Springer Transactions in Civil and Environmental Engineering

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Civil Engineering Applications of Ground Penetrating Radar

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ISSN 2363-7633 ISSN 2363-7641 (electronic)
Springer Transactions in Civil and Environmental Engineering
ISBN 978-3-319-04812-3 ISBN 978-3-319-04813-0 (eBook)
DOI 10.1007/978-3-319-04813-0

Library of Congress Control Number: 2015933624

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media
(www.springer.com)

Introduction

Ground Penetrating Radar (GPR) is a safe, advanced, and non-invasive sensing technique that has several traditional and novel applications, sometimes standardised by national or international regulations. It can be effectively used for subsurface investigation, three-dimensional imaging of composite structures, and diagnostics affecting the whole life-cycle of civil engineering works.

The major GPR strengths, on which its success in the civil engineering field is based, are related to the non-destructiveness and non-intrusiveness of the surveys, notably lower costs compared to traditional methods, high-speed data acquisition, reliability and representativeness of measurements. The time needed for a survey is typically one order of magnitude shorter than with possible alternative technology; this results in obvious business benefits of reduced costs, together with limited or eliminated charges associated to restricting access of other activities to the investigated area. GPR provides significant, dense and accurate data; the resolution is higher, compared to competing geophysical technologies as seismic, transient electromagnetic, electrical and magnetic approaches. The main performance limitations occur in the presence of high-conductivity materials, such as clay or salt-contaminated soils, and in heterogeneous conditions causing complicated electromagnetic-scattering phenomena. Considerable expertise is necessary to effectively design and conduct a survey; moreover, the interpretation of radargrams is generally non-intuitive, thus specific competences are needed to enable measurements to be transformed into clear pictures and engineering decision-making data. We are confident that, thanks to the improvement and evolution of both hardware and software technologies, ground-penetrating radar will become an even more efficient, effective, extensively used and less-invasive technique in the near future.

Looking at the current interest of the scientific community, technicians and professionals all over the world, towards GPR and its civil engineering applications, it could seem that the history of this electromagnetic technique is very long. Then, it may sound odd that its origin is assumed in the first applications of the radio-wave propagation above and along the surface of the Earth that were developed about 60 years ago. The first use in the field of civil engineering is commonly considered to have taken place in Egypt and it was oriented to identify the water table depth: in 1956, El Said implemented a research programme, funded by the Egyptian National Research Council, for the geophysical prospection of underground water in the deserts. It is interesting to underline that the methodology adopted by El Said was essentially the same as is currently used to estimate the thickness of layers or the burial depth of targets. In particular, he used a continuous-wave transmitter to diffuse electromagnetic energy in the ground through an antenna laid on the soil surface. A radio receiver measured the wave reflected by the water table. The distance between receiver and transmitter was known. Following procedures nowadays still used, he calculated the depth of the table by measuring the time delay of the received wave.

The whole history of ground penetrating radar is intertwined with its various applications. A significant activity in the field of civil engineering started up in the 1960s and has become mature in the 1970s. Mines and underground deposit inspections were very frequent. Moreover, in the line of the lunar science missions, strong efforts were spent to improve new technologies that seemed very promising for the subsurface examination. Additional and promising uses were observed in archaeology and geology. The electrical characterisation of geological materials, as well as the relationships between electrical conductivity and dielectric polarisation, were topics of great interest in the research community. In the 1980s, the GPR borehole configuration was successfully proposed for the assessment of nuclear waste disposal sites. Starting from these experiences, the borehole configuration has become a relevant standard for hydrological studies of porous media. Another application, that is now likely the most financed, is mine detection for security and humanitarian purposes. In recent years, the GPR was proposed and successfully used for the localisation of people buried or trapped under snow or debris, aiding rescue activities in disaster scenarios such as avalanches, collapsed buildings and earthquakes.

In the civil engineering field, GPR is currently used for inspection, monitoring and design purposes. The detection of utilities and buried objects, as well as the surveying of road pavements, bridge decks, tunnels, and the measurement of moisture content in natural soils and manmade materials, are the main applications. In addition, interesting examples concerning the use of the ground penetrating radar in structural, geotechnical and railway engineering have to be mentioned.

