic induction (EMI), i.e., in the kHz frequency ranges where diffusive phenomena are dominant. In that respect, Moghadas *et al.* [30] successfully applied this model to a loop antenna operating in the 30-60 kHz range for soil electrical conductivity determination. Whether for GPR or EMI, it was observed that the so-called far-field condition for the planar field approximation holds when the distance between the antenna and the medium is larger than the antenna aperture dimension. For subsurface characterization and imaging, the far-field condition however strongly limits resolution and penetration depth.

More recently, by resorting to the superposition principle, the far-field model of Lambot *et al.* [26] was generalized to near field conditions [31]. With this approach, the radar antennas are described using an equivalent set of infinitesimal electric dipoles and characteristic, frequency-dependent, global reflection, and transmission coefficients (complex valued). These coefficients determine through a planar field decomposition over the antenna aperture wave propagation between the radar reference plane, point sources, and field points. The interactions between the antenna and layered medium, i.e., antenna-medium coupling, are thereby inherently accounted for. Hence, the antenna characteristic functions are independent of the medium. The fields are calculated using 3-D Green's functions for wave propagation in planar layered media. The model was successfully validated using both ultrawideband frequency- and time-domain radars. Yet, it is worth noting that this approach only applies to planar layered media (at least locally).

Considering buried objects or more complex structures in the subsurface still requires further developments. This closed-form modeling approach can, however, be integrated with numerical formulations such as FDTD or other EFIE-based methods that efficiently scattering by an embedded object.

IV. Conclusion

In this review paper the main approaches to the forward modeling of GPR antennas have been briefly summarized and their importance has been emphasized. A strong requirement is the accurate modeling of the radar data for quantitative reconstruction of medium properties or embedded objects using full-wave inversion as well as for improved radar imaging by removing artifacts that arise from the antenna effects, such as multiple reflections. Each approach shows advantages and limitations, but they are ways that are possible for the development of hybrid methods that should be designed to tackle specific problems and provide an optimal tradeoff between model accuracy, complexity and computational cost. Although available computing resources are ever increasing, inverse scattering problems are usually very demanding and practical applications still need new solutions in that respect.

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PROJECT 3.4
"SHAPE-RECONSTRUCTION AND QUANTITATIVE ESTIMATION OF ELECTROMAGNETIC AND PHYSICAL PROPERTIES FROM GPR DATA"
STATE OF THE ART AND OPEN ISSUES

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Abstract

The design of GPR data processing tools aimed at reconstructing in a quantitative way the characteristic features of a monitored region is an open and challenging issue. This not trivial task requires the development of imaging techniques based on sophisticated models capable of properly describing the involved scattering phenomenon as well as the probing wavelet. This paper aims at describing briefly some of the most relevant advancements reached in the last years. Moreover, some open challenges are traced in order to give some hints to address future works.

I. INTRODUCTION

At microwaves, signal-media interactions are mainly sensitive to electromagnetic parameters and diagnostic technologies working in this frequency range, as Ground Penetrating Radar (GPR) systems, are in principle able to quantitatively image these characteristic features of the probed scene [1], [2]. However, retrieving reliable and accurate information on geometrical and electromagnetic parameters from the scattered field data is still an open issue. This is due to the fact that propagation of microwaves in heterogeneous media is a complex phenomenon governed by diffraction rules and scattering interactions across many scales. Therefore, sophisticated models of the involved scattering phenomena are needed to properly describe the data. In addition, because surface data contains subsurface information from one-sided illumination, the non-linear inverse scattering problem is ill-posed and non-unique [3]. This introduces complications related to false solutions, stability, and accuracy of the results that must be tackled [3],

[4]. The idea to reconstruct the characteristic features of a scene from the waves it scatters, when probed with an interrogating electric field, has been widely considered in the last thirty years and a large number of approaches have been proposed [4]. However, only few of them have been applied and assessed in GPR data processing, which is principally focused on filtering and migration techniques [1], [2].

Nowadays, the continuous advancements in computational resources allow using model based approaches, while respecting the constraint to keep the processing time bearable and ensuring the reliability of the results (i.e., absence of false solutions). In addition the new generation of GPR systems exploiting an antenna array introduces the possibility to probe and observe a scene under different angles. In this way an increased amount of independent information can be gathered during a single survey without impairing the acquisition time. These two innovations open the way for new prospective GPR applications. These also motivate an increasing interest in adopting inverse scattering algorithms able to provide high-resolution quantitative images of the investigated scenario.

The inverse scattering literature being remarkably wide, this paper does not aim at providing a complete review, but only a rough snapshot of some of the most valuable shape reconstruction methods and full-wave procedures proposed in the last years. Some open challenges are highlighted in the Conclusions.

II. Shape Reconstruction methods

Shape reconstruction methods belong to the class of the so-called qualitative imaging procedures and are classifiable in techniques based on approximated scattering models and in methods based on exact models but aimed at retrieving only targets location and support.

The first family has been widely considered in GPR surveys and groups all those procedures based on Born and Kirchhoff approximation, such as those given in [5]–[13]. Currently, there are many examples assessing the performance of these approaches in field conditions, hence they can be considered as mature tools ready to be integrated in the frame of standard data processing chains.

The second kind of approaches, instead, is less common in GPR community and involves imaging strategies as those based on level set theory and the linear sampling method.

Recently, level set theory has received a growing attention in those applications where electromagnetic properties of both scatterers and surrounding media are a priori known. Therefore, the imaging can be accurately formulated as the problem to reconstruct the unknown parameters describing location and contour topology of the scatterers. A pioneering approach to retrieve the unknown cross section of a homogeneous cylinder embedded in a homogeneous medium has been given in [14], while the case of a cylindrical object buried in a half-space has been faced in [15]. Shape reconstruction of 3D penetrable and PEC objects has been also considered [16], [17]. In addition, methodologies integrating a multi-scale strategy and a level-set imaging technique have been proposed in order to exploit the information collectable from scattering experiments as well as available a priori knowledge on the scattering object under test [18], [19].

The linear sampling method (LSM) is an imaging approach worth to be considered, since it is able to retrieve the support of single or multiple scatterers without involving approximated models or a priori knowledge on the dielectric or metallic nature of the objects to be imaged. The applicability of the LSM in those cases wherein a theoretical proof is still missing is supported by its physical interpretations [20]–[23]. On the other hand, despite its advantages in term of simple implementation and computational efficiency, the use of the LSM is at this time notably limited. This is due to the fact that data gathered under a multi-view multi-static antenna arrangements are needed and the reconstruction capabilities dramatically deteriorate with decreasing number of sources and measurement points. The applicability of LSM in GPR surveys has been discussed in [24], where the conditions under which LSM can provide satisfactory results while keeping low the complexity of the measurement system, have been investigated.

Another very suitable technique when multi-view data is available is the wave field imaging technique, which extrapolates total wave fields to the image locations. Because this can be done recursively, it is a highly efficient method and is routinely used since the early 1990’s, e.g., [25].

III. FULL-WAVE INVERSION STRATEGIES

Full wave inversion strategies are those imaging approaches aimed at reconstructing from the measured scattered field data dielectric permittivity and electric conductivity spatial profiles characterizing the investigated domain. The magnetic permeability is taken as a constant with the free-space value. Such a task is often faced by solving an optimization problem where the unknown parameters are iteratively retrieved by minimizing a cost functional, which expresses the distance in the data space between the gathered data and the modeled data [4].

Based on the adopted optimization scheme, these full wave inversion strategies can be classified in stochastic and deterministic ones. The first class adopts a global optimization scheme and offers the advantage to assure the convergence at the global minimum provided that a low number of unknowns need to be found. Therefore, their applicability is feasible only in those few cases wherein the scene to be imaged is actually described by a limited number of unknowns. A review dealing with the use of stochastic approaches with reference to different reconstruction modalities, including tomography, buried object detection, and borehole sensing has been given in [26].

The second class is, instead, based on local optimization, such as the conjugate gradient algorithm, and suffers from the fact that the procedure can be trapped in local minima, which are indeed false solutions of the problem [4], [27]. As a consequence, a suitable starting guess and/or refined regularization procedures have to be adopted in order to assure the reliability of the results [28]. An interesting state of art assessing the potentiality of these approaches as tools to reconstruct unknown permittivity and conductivity profiles can be found in [29]–[31], where the performances of several full wave inversion strategies have been assessed against the same datasets measured in laboratory-controlled conditions. In particular, in [29], [30] the imaging problem has been faced under the 2D scalar assumption, while the 3D vector nature of the scattering phenomenon has been tackled in [31].

While a large amount of promising results are available for the case of targets completely surrounded by the antennas and hosted in a known homogeneous medium, only few and preliminary studies are referred to aspect-limited data, as in on-ground or cross-hole GPR surveys. Moreover, large part of these studies deal with synthetic experiments [32]–[35]. An example referred to laboratory data has been given in [36], where it has been shown that, even if a rough model of the scattering phenomenon is considered, an accurate quantitative characterization of a hidden target is still possible provided that a priori knowledge on its nature is available and the hosting medium is known.

One of the first examples devoted to reconstruct the permittivity profile of a layered medium by experimental data has been presented in [37]. In this paper, the conductivity has been supposed to be known, an 1D geometry as well as an off-ground monostatic commercial GPR system have been adopted. In addition, the probing wavelet has been modeled by exploiting the plane wave approximation.

A first major advancement in the imaging of both dielectric permittivity and electric conductivity has been given in [38], where a laboratory realized off-ground monostatic GPR system has been used and a full-wave inversion method exploiting a sophisticated model of the probing wavelet has been proposed and validated against experimental data. Recent relevant contributions have been provided in [39]–[42]. In [39] a full-wave inversion scheme based on a 2D finite-difference time domain scattering model has been proposed to process cross-hole GPR data. Such an approach has been extended to the 3D vectorial case [40] and applied to process experimental cross-hall data [41]. In [42] a full wave inversion procedure to elaborate frequency domain data gathered under a common-midpoint measurement configuration has been considered. The peculiarity of such a procedure is that the amplitude and phase of the probing wavelet is optimized simultaneously with dielectric permittivity and electric conductivity of a single layered subsurface.

Further works addressing the problem to achieve a quantitative characterization of the surveyed medium are [43]–[47]. In particular, the problem to detect and characterize a thin delamination layer in concrete slabs has been discussed in [43], where the antenna effects are filtered from the measured data with an antenna calibration procedure, and in [44], where the effect of the probing antenna has been modeled in the inversion. In [45], a simple technique to estimate soil parameters from multistatic GPR data, which is based on an integral linear equation relating the field reflected from the air-soil interface to the Fresnel reflection coefficient, has been described and preliminary validated against synthetic data. In [46], [47] the problem to characterize the dispersive behavior of concrete media has been faced by exploiting the Jonscher parameterization of the permittivity. In particular, several variants of the Jonscher model, each one considering just few parameters (not more than four), have been compared in [46]. Herein, a computationally efficient two-step procedure for estimating the four model parameters has been also proposed together with a parametric study aimed at correlating the dispersion parameters with physical and hydric characteristics of concrete mixture. In [47], an algorithm devoted to estimate time delays and dispersion indices of a stratified medium, which exploits the Jonscher parameterization, has been introduced and validated against synthetic and experimental data.

Finally, imaging approaches based on the Bayesian theory are worth mentioning wherein the solution of the inverse problem is given as a probability density function. In this frame, considerable contributions have been recently proposed with respect to cross-hole GPR data [48] and under the hypothesis of single and multiples sparse targets [49], [50]. In this latter case, the proposed approaches offer imaging capabilities, which positively compare with standard deterministic conjugate gradient procedures in terms of reconstruction accuracy, robustness against noise and computational efficiency.

IV. Conclusion

Motivated by the advancements in computational resources and the development of new generations of GPR systems an increasing attention is currently addressed on model based imaging approaches. However, their profitable use in GPR applications requires facing several challenges leading to a formidable task ahead.

The necessity to characterize the background in complex scenarios and to model accurately the probing wavelet are among the most relevant open issues. These are key elements in the formulation of inverse scattering problems. In addition, a study devoted at assessing how uncertainties in the background and probing wavelet affect the imaging capabilities is worth mentioning.

A further key challenge concerns the necessity to properly account for the ill-posedness and non-linearity of the inverse problem, while assuring the reliability of the results and their stability against noise. In particular, finding the factors that affect the degree of non-linearity could result in a valuable breakthrough for the design of advanced imaging and inversion approaches and for optimizing measurement configurations, capable of increasing the amount of information in the gathered data, while keeping the complexity of the hardware devices feasible. These topics have been tackled in part in the inverse scattering literature, so a possible starting point could be the study of previously proposed methodologies and their adaptation to GPR imaging problems. Finally, since the reconstruction capabilities of large part of the model based approaches proposed for GPR data processing have been preliminary assessed only on synthetic data, their validation on experimental data is mandatory first for data obtained in controlled conditions followed by data obtained in real conditions. To achieve this, the availability of datasets to be used as a common benchmark could be helpful to assess and compare the achievable performances.

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PROJECT 3.5
"DEVELOPMENT OF ADVANCED GPR DATA PROCESSING TECHNIQUES"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Ground penetrating radar (GPR) is a nondestructive geophysical method that uses radar pulses to image the subsurface. Notwithstanding it is particularly promising for soil characteristics interpretation, GPR is characterized by a notoriously difficult automated data analysis. Hence, the focus of this paper is to provide the reader with a deep understanding of the state of the art and open issues in the field of GPR data processing techniques. We present an overview on noise suppression, deconvolution, migration, attribute analysis and visualization techniques for GPR data.

I. INTRODUCTION

Ground Penetrating Radar (GPR) mainly consists of a radar device which transmits and receives electromagnetic pulses into the subsurface. GPR applications include sedimentology, ground water contamination, glaciology, archaeology and geotechnical engineering [1]. GPR proves to be very useful in road monitoring applications [2]–[5], pipes, cables, tunnels and other buried objects delineation [6], railways ballast condition monitoring [7], [8], concrete structures inspection and bridge deck inspection [9], buried archaeological ruins mapping [10] and many other relevant applications which have already been applied or are to come in the future.

Here, we will discuss the development of GPR data processing techniques for geotechnical applications. We will present the basic and commonly used signal processing techniques and focus mainly on the enhancement of the GPR signal by advanced signal processing methods like denoising, deconvolution, migration and attribute analysis as well as visualization of GPR data.

II. GPR DATA SIGNAL PROCESSING

Accepting the fact that GPR measurements are dense enough for the delineation of the target and the optimum frequency is selected [11], processing should enhance the GPR signal providing sufficient interpretation. The GPR data processing consists of time-zero corrections, dewow, band pass filtering, spatial filters and gain.

Drift of the zero time along the profile can occur due to temperature difference between the instrument electronics and the air temperature or damaged cables. This drift causes misalignment of the reflections and the zero time has to be reset for all traces along the profile [1]. Dewow removes the low frequency harmonics caused by electromagnetic induction. Many automatic algorithms exist for dewowing but, even though they correct for the low frequency undesired harmonics, they sometimes can cause reverberations. Thus, band-pass or time varying low cut filtering can solve this problem [12]. Spatial filters are mainly used for muting specific form of reflections (horizontal or dipping). The most commonly used gain functions are exponential gain (SEC) and windowed gain functions (AGC). SEC, even though keeps information which is lost by AGC, also slightly alters the shape of the wavelet making it time varying [11]. AGC on the other hand even though enhances low amplitudes, it can be misleading because they also enhance unwanted information and loose the initial spatial relation of amplitudes.

The GPR data processing can also include the following techniques: Time varying band-pass filtering [13]–[15], time and frequency analysis [14]-[16], deconvolution [17]–[22], velocity analysis [23]–[25] and migration [26], [27] as well as attribute analysis [28]–[31]. The main purpose of all the above is enhancing the signal in order to interpret the GPR sections.

III. GPR DATA NOISE SUPPRESSION

Discarding background noise improves visual quality of the reflections of interest [32]. Noise will both affect deconvolution and migration techniques. A number of filtering techniques have been proposed to enhance the SNR of the GPR data. However, most techniques are developed to suppress coherent noise [33]–[36], but there are not many publications related to removing incoherent noise [15], [37]. The simplest way of suppressing random noise is stacking. Simple stacking does not always result in satisfactory improvement of the signal due to amplitude fluctuations between the stacked signals mostly because to

DC quantization errors and imperfect alignment related to synchronization errors when sampling [38]. The authors in [15] utilized user defined time varying band pass filters. Noise suppression can be achieved by: (*i*) Stacking using local correlation [39]; (*ii*) Empirical mode decomposition (EMD) [40] and [41] and (*iii*) Smoothing of the spectrum [42], [43].

IV. DECONVOLUTION

Deconvolution is the process needed to improve the temporal resolution in order to clearly visualize the reflections of interest [20]. A deconvolution algorithm should extract the reflectivity series and thus to improve the temporal resolution and facilitate quantitative data interpretation [18]. It is well understood that increased resolution is necessary in geotechnical GPR data. One reason for that is the reduction of the number of involved antennas. If deconvolution satisfactory improves the resolution for the relatively low frequency antennas, which penetrate deeper and have stronger response [2], the higher frequency antennas may prove to be unnecessary. Additionally there is a need for distinguishing overlapping reflections in the GPR sections for any antenna's dominant frequency.

Despite the popularity of GPR reflection, successful deconvolution applications to GPR data are very rare (e.g., [17], [44], [45]). The authors in [18] and in [22] performed blind deconvolution to GPR data. GPR data time varying deconvolution related to geotechnical engineering was also applied in [21], in order to successfully increase the bandwidth and hence the temporal resolution of the time series. Deconvolution of GPR data has been notoriously unsuccessful for many years mainly due to the non-stationarity of the GPR traces and the mixed phase EM wavelets [19]. Even though [16], [44] and [46] presented ways for inverse *Q* filtering, in most of the cases this inverse *Q* filter suffers in the estimation of an apparent Q value [14]. The authors in [15] developed a narrow time-window methodology applied in the t-f domain [47] for spectral balancing [48], [49]. Furthermore, wavelet deconvolution is successful when applied after spectral balancing and followed by the application of the maximum kurtosis method [19], [20], [50]–[54].

V. MIGRATION

Migration is a method which moves events to their correct time or spatial locations and collapses energy from diffractions back to their scattering points. Until three decades ago, migration was the final processing step for seismics [55]. Today, migrated data almost always provide input for several steps such as detailed analysis of attributes and signal processing methods like deconvolution. The authors in [56] presented an improved Stolt migration algorithm for relatively homogeneous velocity media. A split-step migration technique was implemented in [26] in order to account for dispersion effects, while the authors in [57] implemented a finite element migration method which incorporates attenuation. The insufficient application of migration of GPR data is mainly due to the inability to estimate an accurate velocity model. This is mainly the problem for seismics also [55]. For the successful application of GPR data migration multi-fold data must be acquired [23]-[25], [31], [58]-[60]. Migration can be considered as a smoothing technique which alters the amplitude spectrum by lowering the dominant frequency. This results in a low resolution migrated section [61]. So, consideration should be taken in order to apply post-migration deconvolution methods by treating the amplitude and phase spectrum separately [62], [63].

VI. Attribute analysis and visualization

Attribute analysis and classification are useful for the interpretation of GPR data. There are 5 main categories of attributes:

1. Instantaneous attributes ensure the local information and are calculated via Hilbert transform.
2. Wavelet attributes are computed at the peak of the envelope [64].
3. Texture attributes describe the data samples, through gray-level co-occurrence matrices [65], [66].
4. Geometrical-statistical attributes are calculated directly from the data, within a spatiotemporal sliding window.
5. Coherency-semblance attributes provide spatiotemporal relations of the dataset [67].

The authors in [29] used attributes and Self Organizing Maps to interpret GPR data. The authors in [30] utilized the same tools to map a three arched roman cistern and the ducts which supply water to the cistern, [31] focused on archaeological investigations, while [66] utilizes geometrical attributes for the visualization of active faults.

Other classification techniques are based on the exploitation of Learning-by-Example (LBE) strategies for the detection and classification of buried objects by using Support Vector Machines [67] or Support Vector Regression [68]. Great efforts have been also devoted towards the development of inversion techniques able to profitably combine global and local search approaches with multi-focusing strategies, such as the Iterative Multi Scaling Approach [69] or imaging approaches based on Bayesian Compressive Sensing [70], [71] and Interval Analysis [72]. Finally, specific processing has been recently developed, including the Jonscher parameterization of the medium [73] or the so-called a transparent 3D half bird’s-eye view of the GPR data volume or its sub-volumes [74]–[77].