This book is a deliverable of the COST (European COoperation in Science and Technology) Action TU1208 “Civil Engineering Applications of Ground Penetrating Radar.”

COST is the longest-running European (EU) framework supporting cooperation among scientists and researchers across Europe; founded in 1971, it has been confirmed in Horizon 2020. It contributes to reducing the fragmentation in EU research investments, building the European Research Area (ERA) and opening it to cooperation worldwide. It also aims at constituting a “bridge” towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe, and fostering the establishment of excellence in various key scientific domains. Gender balance and early-stage researchers are strategic priorities of this programme.

COST does not fund research itself, but provides support for networking activities carried out within Actions: these are bottom-up science and technology networks, centred around nationally funded research projects, with a 4-year duration and a minimum participation of five COST Countries. The Actions are active through a range of networking tools, such as meetings, workshops, conferences, training schools, short-term scientific missions, and dissemination activities; they are open to researchers and experts from universities, public and private research institutions, non-governmental organisations, industry, and small and medium-sized enterprises.

The Action TU1208 is running in the "Transport and Urban Development" COST domain; it started in April 2013 and focuses on the exchange of scientific-technical knowledge and experience of GPR techniques in civil engineering, aiming at promoting throughout Europe a more effective use of this inspection method. The ambitious and interdisciplinary project of the COST Action TU1208 is being developed within the frame of a unique approach based on the integrated contribution of university researchers, software developers, geophysicists, civil and electronic engineers, archaeologists, non-destructive testing equipment designers and producers, end users from private companies and stakeholders from public agencies. About 300 participants from 130 institutions in 28 COST Countries (Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Malta, Macedonia, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, UK) and a COST Cooperating State (Israel) have joined the Action. Partners from COST Near-Neighbour Countries (Albania, Armenia, Egypt, Jordan, Russia, Ukraine) and International Partner Countries (Australia, Philippines, Rwanda, United States of America) are participating, too. Applications from further Countries are currently under examination.

During the first year of activity, the partners worked on highlighting the advantages and limitations of the currently available equipment, surveying procedures, and electromagnetic/numerical methods for the interpretation of experimental data. Such studies led to a comprehensive assessment of the state of the art in the field of the civil engineering applications of GPR, and to the identification of open issues and gaps in knowledge and technology. The results of this wide and in-depth review activity were fruitfully discussed during Action's meetings and are presented in this book.

The organisation of the book reflects the scientific structure of the Action, which includes four Working Groups (WGs). In particular, the WG 1 of the COST Action TU1208 focuses on the design of innovative GPR equipment, the building of prototypes, the development of testing and calibration procedures, and the optimisation of new systems. The WG 2 deals with surveying of transport infrastructures and buildings, sensing of underground utilities and voids, testing of construction materials and estimation of soil water content. The WG 3 is developing accurate and fast electromagnetic scattering approaches for the characterisation of complex scenarios, inversion and imaging techniques, and data processing algorithms for the elaboration of GPR data collected during civil-engineering surveys. Finally, the WG 4 focuses on the applications of GPR outside from the civil engineering field, as well as on the combination of GPR with other non-destructive testing techniques.

The book is opened with the first chapter of Part I—"GPR Instrumentation"—authored by G. Manacorda et al. and entitled "Design of Advanced GPR Equipment for Civil Engineering Applications," where the main issues in designing ground penetrating radar equipment dedicated to civil engineering applications are described. A comprehensive review on the commonly available system architectures along with the main design challenges to build an effective tool are herein provided. Overall, the work mostly focuses on three major areas where solutions to technical challenges are nowadays more than ever needed, namely, radio-frequency system design, antenna design and data analysis.

The transmitting and receiving antennas are among the most critical parts of a ground penetrating radar, performing the essential functions of transferring electromagnetic energy to the surveyed scenario with the required pattern, bandwidth and efficiency, and receiving the energy scattered-reflected by the environment. For this reason, Part I is complemented with the chapter by L. Pajewski et al., entitled "Antennas for GPR Systems." This contribution offers a review on the antennas currently used in GPRs, suggesting ideas for their improvement, and resuming the numerical and experimental methods for their electromagnetic characterisation.