VII. Conclusions

This paper presents a review of GPR data processing techniques needed for geotechnical applications. We have focused mainly on the enhancement of the GPR signal by signal processing methods like denoising, deconvolution, migration and attribute analysis. Notwithstanding this research area has already been well studied by many researchers, more is needed and even more is expected from automatic GPR data analysis.

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WORKING GROUP 4

Different applications of GPR and other NDT technologies in CE

PROJECT 4.1
"APPLICATIONS OF GPR AND OTHER NON-DESTRUCTIVE TESTING METHODS IN ARCHAEOLOGICAL PROSPECTING AND CULTURAL HERITAGE DIAGNOSTICS"
STATE OF THE ART AND OPEN ISSUES

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Abstract

This paper is concerned with a brief review of the recent advances related to the use of GPR and its integration with other techniques in the applicative domain of the archaeological prospecting and cultural heritage diagnostics and monitoring. In particular, the main scientific/technological challenges are identified and possible strategies to tackle them are devised with a particular interest to the role that the COST Action TU1208 could play.

I. INTRODUCTION

Ground Penetrating Radar (GPR) represents a well assessed technology, of huge interest in all those applicative contexts where non-invasive diagnostic surveys are required, such as infrastructure and cultural heritage monitoring as well as archaeological and subsurface prospecting [1]–[3]. In fact, non-invasive diagnostic tools, as GPR, offer the significant advantage to gather information about not directly accessible objects, such as undiscovered targets, building inner features, non-homogeneities and/or fractures affecting the integrity of monuments, in a quick way and without performing any invasive action on the surveyed area.

As well known, GPR is an active electromagnetic imaging technology for in situ surveys, which allows us to achieve images with a resolution from centimeters to few meters) of the inside of the investigated region. The usual result of a GPR measurement is usually given a 2D map, known as B-scan, from which expert user may detect and localize hidden objects and infer information about their geometrical features [1]–[3].

By turning to the specific area of the archaeological prospecting and cultural heritage diagnostics, the first advantage of the GPR instrumentation resides in the moderate cost and easiness of employ; in fact no significant expertise is required to collect the data. Secondly, the instrumentation is easily portable (unless very low frequencies are exploited with a consequent increase of the antennas size) and allows to survey regions even of many hundreds of square meters in a reasonable time. Finally, the flexibility of the GPR system, in terms of a trade-off between spatial resolution and investigated depth, is ensured by the adoption of antennas, working at different frequency band, which can be easily changed on site.

Despite of its widespread applicability, several efforts are continuously addressed towards the optimization of GPR systems so to comply with the end-users necessities. From the point of view of the end-users (archaeologists, cultural heritage stakeholders,..), the first requirement is to manage different “objects” in terms of size, construction details, investigation depth and so on. Furthermore, as other desirable feature, GPR should be able to act in all the phases of the life cycle of the cultural heritage, from the discovery to the preservation and conservation, to the fruition; in addition, it is desirable to use GPR as a tool for fast inspections during the crisis events (earthquakes, floods, terroristic attacks..).

These end-users necessities demand for the use of GPR as a tool embedded in an integrated approach, where the global vision/observation technologies (as optical/radar technologies from satellite, airborne platforms) [4]–[6] are able to perform a very large scale survey and after drive the in-situ inspections, based not only on GPR but even on other geophysical/sensing techniques. In this way, it is also possible to achieve a monitoring, which is multi-scale in both spatial and temporal dimensions.

Another specific GPR requirement regards the improvement of the interpretability of the radar images, so that the information is rendered to the stakeholders in a friendly, interpretable and useful way. This is important for different aims such as: to ensure an always updated current monitoring; to help the crisis management; to improve the discovery and fruition. In this context, the final objective should be to translate the GPR outcomes in indexes and images truly supporting the vulnerability assessment of the heritage.

All the above sketched for end-users necessities should be translated in scientific and technological challenges, which demand for advances in hardware and data processing of GPR as well as for the integration with other sensing techniques.

II. Scientific and technological challenges

As outlined in the Section above, several scientific and technological challenges have to be faced for a truly successful and useful use of GPR in operative conditions.

The first issue regards the improvement and development of novel hardware with different aims, such as: to speed-up the surveys and cover very large scale areas; to improve radar performances in terms of sensitivity and clutter rejection; to permit new measurement configurations also in view of the use of advanced data processing approaches. For a large scale survey, it is necessary to conjugate the requirements of a good portability/usability of the radar system with the possibilities of using antenna arrays for a multiple acquisitions [7]–[9]. Interesting cases of this strategy are depicted in [10]–[13], regarding large scale archaeological surveys in view of an effective 3D pseudo-representation of the site. Still for the hardware, another recent advance regards the development of novel GPR systems based on stepped frequency and CW modulation techniques [14], [15], as well as differential systems [16], for an improved clutter rejection and sensitivity; very recent efforts have been performed also in the field of reconfigurable systems able to manage different operative situations in a flexible and automatic way [17].

Other advances regard the adoption of antenna arrays able to deal with measurement configurations different from the monostatic one. In fact, the use of arrays enabling multi-view/multi-static/multi-polarization observations allows not only to enrich the dataset and improve the qualitative reconstruction [18], [19], but even to activate sophisticated data processing for a reconstruction of the electromagnetic properties of the targets [20], [21].

Finally, very recent advances are concerned with the development and use of GPR system on airborne/helicopter platforms; these systems are already used in other application domains [22] but the extension to the archaeology and cultural heritage is on-going [23].

The other main challenge regards the data processing, for which we can identify two main classes of approaches: linear inversion approaches for a qualitative reconstruction (location and geometry of the targets); non-linear reconstruction approaches for a quantitative estimation of the electromagnetic properties of the targets.

The imaging approaches as migration, back-propagation, and more generally linear inverse scattering approaches, [24]–[26] are now usually employed and assessed in realistic conditions for the practical advantage to provide processed images of the investigated scene in a short time and with good reliability. Despite of the well assessed use of these approaches, many challenges are still present as the possibility of dealing with non-canonical geometries (different from the half-space geometry) as the curved surfaces and layered media. In fact, the available commercial codes for GPR data processing are essentially based on migration approach, which assumes a flat air-medium interface and homogeneous regions. It is worth noting the flexibility of the inverse scattering approaches to take easily account the complexity of the scenarios [27]; in addition, the use of very efficient numerical forward modeling represents a good option to build the key elements of the inversion approaches and improve the interpretability of the results [28], [29].

The other main issue for the imaging approaches regards the development of 3D full reconstruction algorithms, for an improved performances compared to the usual strategy, where a pseudo 3D representation is achieved by building a data volume starting from the single reconstructed/measured profiles [30]. This scientific advance is a really hot topic, as testified by many present efforts not only for the development of the approaches but even for their experimentation in real situations [31], [32]. Associated to the above sketched imaging strategies, a recent interest is towards the development of change detection approaches in order to monitor the cultural heritage by comparing, possibly in an automatic way, the GPR measured data/processed images achieved at different times [33].

For reconstruction approaches, one of the scientific challenges regards the development, and more important, the use on-field of non-linear inversion approaches. In fact, these approaches are able to overcome the main limitations of the imaging approaches as to neglect mutual interactions between the targets and the impossibility to have reliable information about the EM properties [34], [35]. However, the development of the non-linear inversion approaches entails very challenging theoretical issues [36], which, at this moment, make it not possible their use on field. Besides the mathematical challenges, a reliable application of this kind of approaches needs of an accurate estimation of the background scenario and of the antenna radiation in presence of the investigated structure [37]. Anyway, the use of these non-linear inversion approaches represents a decisive advance for the accurate imaging of layered media (masonries) when the a-priori information about the scenario is poor or missing.

Another topic of great interest is the use of GPR integrated with other diagnostics/geophysical in-situ techniques. It is worth noting that the integration strategy depends on the “object” to be investigated. In fact, for the case of archaeological prospecting, characterized by a not negligible investigated depth, the most common approach is to exploit geophysical techniques as EM induction [38], Electrical Resistivity tomography and GPR, so to make it possible a survey ranging from large scale to the high resolution diagnostics ensured by the GPR [39]–[41]. Another example of integrated use of GPR with other techniques is for vertical structures (masonries, columns,..), where GPR can be used even in combination with other methods as acoustic ones, photogrammetry, infrared cameras, hyperspectral imaging, etc. [42]–[47]. In this context, the effort should be performed in two directions; in fact, the integrated use of GPR demands for the development of integration approaches for the data correlation, or, more difficult, based on physical models of the sensing. The final end is the definition of observation/sensing protocols, where one can think to use global vision techniques in order to drive the in-situ techniques for a detailed inspection of the most interesting areas and/or elements. This strategy complies with the necessity of the end-users about the economic sustainability; in fact, more sophisticated sensing techniques are activated only in presence of real necessities pointed out by the remote sensing techniques.

All the above described points are closely related to the last topic, where research efforts are required as the digitalization and virtual rendering of non-accessible/excavated sites/objects [48]–[50] (see an example in Fig. 1). In this case, advances are required not only to "translate" the geophysical/diagnostics scientific results in images really understandable by non-expert users as visitors, but also to improve their sensorial experience. In this frame, 3D digitalised representation of the non-visible scene should be able to include other kinds of media contents too (image, audio, video...). For example, the visitors could find these augmented landmarks disseminated throughout the archaeological site, urging them to point their mobile phones at the place where the augmented information sources will be installed. It is clear how this last point requires a strong information/knowledge exchange between different worlds as the sensing/observation technologists/scientists, ICT technologists and the different end-users communities involved in the cultural heritage.