Part II of the book is entitled "GPR Surveying of Pavements, Bridges, Tunnels and Buildings; Underground Utility and Void Sensing." It includes five contributions on this topic.

The chapter authored by J. Stryk et al. is entitled "Innovative Inspection Procedures for Effective GPR Surveying of Critical Transport Infrastructures (Pavements, Bridges and Tunnels)." This work thoroughly reviews individual applications, which are currently in use, and outlines those that are still in the phase of research and verification. An overview on issues that need to be dealt with GPR is also addressed, to enable the larger applicability of this non-destructive method in critical transport infrastructures.

The following chapter is entitled "Inspection Procedures for Effective GPR Surveying of Buildings," by V. Pérez-Gracia and M. Solla. It focuses on the main achievements in surveying different types of buildings, on the software development for enhancing data interpretation and on laboratory studies that can be overall relevant for the analyses of complex scenarios. Open issues are also defined as a final conclusion, based on the revision of different works.

In their chapter "Inspection Procedures for Effective GPR Sensing and Mapping of Underground Utilities and Voids, with a Focus to Urban Areas," C. Plati and X. Dérobert present some studies showing the ground penetrating radar performances and limitations in locating and mapping objects such as pipes, drums, tanks, cables and underground features or in detecting subsurface voids related to subsidence and erosion of ground materials, from single-channel systems to the potential of multi-channel three-dimensional imaging and integrating systems. The Authors also discuss the importance of achieving cost-effective installations from the deployment of GPR prior to directional drilling for the prevention of damage to existing utilities.

L. Krysinski and J. Hugenschmidt authored the chapter "Effective GPR Inspection Procedures for Construction Materials and Structures," in which a review of approaches related to the assessment of construction details and material properties by using ground penetrating radar is presented. The analysis of the authors relies on the assessment of electromagnetic properties as a fundamental mean for understanding both materials physical properties and as an inherent part of any GPR structural study necessary for correcting uncalibrated electromagnetic parameters. Major directions of research along with some benefits and limits of different approaches are herein described.

To complete Part II of the book, the chapter by F. Tosti and E. Slob, entitled "Determination, by Using GPR, of the Volumetric Water Content in Structures, Substructures, Foundations and Soil," describes the use of several instruments and processing techniques for the evaluation of volumetric water content in concrete structures and unsaturated soils, at different investigation scales. Strength points and main drawbacks of the commonly used approaches for moisture sensing are discussed, relative to the most recent research studies on this issue. In addition, recently developed methods on this field of application are introduced.

Part III of the book is entitled "Electromagnetic Methods for Near-Field Scattering Problems by Buried Structures; Data Processing Techniques;" it includes overall four contributions on these issues

This part of the book is opened by the chapter "Methods for the Electromagnetic Forward Scattering by Buried Objects," written by C. Ponti, in which the usefulness in using dedicated tools for the solution of forward electromagnetic scattering by buried objects is outlined, with the main purpose of interpreting the GPR responses. A review on the most established approaches in the modelling of impulse radar systems, such as Finite-Difference Time Domain or space-time integral equations, is developed. Furthermore, the issue of implementing novel approaches to approximate the integral equations via series expansions with lower computational complexity, when adopting a Method of Moments discretisation, is addressed. The spectral-domain Cylindrical Wave Approach is presented.

In the following chapter, entitled "Development of Intrinsic Models for Describing Near-field Antenna Effects, Including Antenna-Medium Coupling, for Improved Radar Data Processing Using Full-Wave Inversion," A.P. Tran and S. Lambot deal with the proper description of antenna effects on GPR data and resume the methods that have been developed for this purpose. Traditional numerical methods are computationally expansive and often not able to provide an accurate reproduction of real measurements. The Authors thoroughly describe how intrinsic modelling approaches, through which radar antennas can be effectively described taking into account their fundamental properties, have demonstrated great promise for fast and accurate near-field radar antenna modelling in order to reliably estimate medium electrical properties.

In the chapter "GPR Imaging via Qualitative and Quantitative Approaches," I. Catapano et al. resume the issue of solving an inverse scattering problem, where a set of parameters describing the underground scenario must be retrieved starting from samples of the measured electromagnetic field. The authors provide an overview of different approaches and algorithms for both quantitative and qualitative buried scatterer reconstruction.