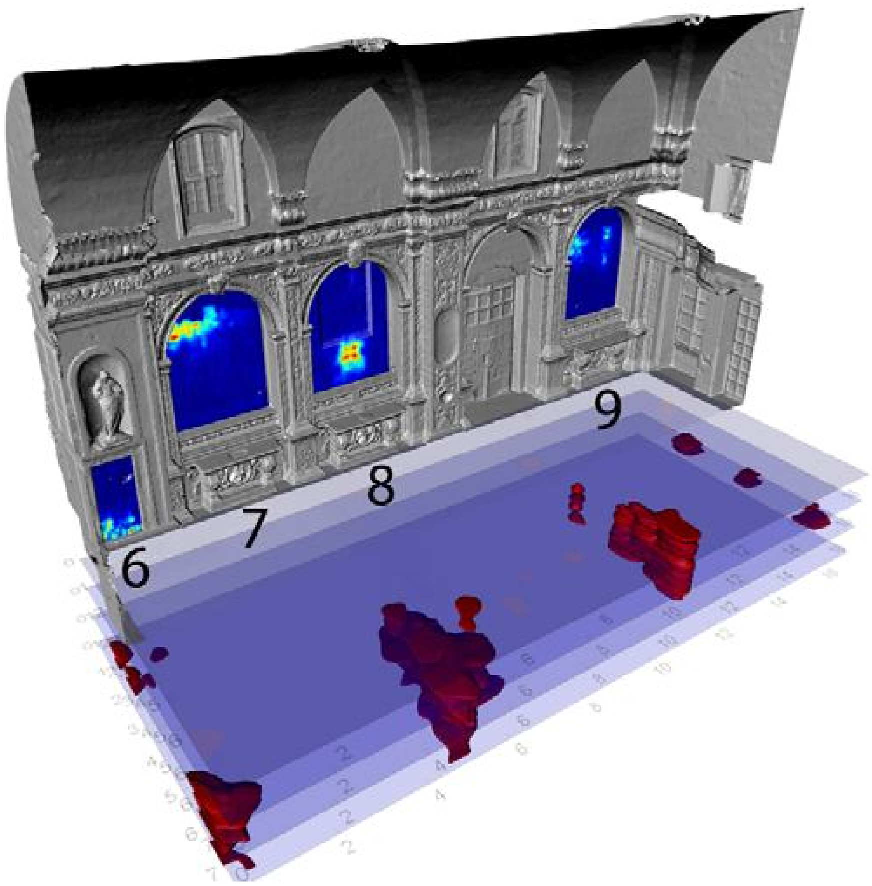

FIG. 1 – An augmented reality application performed in order to improve the fruition of both the visible and the non-visible features of a renaissance monument in Lecce (Italy), derived from GPR data processing and laser scanner based 3D reconstruction (http://www.itlab.ibam.cnr.it/QTVR.html).

III. THE ROLE OF THE COST TO TACKLE THE CHALLENGES

The challenges sketched for in the above Section could benefit of the COST Action TU1208; in particular, besides the effort in the present Project 4.1, the activities could benefit of the interaction with the other Working groups and projects especially in the fields of hardware and data processing advances and the integration with different sensing technologies in other fields (WG 4).

In this way, the project 4.1 “Applications of gpr and other non-destructive testing methods in archaeological prospecting and cultural heritage diagnostics” could be the “test bed”, where several outcomes of the other WGs could be finalized for a real use in operative conditions. Therefore, Project 4.1 could be very important to provide a feedback about the true effectiveness of the scientific/technological outcomes of the COST Action TU1208 in real world for archaeological and cultural heritage contexts. On the basis of a very preliminary survey among the participants to the Project 4.1, the main specific challenges that have been arisen and could be tackled can be summarized as follows.

The development of GPR acquisition and data processing methodologies for not canonical geometries as in the case of columns (cylindrical objects), the case of arches and intradoses, and for the case of not regular surfaces. For this kind of targets, a technological challenge regards the high precise positioning of the radar systems or at least the accurate knowledge of the position [51].

This points calls for another challenge regarding the development and use in real conditions of full 3D reconstruction approaches also in comparison with the 3D pseudo-representation approaches. This 3D opportunity should be accompanied by the implementation of reconstruction approaches able to: give information about the electromagnetic properties of the targets: to provide improved performances in terms of spatial resolution, so to be applied for example in cracking/fractures status assessment.

The other possible activity will regards the information/knowledge exchange between GPR technologists and practitioners and the partners more involved in other sensing techniques, as EM induction, ERT, infrared cameras, Very High Spatial Resolution (VHSR) multispectral imaging, and with analysis techniques for material characterization and identification. This interaction will be very useful to develop operative protocols and data correlation/synergy to achieve effective integration strategies in operative conditions. In this frame, it could be convenient to define a catalog of the anomalies of interest and to build for each type of element of the catalog the possible measurement strategy to be used. Finally, it would be interesting to focus on the development of strategies for advanced rendering and visualization modalities and augmented reality so to improve the discovery and the fruition of non-accessible/excavated heritage.

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PROJECT 4.2
"ADVANCED APPLICATION OF GPR TO THE LOCALIZATION AND VITAL SIGNS DETECTION OF BURIED AND TRAPPED PEOPLE"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Project 4.2 of COST Action TU1208 addresses a challenging and emerging field of application of Ground Penetrating Radar (GPR), namely the localization of people buried or trapped, possibly exploiting the detection of the Doppler frequency changes induced by their physiological movements (i.e., heart-beat, breathing). This paper outlines the main motivations for which the topic is worth to be considered in the framework of the COST Action and provides an overview of some relevant literature. Moreover, a first plan of the Project's activities is sketched, together with a discussion of which are some of the expected Project's outcomes.

I. INTRODUCTION

The detection of buried or trapped human beings is an important issue that is typical of disaster post-event scenarios, such as earthquakes, collapsed buildings in consequence of anthropogenic disasters, avalanches and so on. In such a framework, technologies deployed to supply the operations of rescue squads can play a crucial role. As a matter of fact, disaster survivors that are trapped under rubbles or snow need to be saved in a very short time. For instance, victims buried under collapsed buildings must be usually rescued within the first 72 hours, depending upon the type of entrapment, the pulverization of debris and climatic conditions. In case of avalanches, this time interval is dramatically reduced, since the probability of survival decreases to 90, 40 and 30 per cent, if the victim is removed from the snow within 15, 30 and 60 minutes, respectively. For these reasons, detection technologies must comply with the requirement of locating trapped subjects with precision and quickly. Moreover, some victims can be unconscious and motionless and their localization can be very complicated. In these cases, the actual possibility of rescuing them can only rely on the capability of detecting their vital signs, like breathing and heartbeat. Obviously, this is a difficult task given the harsh and hostile environment typical of post-disaster scenarios.

The above outlined conditions and operational requirements naturally suggest the exploitation of the non-invasive capabilities of acoustic and electromagnetic waves. For instance, a technology solution of this kind is based on the use of a network of geophones [1], which are quite simple to use and are indeed already adopted in surveillance tasks, like detection of clandestine immigrants concealed in truck trailers. However, these devices aim at an on-off detection, and do not provide a precise localization of the victims. Moreover, their use requires a quiet working environment, which is obviously not the case in rescue operations at disaster sites.

Other technologies, based on radio-wave propagation, rely on the fact that avalanche victims often wear electronic equipment transceivers, such as Beacon or Appareil de Recherche de Victimes en Avalanche (ARVA). Therefore, detection methods can exploit suitable algorithms and interrogating signals to cooperatively interact with these (known) radiating sources. More in general, the same principle inspires other technologies aimed at detecting personal electronic devices possibly carried by the victims [2]. However, in both cases, it cannot be guaranteed that these devices are located next to a buried subject, nor that trapped persons are indeed wearing them. Moreover, this is certainly not a reliable assumption for people buried under debris.

With respect to the above framework, GPR systems appear as a valid and viable option to tackle the problem of detecting conscious or unconscious buried victims, as long as radio-wave penetration is not hindered by layers of reinforced concrete slabs or structures mainly made of metallic materials that, as well known, dramatically reduce the effectiveness of the method, due to the arising of multiple reflections and the lowering of the penetration depth.

Project 4.2 of COST Action TU1208 is hence focused on the applications of GPR for locating buried or trapped victims, possibly relying on the detection of their vital signs, and aims at supporting joint research advancements as well as fostering industrial applications and fall-outs.

In the following, we provide a brief overview of some relevant literature, which can be helpful to trigger the discussion among the COST participants, focusing their attention on some of the existing technologies and implemented solutions. Then, we outline a first plan of the Project's activities, together with a discussion of which are some of the expected outcomes of considering such a topic within a COST framework.

II. An Overview of Some Relevant Literature

To provide a brief overview of some relevant results available in the open literature concerned with the project's topic, it is convenient to split the applicative environment into two subcases. The first one is related to the detection of buried victims "seen" as classic targets of GPR surveys, that is as a perturbation of the backscattered signal due to dielectric discontinuity represented by the human body with respect to the surrounding environment. The second case is instead focused on the detection via GPR measurements of vital signs characterizing the trapped victim, such as heartbeat or breathing, which induce a low frequency perturbation of the backscattered radar signal.

The first scenario occurs in the search for avalanche victims and is the one that has been more broadly addressed in the literature. This is due to the fact that deployment of GPR in the cryosphere has been since long object of interest, thanks to the quite good penetration of microwaves in snow. In this case, the contrast existing between the human body and the snow characterizing an avalanche allows for the adoption of "standard" GPR processing methodologies [3]. On the other hand, a crucial requirement in this framework, as mentioned in the introduction, is the need of keeping the time of the intervention as low as possible, in order to allow saving the victim's life.

In this specific case, the problem is hence that of surveying in the shortest time as possible the avalanche area, by the relying on the fact that avalanche snow is a quite favorable medium for radio-wave penetration and that the body of the buried person reacts as a "strong" scattering target hosted within an almost homogeneous medium. For these reasons, the technological solutions typically rely on standard UHF GPR systems (operating in the 0.4-2 GHz band) mounted on an airborne platform (e.g. a helicopter or an unmanned aerial vehicle) or on a moving tower, so to scan the area of interest in the shortest time possible. Then, the need of very fast processing tools (in order to provide almost real-time results) suggests the adoption of automated image processing tools directly acting on the radargram and aiming at extracting the possible victim's signature from the raw signal.

Some interesting studies in this respect have been proposed by Heilig et *al*. [4] and Fruehauf et *al*. [5] where an IDS RIS system, equipped with properly designed processing tools, has been experimentally tested. Also, the experimental test carried out by IDS in cooperation with other subjects (www.idscorporation.com/en/georadar/more-information/case-studies?task=document.download&id=88) using a 400-MHz antenna mounted on an helicopter is worth to mentioned as an example of the industrial interest on this topic.

The second scenario, which is representative of rescue and search of victims buried or trapped under debris or snow, is a less conventional one, as it is indeed claims for GPR systems and processing tools that are different from the ones routinely adopted in GPR surveys. On the other hand, resorting to these different approaches is necessary for several reasons.

First of all, the very inhomogeneous nature of the medium in which survivors are trapped makes it impossible to exploit the retrieval of the dielectric contrast features as the only means for detection, unless sophisticated model-based processing tools are exploited. However, these latter require some modeling assumptions on the surrounding medium, which is indeed difficult owing to its aforementioned complex nature. In addition, in the case of debris, traditional linear scans cannot be performed, thus making further difficult the correct localization of the possibly detected target on the GPR image.

To overcome this difficulty, the idea that has been pursued in the last years by several researchers is to exploit the capability of radars to monitoring breathing or heartbeat [6]. As a matter of fact, since from the ’70 of the last century, studies in the field of biomedical engineering have proposed and demonstrated the possibility of using radars to extract vital signs. The underlying physical principle is the specific Doppler signature associated with physiological processes such as heartbeat and breathing, which results in a measurable frequency shift induced in the reflected signal. Accordingly, when an unmodulated radiofrequency signal is transmitted towards the human body, the chest movements (due to heartbeat and breathing) modulate the phase of reflected signal, which can be then demodulated by the radar receiver to finally extract the vital signs’ signal components.

Owing to their simplicity of implementation, continuous-wave (CW) radars, typically operating in the Instrumental Scientific Medical (ISM) band around 2.4 GHz (which has the additional advantage of does not needing a specific license), have been first considered for both people buried under debris [7] and snow [8].

In CW-radars for survivors’ detection, a monochromatic wave is transmitted in medium in the direction of investigation and the reflected signal is used to provide information on the possible presence of a living body, by appraising the Doppler frequency shift resulting from breathing and heartbeat. However, a CW-radar assumes that the subject is within beam of its antenna and cannot give any information about the distance where the subject is located. Moreover, if different targets to be detected are simultaneously present, this measurement system needs multiple antenna CW radars and more sophisticated digital signal–processing. In addition, in practical applications, this kind of radars shows null detection points and co-frequency interference. To overcome these problems many demodulation methods have been developed and different architectures have been proposed.

A work which is interesting in this respect is the pioneering one by Chen et *al*. [7], in which the possibility of detecting vital signs through several layers of debris has been demonstrated using two CW systems working at 450 and 1150 MHz, respectively, and finding that the higher frequency one is better suited for the purpose. Also, the work by Pieraccini et *al*. [8] is an interesting one, since it shows for the first time the possibility of detecting both heartbeat and breathing through snow layers, using a CW radar working at 2.4 GHz. In particular, an *I*/*Q* receiver is exploited to avoid also null points, together with a simple clutter removal least square minimization procedure.

As usual in radar technologies, some of the limitations of CW systems can be overcome by resorting to frequency-modulated continuous-wave (FMCW) radars and ultra wide-band (UWB) pulse radars. As compared to CW radars, FMCW ones allow to measuring the distance of the detected subject: pulse radars transmit a sequence of short RF pulses, and evaluate the range position of the target by measuring the time delay of the returning pulses. In more recent systems, an UWB electromagnetic wave source generates short pulses that spread their energy over a broad frequency range. These UWB systems then employ the difference of the time-of-arrival of the backreflected wave due to the movement of the chest of the person to extract the desired features. One of the interesting features of UWB radars is the enhanced capabilities they offer for clutter cancelation, which have been for instance exploited by Zaikov and Sachs [9] to design a prototype UWB radar, in which signal to clutter separation is also pursued via principal component analysis. The same authors recently performed a thorough analysis of the different sources of noise faced in UWB detection of buried victims, and developed a model for a pseudo-random radar which is similar to GPS, tri-lateration included [10]. Loschonsky et *al*. have exploited different signal processing algorithms based on windowed Fourier Transform and Continuous Wavelet Transform [2] to extract the sought signature. More recently, Li et al. have proposed the use of a processing chain made out of several blocks (curvelet transform, singular value decomposition and Hilbert-Huang transform) to remove the direct wave, reduce noise and extract the sought features [11].

As an alternative to monostatic or bistatic UWB radars, the use of a moving UWB array to detect breathing has been proposed and experimentally validated by Akiyama et *al*. [12]. Whereas, the work by Grazzini et *al*. [13] is interesting due to proposed adoption of a Stepped Frequency CW radar (SFCW) as a solution to overcome the poor time stability of UWB impulse radar, which due to the jitter effect in the pulse triggering process. This solution improves the overall capability of detecting low frequency movements, also thanks to the enhancement in the dynamic range allowed by this class of radars.

Recently, some of these concepts have been exploited by the Sensor&Software “Rescue Radar” GPR system [14], which has been tested in 2012 at a facility provided by the Ontario Provincial Police. Interestingly, besides confirming the capability of GPR as a potential tool for survivors’ detection, the experiment pointed some open issues which have to be accounted for in tackling this topic, such as:

- the increase of sensitivity improves the probability of detection, but also results in the occurrence of a larger number of false alarms;
- clambering over debris is more time consuming than performing data acquisition itself;
- moving objects (or rubble) located in the vicinity of the sensor appear to be the main source of false alarms;
- radio sources and cell phones (unavoidably present in the operative scenario) create an interference that has to be accounted for by some kind of integrated background noise monitor in order not to impair the GPR survey;
- although difficult (see above), performing the measurement over a regular grid seems to enhance detection probability.

In addition to the above points, some others are certainly worth of consideration within the activities of the Project. A first one is related to the different Doppler nature of the considered vital signs. As a matter of fact, since a larger portion of the body is involved in breathing, the Doppler radar cross section associated with this latter movement is usually greater than that of heartbeat induced movements. As such, it is quite likely that vital signs associated to heartbeat can be appraised only in relatively simple situations (such as a subject buried under snow), but cannot provide a useful signature to detect victims trapped under debris. In addition, it is interesting to recall that the development of GPR techniques for buried or trapped victims detection can take advantage and mutuate results achieved in other applications. In particular, an attention should be given to bioradiolocalization, wherein vital signs monitoring capabilities of radars are exploited for biomedical purposes, as well as through the wall (TTW) radars, where the aim is to detecting moving or static targets and human beings hidden behind an obstacle. As a matter of fact, in these applications, the same principles and methods as the ones herein considered are exploited and similar issues are faced. However, it has to be kept in mind that working conditions of TTW radars typically operating in the ISM band are in some sense simpler (the wall is homogenous, or reliably approximated as homogeneous, whereas a collapsed building creates stratified slabs of heavy rubble at different inclinations). Whereas, bioradiolocalization systems operating in absence of obstacles between the sensor and the examinee, can exploit higher frequencies (such as the Ka-band, 27-40 GHz, or the X-band, 10 GHz) than those actually useful to detect vital signs of buried or trapped people (typically the ISM band around 2.4 GHz). As an example, TTW applications aimed at detecting the vital signs of a subject behind a wall through micro-Doppler shifts are worth to be considered. For instance, the self-injection-locked (SIL) method proposed by Wang et *al*. [15], in which the signal partially reflected from a distant target is injected in the same oscillator that produced the transmitted wave, is an interesting solution. As a matter of fact, this technique improves the sensitivity of demodulation and allows the radar system to achieving higher signal-to-noise ratios (SNR). By so doing, the TTW radar sensor can monitor tiny body movements of subjects that stay still, e.g., seated persons, while at the same time efficiently detecting the position of individuals concealed behind the wall.

III. CONCLUSION: A FIRST WORKPLAN FOR FUTURE ACTIVITIES

The motivations outlined in the introduction and the necessarily brief overview of some recent achievements in the field of GPR for detecting buried or trapped people are meant as a starting point for the discussion among the COST's participants about the possible contributions that can be provided by our COST actions. In this respect, we feel that a first important step to pursue would be to establish an open database of the relevant literature that can be accessed, compiled and modified by all the project's participants. This would allow to creating, in a cooperative, unbiased, fashion a useful resource for the academic and non-academic community that is interested in this topic. In addition, the evolution of this open database could provide a tool to re-directing the project activities along the lines emerging from a constantly updated and accurate observation of the stare of the art. As a second point, the need of interfacing the academic efforts with the already existing industrial activities is an important mission for a Project carried out in a COST framework. To this end, it can be foreseen that in future workshops of COST TU1208, specific focus sessions (with standard and/or interactive presentations, or based on a round-table scheme) will be organized gathering together different expertise and experiences, so to foster cooperation. Hopefully, this should allow manufacturers to becoming aware of recent academic advancements and academic people to focus their efforts to the challenges poses by the on-field applications. In this perspective, the involvement of representatives of Governmental agencies in charge of search and rescue operation is another important aspect.

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PROJECT 4.3
"APPLICATIONS OF GPR IN ASSOCIATION WITH OTHER NON-DESTRUCTIVE TESTING METHODS IN SURVEYING OF TRANSPORT INFRASTRUCTURES"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Preservation and maintenance of transport infrastructure is a global concern that affects social and economic development in all countries. During the last decades, there has been a continuous increase in the use of non-destructive testing (NDT) applied to many aspects related to civil engineering field. Ground Penetrating Radar (GPR) has become an established method of inspection. This paper presents a compilation of works in the frame of the COST Action TU-1208, showing the most of the applications of GPR and other NDT methods concerning the topic of the Project 4.3. Published works in roads and pavements, concrete and masonry structures, and tunnel testing, the participants of the Project participated on, are mentioned. It has been demonstrated that such methods have significantly benefited the procedures for inspection and also, successfully solved some of the limitations of traditional methods.

I. INTRODUCTION

The deterioration and distress mechanisms that are active under the surface cannot be assessed by traditional visual and optical inspection. Alternative methods are therefore required for inspection. GPR has been established as one of the most recommended NDT methods for routine sub-surface inspections.

The use of GPR in civil engineering applications began to appear in the mid-1970s and the 1980s. Some of its main applications include services such as pavements, utilities and voids detection, as well as different structures associated with the transport infrastructure, such as bridge decks, retaining walls, masonry structures and tunnel inspections [1].

In the next Section, "Applications of GPR", some of the published works has been compiled to show the potential of the method.

A brief review regarding the use of other NDT methods was also included.

II. Applications of GPR

This Section is divided into four sub-sections regarding the main types of structures in the transport infrastructure:

Roads and Pavements

The pavement life-cycle is not only affected by the number of heavy loads but also layer thickness is a vital factor defining the quality of pavements. Deficiencies in thickness reduce their lives, and periodical rehabilitation is therefore necessary in any country's road management program to maintain roads in optimal conditions of use or monitor quality control. Road inspections imply the evaluation of different parameters such as roughness of the pavement, skid resistance, and presence and condition of cracks, voids and delamination.