N. Economou et al. complete Part III of the book with a chapter on "GPR Data Processing Techniques," wherein the difficulties in automating data analysis are mainly addressed. In this regard, after providing the reader with a deep understanding of the state of the art and open issues in the field of GPR data processing techniques, the authors present an overview on noise suppression, deconvolution, migration, attribute analysis and classification techniques with a particular focus on data collected during civil engineering surveys.

This book is concluded with Part IV "Different Applications of GPR and Other Non-Destructive Testing Technologies in Civil Engineering," which includes four chapters.

The first contribution is entitled "Applications of GPR for Humanitarian Assistance and Security," by X. Núñez-Nieto et al. This chapter reviews a series of published works in the frame of the ground penetrating radar applications for humanitarian assistance and security, with a special reference to the detection of mines and unexploded ordnances. The location of underground spaces and the GPR use in rescue operations is also addressed, wherein its contribution in locating human remains or living victims in disaster areas is always more demanded. The authors analyse specific systems, methodologies and processing algorithms specifically developed for these applications.

The following chapter, entitled "Applications of GPR in Association with Other Non-Destructive Testing Methods in Surveying of Transport Infrastructures," written by M. Solla et al., reviews a compilation of works in the frame of the applications of GPR combined to other non-invasive methods in the evaluation of transport infrastructures. The authors demonstrate that these integrated approaches have significantly benefited the procedures for inspection and they successfully solved some of the limitations of traditional methods in monitoring roads and pavements, concrete and masonry structures, and tunnels.

The next chapter, entitled "Advanced Electric and Electromagnetic Methods for the Characterisation of Soil," by M. Van Meirvenne, deals with the detailed spatial characterisation of soil properties with different electric and electromagnetic methods, which is essential for the management of soil to provide all its functions and essential services to the environment. Electrical resistivity sensors, ground penetrating radar systems and electromagnetic induction sensors are herein thoroughly compared by outlining potential targets of each measurement technique, along with advantages and limitations. Despite the strengths of every type of sensing system, it is suggested by the author an increased integration of soil sensors into multi-sensor systems enabling their fused processing as a future challenge for enhancing the reliability of soil analyses.

The last chapter, entitled "Applications of radar systems in planetary sciences: an overview," by F. Tosti and L. Pajewski, focuses on the remarkable results and sophistication of radar systems achieved over the history in several planetary explorations, by dividing the treatment according to different planets and celestial bodies investigated.

We would like to thank very much the Authors of all the Chapters, for contributing to this book. We are also sincerely grateful to Springer, to Dr. Pierpaolo Riva, Springer Engineering and Applied Sciences Editor, and to the Springer Editorial Staff, for giving us the opportunity to publish this book, for their patience, suggestions and support, and for the efficient handling of the editorial process. Finally, we would like to thank COST for funding the Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar."

Andrea Benedetto
Lara Pajewski

Contents

Part I
GPR Instrumentation

Design of Advanced GPR Equipment for Civil Engineering Applications

Guido Manacorda, Raffaele Persico and Howard F. Scott

Abstract This chapter describes the issues to be addressed in the design of Ground Penetrating Radar equipment dedicated to civil engineering applications. Radar is well known for its ability to detect aircraft, ships, vehicles, birds, rainstorms and other above-ground objects. It relies for its operation on the transmission of electro-magnetic energy, usually in the form of a pulse, and the detection of the small amount of energy that is reflected from the target. The round-trip transit time of the pulse and its reflection provide range information on the target. The application of radar in the detection of buried objects is quite old; there are details of such work dating back to 1910, with the first pulsed experiments reported in 1926 when the depths of rock strata were determined by time-of-flight methods. The design of effective Ground Penetrating Radars requires solutions to technical challenges in three major areas:

- Radio Frequency system design.
- Antenna design.
- Data analysis.

Hence, this chapter reviews the commonly available GPR system architectures and summarises main design challenges to build an effective tool.

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A. Benedetto and L. Pajewski (eds.), *Civil Engineering Applications of Ground Penetrating Radar*, Springer Transactions in Civil and Environmental Engineering,
DOI 10.1007/978-3-319-04813-0_1

1 Introduction

The use of Ground Penetrating Radars (GPRs) in civil engineering is well established 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 hydro-geological surveys.

The main applications of GPR to transportation infrastructures generally include measuring the thickness of pavement layers, detecting voids beneath layers, detecting and locating reinforcing bars, inspecting pavement structure, and mapping of the underground utilities.

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.

Requirements for civil engineering applications differ, depending upon the application, 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 1.5–2 m 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 any one of a wide range of soil types, with implications for large differences in both the absorption and the velocity of propagation of electro-magnetic 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 other hand, surveys 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 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 sometimes be 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.

Images, such as that shown in Fig. 1 can easily be understood even by an unskilled 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 graphics software will solve neither the basic signal problem nor the detection performance.

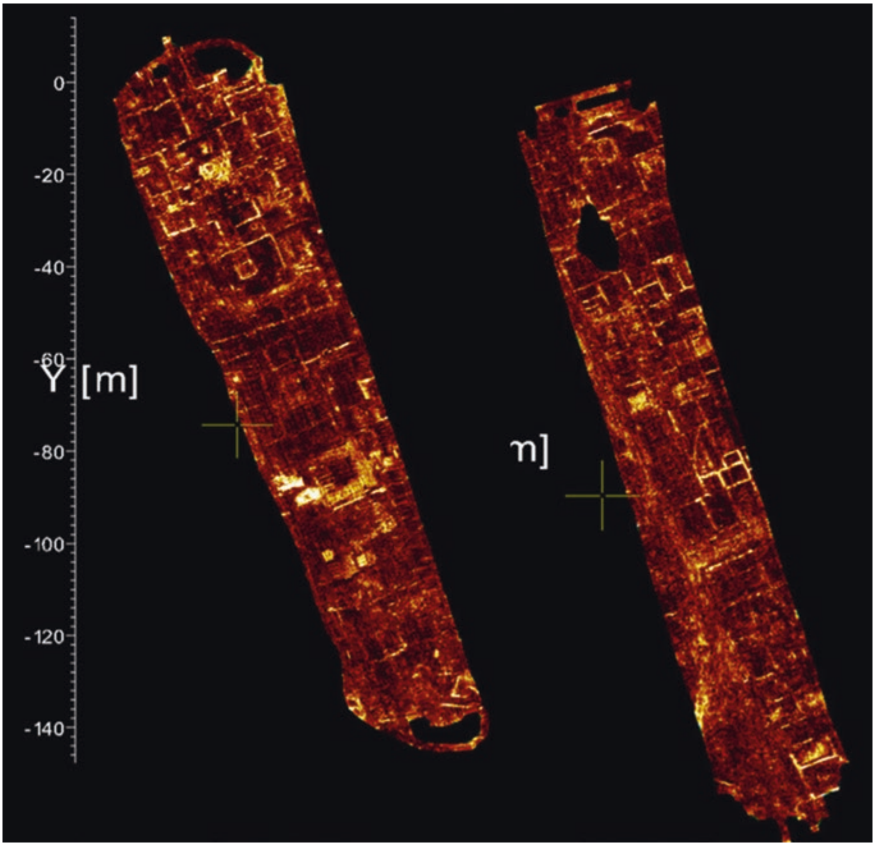

Fig. 1 High resolution GPR image of the archaeological site of Empúries (Spain) (Courtesy of Geostudi Astier—Italy)

Consequently, the design of high performance equipment is a complex but fascinating task for engineers and researchers as it involves a wide range of expertise such as electromagnetic wave propagation in media, antenna technology, radar design and electronics as well as advanced signal processing techniques and computer graphics.

2 The Radio Frequency System

2.1 Introduction

The purpose of the Radio Frequency (RF) system is:

- To generate an electrical signal of appropriate power level, frequency range and spectral characteristics, and to apply it to the transmit antenna.
- To process energy collected by the receive antenna into a form suitable for data analysis.