GPR technology is rapid, cost effective, and allows field surveys to be conducted without disturbing the pavement structure and the normal traffic flow [2], [3]. GPR has been successfully used to find voids and cracks under pavement [4]–[6] as well as to monitor quality control on new asphalt overlays or to evaluate base course quality [7]. But above all, measuring pavement layer thickness is one of the most known applications of GPR [8]–[12].

There are complementary NDT technologies to the measuring of different road characteristics. Some examples are mobile LiDAR for geometric measurements and laser profilers for the evaluation of the pavement surface roughness (International Roughness Index - IRI). In [13], a novel method consisting of mobile LiDAR technology is presented to evaluate layer thicknesses and volumes for newly constructed pavements. The method was favourably validated by GPR. Additional geophysics is also commonly applied in combination with GPR. Reference [14] applies infrared thermography for the detection of pavement cracks or moisture content. The structural evaluation (bearing capacity and layer stability) is quantitatively evaluated with the Falling Weight Deflectometer (FWD) [15] that measures the deformations of the pavement in response to heavy loads. Reference [16] presents a case study of premature cracking where combination of GPR with FWD methods and laboratory measurements allowed the identification of severe water content as the reason for cracking. Reference [17] deals with the comparison of pavement layer moduli calculated from FWD deflection data using layer thickness obtained by GPR and coring. Furthermore, this paper concluded that there is a tendency in reinforcement projects to apply recycling methods and use recycled materials so, knowing the continuous thickness of asphalt layers by GPR is essential in order to determine the optimum thickness available for milling and thus achieve optimization of recycling process.
In addition to road/highway pavements, this sub-section includes airport runways and railroad ballast. Delamination, cracks and voids

are the most common diseases in airport runway, which are particularly more severe due to the higher traffic loads that pavements are supporting. GPR is commonly combined with the Heavy Weigh Deflectometer (HWD) for airfield pavements inspection.

GPR also provides noteworthy information of the ballast quality and the track bed condition [18], in addition to the geotechnical properties or subgrade and subsoil materials [19]. Reference [20] combines different geophysical techniques (3D GPR, Electrical, and microgravity) to analyse the stability of railways, which allowed the determination of deformation of the layering of the railway, and other anomalies such as voids.

Concrete Structures

Concrete structures are also included in the diagnosis of transport infrastructure such as bridge decks and retaining walls along roads and railway lines, as well as over/underpasses to ensure the passage of wildlife animals, person and agricultural machinery. The diagnosis of concrete includes: estimation of thicknesses, location of reinforcing bars and metallic ducts, estimation of bar size, location of voids, effects of water, chloride content and delamination or cracking.

GPR has proven to be a suitable NDT method for the inspection of concrete structures as demonstrated by several publications within the past decades [21]. Detecting water content is an important phase for the diagnosis of concrete. Reference [22] observed a linear relation between the velocity of propagation of the direct wave and moisture. In addition, GPR can be successfully used for the location of salt ingress due to the influence of chloride content on the permittivity of the concrete [23]. What is more, [24] shows its capabilities to analyse the corrosion of reinforcing induced by chloride content.

In other published works, the method enables inspectors to obtain information about reinforcing bars, defining depth of rebar, and location of tendon-ducts on bridge decks [25]. The reflection coefficient of a thin layer into concrete was evaluated in [26] in order to estimate the detection limit of the GPR antenna. The reflection coefficient revealed to be linearly dependent on the thickness-on-wavelength ratio for thicknesses less than $\lambda/11$. Other NDT measurements (such as electrical, sonic, seismic and infrared thermography) combined with GPR have earned the interest of researchers on the assessment of water content and alkalini-aggregate reaction on concrete, as well as concrete quality and delamination [27], [28]. Reference [29] presents a combination of GPR, capacitive and impact-echo measurements to analyse porosity and water and chloride contents. Other possibility which is currently promoted is combination of GPR with laser scanning that provides exact information about the surface of roads and structures, and their suburb in combination to GPR data of the sub-surface [30].

Mansory Structures

The most of the masonry bridges are the oldest structures still in use in the transport infrastructure. These constructions are subjected to special tension conditions because of the increase in traffic loads and ageing, which produce material degradation and structural damage. Some of the most typical damages in masonry bridges are: moisture, differential settlements, and thermal deformation with subsequent bulging of spandrels, damages in wing walls, cracking, as well as arch mechanism failure and loss of ashlar.

During the last few decades, GPR has been demonstrated its capabilities for bridge inspection. Reference [31] successfully applied GPR for assessing masonry bridges, which determined the effectiveness of the method in obtaining relevant structural information concerning the presence of cavities and faults, and reinforcement elements, in addition to ring stone thickness and foundation conditions.

Other studies employed GPR together with other NDT methods for more exhaustive evaluation of stability. Reference [32] have shown the joint effectiveness of GPR, infrared thermography, and sonic methods for obtaining unknown geometric data and finding hidden characteristics such as voids, moisture content, and inhomogeneous filling.

In addition to geophysical inspection, other NDT optical methods were also for appropriate combination. The metric information obtained by photogrammetry or laser scanning allows for the characterization of the stonework and filling, which provides better understanding of the GPR propagation phenomena. This combined approach can be also used to define a hypothesis for structural analysis, which describes structural behaviour of the structure or structural stability of arches [33]. Masonry structures are built using heterogeneous filling that often complicates the interpretation and analysis of field GPR data. FDTD modelling of the GPR signal is therefore typically used as additional interpretational tool. Some authors [34] have employed novel FDTD numerical modelling sub-gridding scheme to simulate GPR responses from delamination or ring separation in brick masonry arch bridges, in which different aspects were considered such as, the effect of varying the thickness of faults, their location, and the effect of water ingress in hairline delamination on GPR signals. More sophisticated and realistic modelling can be obtained when a combination of different NDT, such as infrared thermography and GPR, is considered to create models [35].

Tunnels

GPR has proved a valuable method for tunnel quality management and detection. There are successful works in detecting thicknesses of both lining and backfill grouting layers behind the concrete lining [36], as well as to identify defects in lining such as voids and cracks [37].

Additional information can be obtained to define rebar geometry, including corrosion detection. Variations in water content, and other aspects, as the presence of reinforcement elements embedded in lining [38], can be also obtained by GPR.

Integration of different geophysical methods was also considered for evaluating tunnel stability. There is published works which integrate GPR with seismic method in order to provide additional mechanical characteristics of the damage in addition to elastics characteristics of discontinuities in order to examine possible areas of instability [39]. Other advanced NTD optical methods, such as 3D laser scanning, have shown also their capabilities to be integrated with GPR [40]. Such technology allows for the detection of defects on tunnel surface such as water exudation, which could be directly related with inner faults detected by GPR.

III. Conclusion

Although GPR have demonstrated its capabilities for roads and transport infrastructure inspection, alone or in combination with other NDT, further research is required in developing more cost-effective acquisition methodologies and processing.

The presence of defects in pavements, as well as concrete and masonry structures is difficult to detect using standard procedures. Combined approaches by considering different NDT methods are needed because there are many different aspects influencing the detection of such defects. For example, improvements were recommended by several authors to detect and characterize cracking. The existence of cracking can be related to local variations in the amplitude value registered when collecting data over the crack. However, it seems difficult to quantify the defect as many previously unknown aspects are influencing this amplitude value such as crack filling, crack aperture, crack height, and crack angle. An interesting combination could be GPR and infrared thermography, since this complementary technique has shown its capabilities for determining the depth of cracks due to the temperature difference between the unaffected area and the depth (in pixels) of the crack. Infrared thermography is also useful in combination with GPR to map shallower moisture content, in addition to the use of LiDAR or even multispectral cameras that delimit moist areas from the intensity attribute.

Further development is also demanded concerning to affordable systems for road/highways inspection, as well as to use in airport runways and railways diagnosis. The tendency is to integrate complementary sensors such as LiDAR, RGB cameras, profilometer or video camera, thermography, and GPR, all mounted in a moving vehicle and spatially related to a common trajectory defined by global position systems (GPS/GLONASS) aided with inertial measurement unit (IMU)

Examples of recent automatic systems that combine some of related sensors are Road Doctor (Roadscanner), SITEGI (Uvigo), and SITECO.

The large amount of data collected when surveying relevant infrastructure makes difficult to process all the data and manage in a reasonable amount of time. More powerful and versatile processing tools are therefore demanded to optimize time and resources invested.

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PROJECT 4.4
"APPLICATIONS OF GPR IN ASSOCIATION WITH OTHER NON-DESTRUCTIVE TESTING METHODS IN BUILDING ASSESSMENT AND IN GEOLOGICAL/GEOTECHNICAL TASKS"
STATE OF THE ART AND OPEN ISSUES

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Abstract

Geophysics is the study of the earth's interior, using measurements based on physics principles. A part of this, geophysics is also used to explore the interior of construction materials of buildings and Monuments. The major advantage of this science is its absolute non-destructive character. However, despite geophysics exist since the beginning of the 19th century the Ground Penetrating Radar (GPR) method is recently introduced in this domain, counting almost 50 years of active contribution. During these years, GPR was proved very effective in the building assessment. In the field of geotechnical tasks and especially in geological tasks, its efficiency was limited and strongly dependent on the site conditions, mostly due to its limited in-depth penetration and relative target discrimination. Future research must be oriented to the improvement of these two major milestones, mostly into the antennas design and related instruments electronics design.

I. INTRODUCTION

The GPR method was invented during the Vietnam War from the Americans, as a tool to locate the mines below the ground surface. Even today, the method is still used for the same purpose, apart from all the other areas of application. The principle of GPR is to send with an emitter antenna, very short electromagnetic pulses through the ground or the structure. Those pulses propagate towards all directions (or in the half-space downward only, if the antenna is shielded) and are reflected when they meet interfaces between media of different electromagnetic properties. A receiver antenna measures the amplitude of the signal over time (Fig. 1). On the resulting scan, both the direct wave and the waves reflected on the different interface scan are observed. This method allows detecting voids, layers interfaces, humid zones and material modifications. In reality, the GPR method is closely related with the classic seismic reflection method. The difference in these methods is the type of wave used to travel in the media. In the case of the seismic reflection method, the wave is a brief acoustic pulse where in the case of GPR it is an electromagnetic pulse (Dirac). Based on the above concept, the applications of GPR extend from the allocation of small cracks into the concrete or the stone, up to the deep mapping of lake bottoms, or even glaciers thickness of several hundreds of meters.