The RF energy is usually in the form of a short pulse, a frequency modulated burst of electromagnetic energy or discrete frequencies transmitted in a known sequence. RF system design and costs are significantly affected by the choice of modulation technique. Pulse modulation is, at present, cheaper to implement and is the method used in most commercial systems. Performance benefits, particularly increased dynamic range, are available from Frequency Modulated Continuous Wave (FMCW) and stepped frequency systems, but practical limitations imposed by the physics of the process make the benefits difficult, but not impossible, to realise in practice. Other modulation techniques are possible, such as noise and pseudorandom coding, but these are very seldom used.

The critical performance parameter of the RF system is dynamic range. Pulse modulated systems use sampling receiver techniques where, typically, the dynamic range will be 70 dB. Time varying gain is usually applied which can increase the dynamic range to 90 dB or more. In addition, averaging may be used (if acquisition times permit) which can provide a further increase. Frequency modulated systems, either continuous wave or stepped, can increase dynamic range.

However, when the RF system is connected to practical antennas, internal system reflections, ground returns and transmit to receive antenna leakage generate time dependent clutter (clutter is the term used for returns identified by the system as targets that do not correspond to intended targets or to noise). Unless special measures are taken, clutter limits dynamic range regardless of whether time or frequency domain systems are used.

The final stage of the RF system transforms the analogue signal into digital form for data analysis and display purposes; this conversion must be executed with a suitable sampler resolution that prevents the limiting effects on dynamic range of quantization noise.

2.2 Time Domain GPR

Usually, Time Domain GPRs produce transmit signals with the required frequency range by using 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 ns, as shown in the diagram Fig. 2). 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, which limits the inherent dynamic range of the system.

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 top diagram in Fig. 3 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

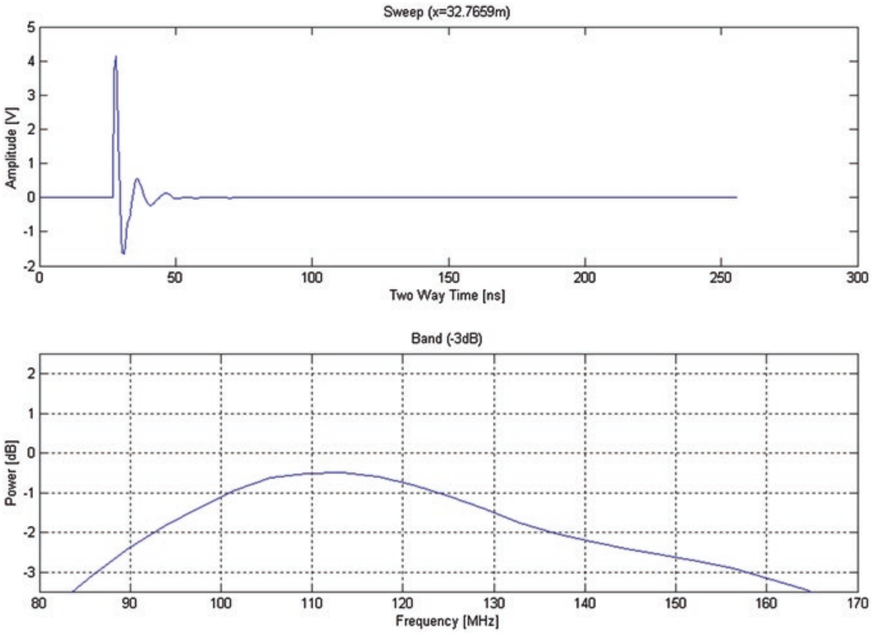

Fig. 2 Impulse radar pulse and spectrum envelope

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 in the Fig. 3 bottom 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 minimise its decay time and to make it, as far as possible, independent of the electrical properties of the ground.

2.3 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.

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

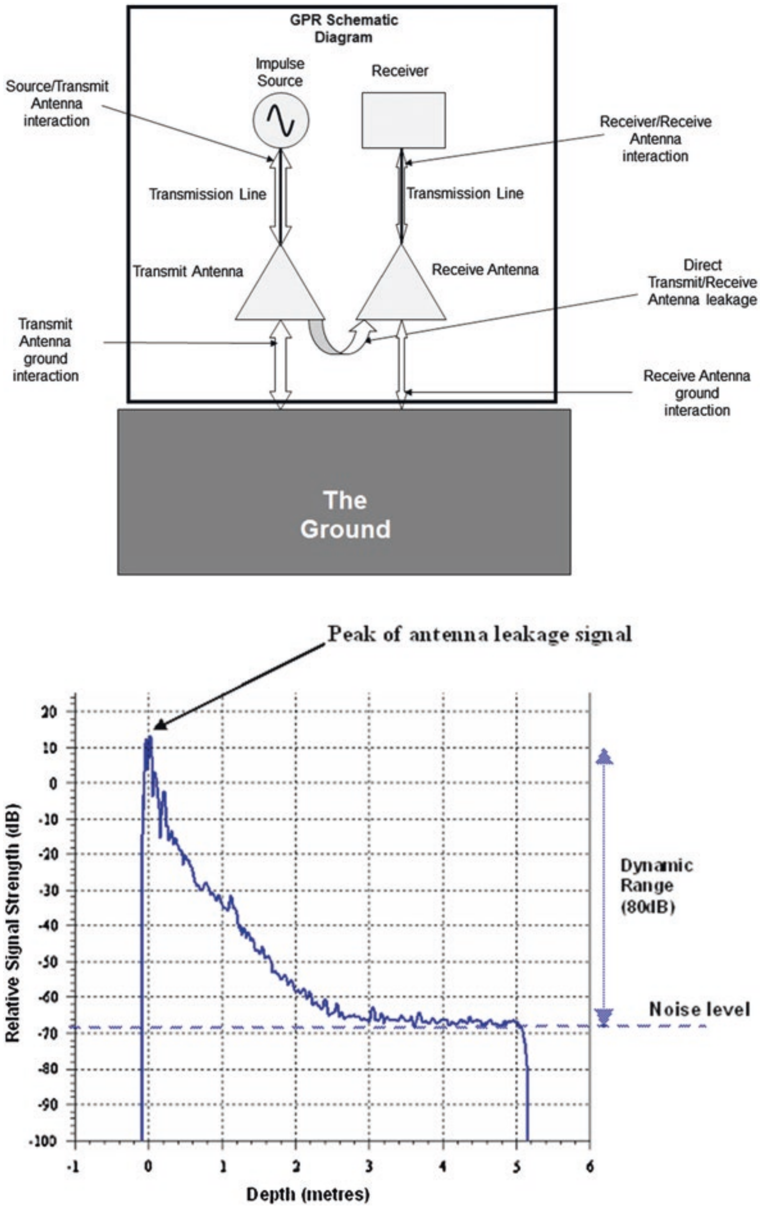

Fig. 3 Impulse radar GPR Scheme with major signal interaction paths (*above*) and consequent GPR clutter response (*below*)

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.

2.3.1 Principles of Frequency Modulated Continuous Wave (FMCW) Receivers

FMCW radar systems are able to detect motionless targets because of the time delay between the energy originally transmitted and the reception of energy reflected from the remote target. Because the frequency of the transmitted signal is constantly varying with time, the signal from the target will be different to that currently being transmitted. If the transmitted frequency changes linearly with time, then the frequency difference is a direct measure of the range of the target (Fig. 4).

By choosing the rate of change of frequency appropriate to the target range, the difference frequency can be set so that it lies within a range that can be processed by audio frequency devices. A typical difference frequency might be 10 kHz, so that a narrow-band filter can be used to minimise the noise bandwidth and, hence, maximise the dynamic range.

By applying a sample of the transmitted signal and the received signal to a nonlinear receiver, sum and difference frequencies are created. A low pass filter easily separates the required difference and sum frequencies.

The diagram in Fig. 5 depicts a simple FMCW radar system. In the GPR application illustrated, the same signal interactions are present as in the impulse radar.