II. The GPR in concrete and buildings evaluation

The reinforced concrete (RC) is the modern building material in our world today and its degradation with time, the corrosion of its reinforcing bars creates conditions that require a periodic control of its critical properties. For this reason, assessing concrete properties and durability indicators (strength, porosity, moisture content, etc.) using NDT methods can play an important role in the process of RC structures management before any expensive maintenance is undertaken. However, the main problem is the limitation of only one NDT technique to evaluate one concrete property. For instance, GPR technology is sensitive to water saturation but also slightly sensitive to porosity [1], ultrasound is able to evaluate the modulus of elasticity but it is also sensitive to moisture and density, and so on. For these reasons, some researchers have proposed combining several techniques for concrete strength evaluation or for detection and visualization in concrete structures, or the combination of several NDT parameters obtained with the same technique [2] in an attempt to confirm the diagnosis or to reduce the measurement noise. This original approach, which consists in combining NDT data, is promising but only if the additional cost is balanced by an enhancement of the diagnosis quality. In the context of concrete evaluation of existing structures as building, GPR can be used as a complementary method for the rapid evaluation of moisture which could lead to correction of the effect of moisture on seismic methods. The term “seismic” includes all methods based on acoustic pulses, ranging from ultrasonic to subsonic spectra, i.e., ambient vibrations, Impact-echo and down to seismic refraction tomography profiling). Seismic data provide valuable and complementary information like dynamics modulus and vibration modes, highly related to damages and structural solutions. Masonry structures are also frequently evaluated by means of GPR in combination with other techniques, as i.e., in historical buildings. In this case, non-destructive analysis is a helpful process to assess their conditions. Notwithstanding, some problems appear in the case of these special constructions: the high variability of the materials and structural elements (frequently poorly documented) and their irregular surfaces. Recently, the question of detection limits of commercial antennas was studied. It is proved that for layers thinner than $\lambda/11$(for an error inferior to 10 %), the reflection coefficient still depends linearly on the thickness to wavelength ratio [3]. It is also proved that layers with a thickness inferior to $\lambda/100$ (about 1.3 mm here) could be visible with GPR. By this method, the amplitude reflected by a thin layer can be estimated. The layer will then be visible if this reflected amplitude, after subtraction of the losses (including the intrinsic and geometric attenuations), is superior to the signal noise.

III. THE GPR IN THE GEOTECHNICAL SECTOR

In the geotechnical sector and a part of road infrastructures assessment, GPR is used mostly in foundation studies and sometimes in cuts & retaining structures studies for the assessment of the geometry of the shallow geological layers. During the last years, GPR was frequently used in studies of wind generators foundations. Usually, these constructions are installed at very high altitudes, top of mountain areas, where the rock is strongly weathered and very often hides large cavities or entire caves. The depth of investigation must be in the range of 7-8 m and GPR becomes a good method for a fast subsurface 3D mapping. A significant constraint is always the superficial “skin” layer that in many times is presented as a very conductive clay layer. In these cases, GPR cannot be applied and the use of electrical 2D profiling is inevitable. In almost all cases of wind generators foundations, a skin layer exists, either as one clay layer, or as one thin gravel layer. The gravel layer imposes problems in GPR application on site, mostly from the irregular scattering of the pulse into the gravel voids. This problem can be avoided by using lower antenna frequencies but this reduces the target resolution. Other applications in the geotechnical sector include mapping of utilities or unknown infrastructures like pipe networks, hidden reservoirs and other. Due to low depth of these features, the GPR can be used alone, although is advised to be used with another geophysical method in a parallel sense to reduce uncertainty. A typical example is shown in the (Fig. 2), where the existence of one old subsurface drainage system below an ancient prehistoric grave (Tholos Acharnon, Greece) was identified with GPR and mapped with accuracy with 2D electrical imaging. However, the major problem of GPR is also noticed here. Is it obvious that features with high resistivity (hot red areas: drainage system) are easily mapped with GPR (see at the offsets of 0 to 8 m of the electrical profile). In contrary, a thin low resistivity layer (see at the offset of 15 to 18 m – thin blue region with resistivity down to 15 Ohm*m) makes almost invisible the second feature (rectangular tank) in the GPR corresponding section. Other applications are related to subsurface imaging below the foundations of Monuments. Damages in these structures could be due to foundations problems or shallow geological features. Usually antennas from 400 to 100 MHz are utilized. Seismic methods use to be the most applied as complementary survey, and in shallow profiles, seismic shear-wave velocity layering correlates well with GPR layers interfaces. In many cases resistivity methods could provide also layers stratification to correlate with GPR interfaces. An example is shown in (Fig. 3), where results from the study of the ground under the Cathedral of Mallorca [4] are presented. Two different geological zones produce different images in GPR diagrams and in resistivity images, being also different the seismic wave velocities associated to the layers in both areas. It is usual to combine geophysical methods to different techniques or evaluations, like finite elements models or other, photogrammetry, laser scanning or other optic or topographic measurements. In Greece, GPR method is widely applied in geotechnical issues regarding ancient monuments. In the retaining wall of the sanctuary of Oropos, the GPR method was used for the assessment of the soil as well as the construction details of the wall [5]. The width of the wall has been defined, using a 800 MHz antenna, providing valuable information for the geometry and therefore the load bearing capacity of the structure.

IV. THE GPR IN GEOLOGICAL APPLICATIONS

In the area of geological applications, the classic geophysical methods like seismic refraction and electrical resistivity profiling dominate today in the private sector services. In addition to these methods, Low Frequency Electromagnetics (VLF) in combination with very old geophysical practices like the Spontaneous Potential method, or Micro-gravimetry fill the modern services palette of today's modern geophysical services providers. The GPR method is not widely used today in the geological services sector. This is mostly due to two major disadvantages of the GPR, the penetration depth and the difficulty of application on true site conditions. An additional disadvantage of GPR, in relation to other geophysical prospecting methods is the inability to penetrate into the water saturated zone. The groundwater level presents for GPR an absolute reflector of all the transmitted energy so there is no possibility to map any kind of geological or anthropogenic features below the groundwater level.

In general, GPR is considered a valuable method for shallow geophysical investigations, as archaeology, where all targets are covered from a shallow earth skin layer and the resistivity contrast between the environment (usually sediments) and the building material (usually rocks) is high. In this case, GPR is very effective but still as long as the site and soil conditions permit the application of the method. In a wide number of cases, GPR is used as supporting survey, being other geophysical methods the main exploration procedure. Perhaps the exception is in archaeological sites first evaluations, where 3D GPR imaging provides valuable information about the shapes and structures existing in the site, and use to be applied as main study before excavations. Working with GPR to support other geophysical methods in exploration geology means to operate at frequencies of 100 MHz and below, up to 25 MHz. Using antennas in these frequencies, penetration depth can reach sometimes to 40 m in very resistive formations like limestone or granite. In these cases it is possible to map with accuracy the fault zones and shallow strata with one outstanding resolution, as long as there is no earth skin cover to attenuate the signal. Fault mapping is one critical geological application in the initial phase of tunnel design works and assessment. It is evident that faults affect strongly the tunnels construction and especially when a significant overburden exists, a fault may induce inflows into the tunnel front, slowing down the entire project and imposing a significant increase in construction costs to stabilize the front. In this specific case, the GPR method when applied in low frequency antennas can be very helpful. Significant correlation of GPR (at 25 MHz range) with Very Low Frequency Electromagnetics (VLF) has been proven. This is due to the fact that the fault zones identified from very low frequency EM currents are wide enough in space (20 – 30 m fractured zones) to be allocated with these antenna wavelengths. In addition, due to their high resistivity contrast with the hosting environment (high resistive rocks) together with their irregular geometry and step inclination, these zones are easily identified with GPR. The Rough Terrain Concept antenna of MALA GEOSCIENCE at 25 MHz frequency performs very well in these application areas. In resistive environments, the 250 MHz ground coupled antennas can reach depths of 6–7 m maximum, being still in the range of some geological – geotechnical applications such as the mapping of cavities, fractures or voids. In this sector, the GPR is used in a complementary sense with the geophysical 2D resistivity imaging method. In fact, the depth of penetration of 6 m is enriched from the resistivity profiling and the accuracy on the discontinuities of rock is enriched from the GPR profiling. This complementary use of these two different methods has been proved very effective on site and provides accurate results. In tunneling assessment during the construction phase, GPR survey is also possible, mainly using borehole antennas in the tunnel front when potential faults and cracks could exist. However, in many cases, non-directional antennas are used in borehole applications. In this case, the main difficulty is to define the azimuth of the different targets, and three or more boreholes are needed in order to place accurately the anomaly. Notwithstanding, faults and non-stable areas could be well defined. Borehole GPR is also applied to study buildings foundations before tunneling in dense areas (e.g., in cities) where constructions are poorly documented. Detection of paleo-channels and streams is other possible GPR application, used for different studies. Microzonation is used to define soil predominant period values, usually associated to extended areas. GPR could be a useful tool to determine shallow geological features and to define different ground areas, previously to the vibration measures. These zones could be determined by the existence of paleochannels or streams in quaternary materials, because soil seismic response change due to the presence of these geological structures.

Plus and Cons of GPR in geological applications

A part of the penetration problem, the field irregular topography imposes always a problem in the application of GPR, especially with the ground coupled antennas. This is a serious application problem because even with a topography correction the ground roughness induces a very high noise level in the data. Clearing the paths prior to measurements is impossible for geological applications. With the RTA 25 MHz unshielded antenna, MALA has done one important step toward this direction. However, unshielded antennas are not the best tool when operating outwards due to the high amount of unwanted surface reflections (trees, buildings etc). The need for a new type of antenna strongly exists in these areas. This antenna must be of an air coupled type, shielded in order to send all the energy downwards and in low frequency ranges, to be able to penetrate enough into the subsurface. The first requirement (air coupled type) is the most important for geological applications, due to the fact that an air coupled antenna will be easily carried above the ground with a constant motion or alternatively with a mechanism, avoids also the vegetation or other obstacles.

V. FIGURES

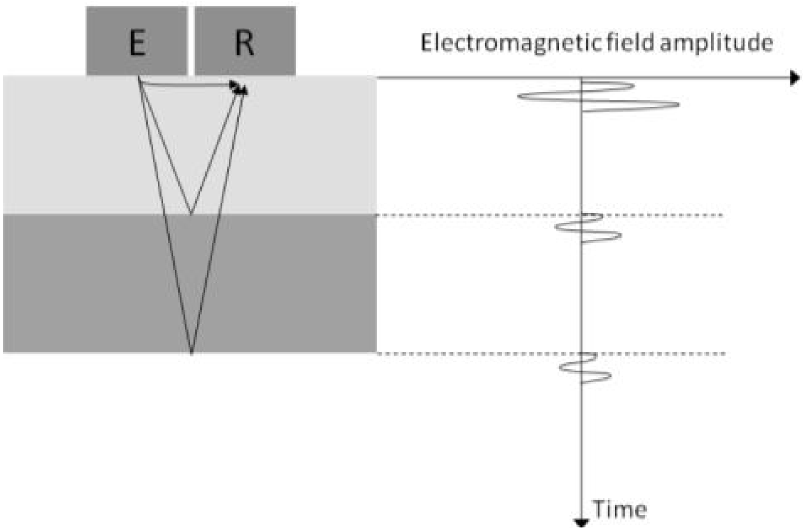

FIG. 1 – Simplified GPR signal measured on a two layers structure.

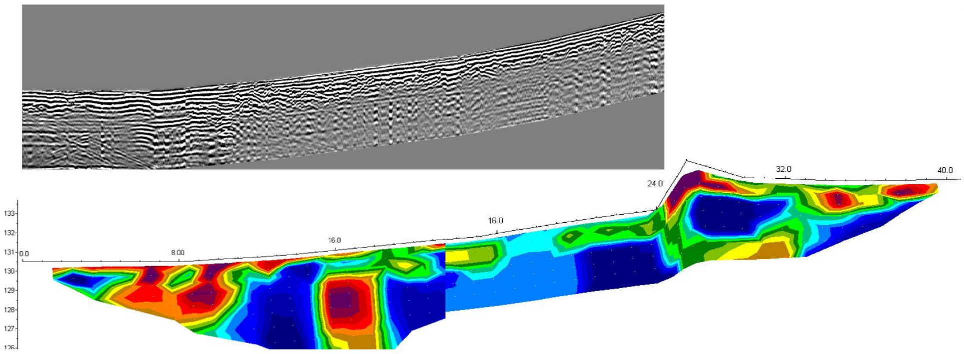

FIG. 2 – GPR and 2D electrical imaging profiles of one old drainage system below an ancient grave (Tholos Acharnon).

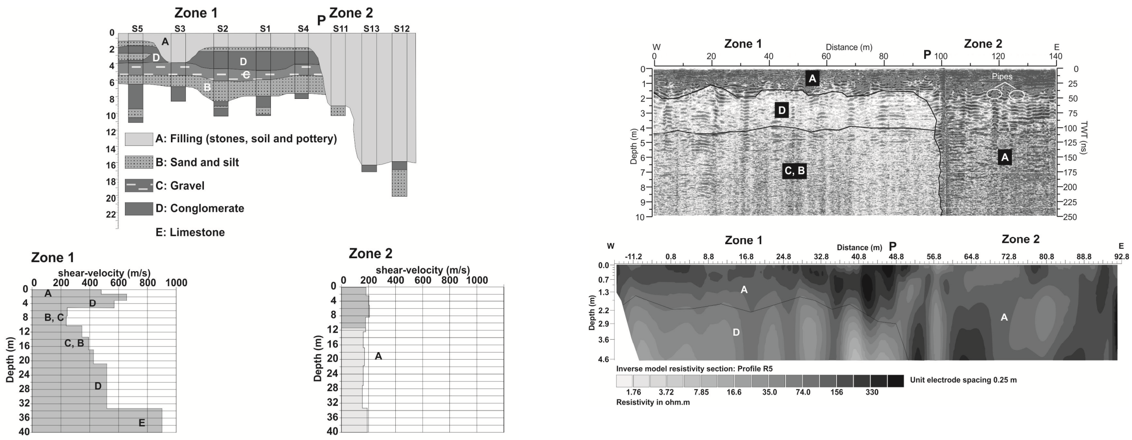

FIG. 3 – GPR data compared to resistivity imaging, ReMi (seismic shear-wave velocity) and strata from borehole data, in the evaluation of the ground under the Cathedral of Mallorca (from Pérez-Gracia et *al*. [9]).

VI. CONCLUSION

Major milestones for the GPR method in geological and geotechnical sectors remain the penetration depth that is seriously lower to other geophysical methods and the easiness of the application of the method in the rough field conditions. Although the problem of penetration is unsolvable so far as it depends on the signal energy, efforts must be oriented to increase the penetration of the signal. Air coupled antennas in the low frequency range are also a promising orientation but so far, only a few are present in the active market. Another issue is the improvement of the borehole GPR antennas especially in positioning and especially in azimuth. Horizontal Directional Drilling technologies are very elaborated in these fields and possibly a combination with the these technologies (beacons) could solve the position problem. In the buildings assessment in contrary, the GPR method is much more elaborated and marketed especially from his fastness and easiness on site. This is a promising sector, taking into account that parallel methods are elaborated in the same time, like for example the multi-spectral image analysis of concrete [6] and other.

ACKNOWLEDGEMENT

The authors acknowledge the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar", supporting this work.

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TABLE OF CONTENTS

Title	Project 4.4: “Applications of GPR in Association with Other Non-Destructive Testing Methods in Building Assessment and in Geological/Geotechnical Tasks” – State of the Art and Open Issues
Authors	K. Dimitriadis and V. Perez-Gracia
Page	183

The scientific activities of the COST Action TU1208 are carried out within four WGs.

The effectiveness of this scheme will be checked after the first year of activities and will eventually be modified, considering the actual number of active participants in each WG and the number of new participants that join the Action.

The structure of each WG will always be kept as flexible as possible, in order to enable other participants to join the Action. All the participants, when joining the Action, are invited to provide basic information on their experience, interests, and current research projects. They are also invited to provide WGs and Projects preference. Each participant can belong to two WGs; within each WG, each participant may join an arbitrary number of projects.

The four WGs of the COST Action TU1208 are:

WG1 – Novel GPR instrumentation

WG2 – GPR surveying of pavements, bridges, tunnels and buildings; underground utility and void sensing

WG3 – EM methods for near-field scattering problems by buried structures; data processing techniques

WG4 – Different applications of GPR and other NDT technologies in CE

Each WG is managed by a Chair and a Vice Chair.

The WG meetings constitute an opportunity to present activities, results and plans for the future. Between meetings, the WG members regularly interact.

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COST ACTION TU1208

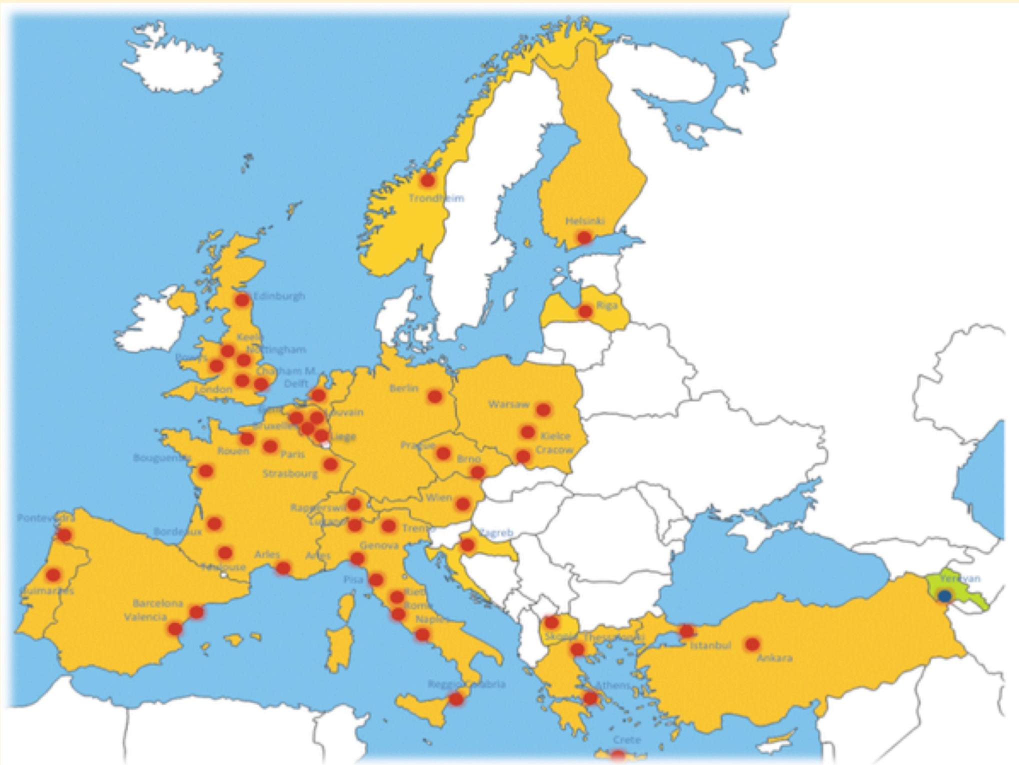
CIVIL ENGINEERING APPLICATIONS OF GROUND PENETRATING RADAR

Proceedings

First Action's General Meeting

Rome, 22nd – 24th July 2013

The COST Action TU1208 focuses on the exchange of scientific-technical knowledge and experience of Ground Penetrating Radar (GPR) techniques in Civil Engineering (CE). The project is being developed within the frame of a unique approach based on the integrated contribution of University researchers, software developers, geophysics experts, Non-Destructive Testing equipment designers and producers, end users from private companies and public agencies. In this interdisciplinary Action, advantages and limitations of GPR will be highlighted leading to the identification of gaps in knowledge and technology. Protocols and guidelines for EU Standards will be developed, for effective application of GPR in CE. A novel GPR will be designed and realized: a multi-static system, with dedicated software and calibration procedures, able to construct real-time lane 3D high resolution images of investigated areas. Advanced electromagnetic-scattering and data-processing techniques will be developed. The understanding of relationships between geophysical parameters and CE needs will be improved. Freeware software will be released, for inspection and monitoring of structures and infrastructures, buried-object localization, shape reconstruction and estimation of useful parameters. A high level training program will be organized. Mobility of early career researchers will be encouraged. The project has already received the interest of key end users and excellent EU Institutions.



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