Detection is achieved by taking a sample of the transmitted waveform, and using it as a Local Oscillator (LO) input to a diode. The much weaker received signal is also fed into the diode, which acts as a 'phase coherent' detector. This

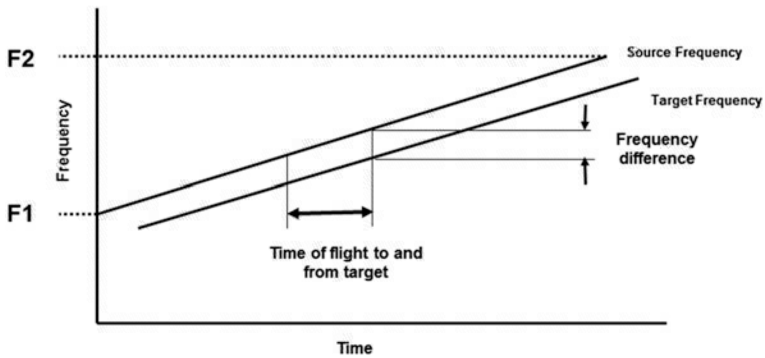

Fig. 4 FMCW difference frequency generation

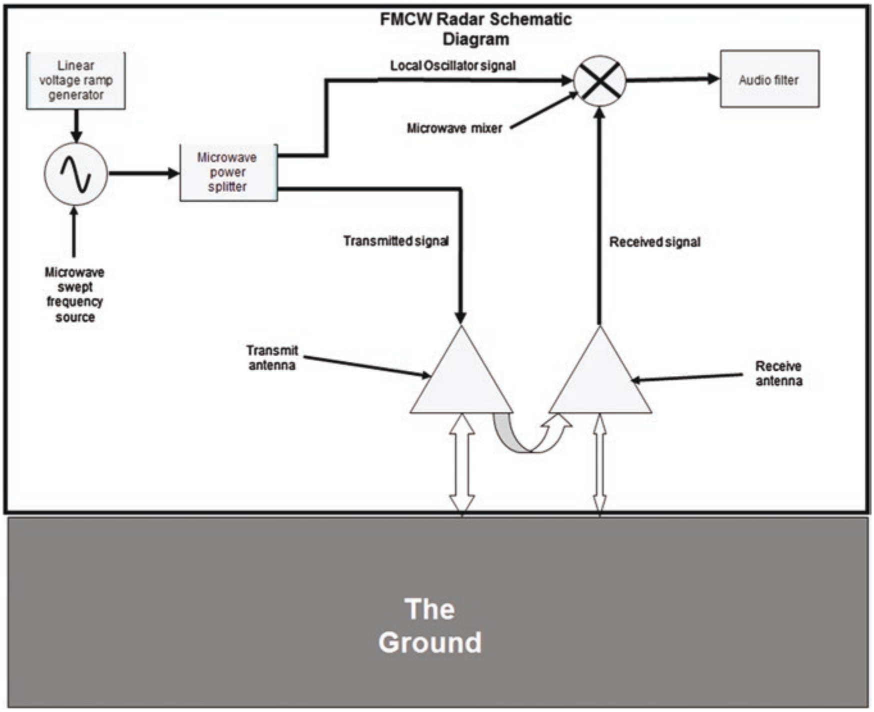

Fig. 5 FMCW radar schematic diagram

signal mixing (heterodyning) in the diode creates sum and difference frequencies from the LO and received signals. The sum frequency is outside the frequency range of the receiver and is thus filtered out, whilst the difference frequency is processed further to yield the required target information. This processing takes the form of a transformation of the difference frequency data, by means of a Fourier Transform, into the time domain so that range information may be extracted.

FMCW radars offer wider dynamic range, lower noise figures and can radiate higher mean powers than the time domain counterpart. In addition, the frequency range used is easily tailored to suit the characteristics of the material and targets under investigation. If, however, degradation of the system resolution by spectral widening of the Intermediate Frequency (IF) is to be avoided, then a high degree of the linearity in the variation in frequency as a function of time is required.

2.3.2 Time Domain to Frequency Domain Transformation

Fourier, in his *Théorie analytique de la chaleur* (1822), stated that any periodic signal can be represented by the sum of an infinite series of sine waves separated by the repetition frequency of the time domain signal. The process has become known as the Fourier Transform. Further, an inverse process may be applied to the series of sine waves to transform them from the frequency domain into the time domain. This is known as an Inverse Fourier Transform.

All time domain signals are represented by a single value that describes their amplitude at any instant in time. On the other hand, the frequency domain description of a sinusoid requires both amplitude and phase. The output, therefore, of the Fourier Transform requires two channels of information to convey a full description. This can be amplitude and phase, but it can also be the real and imaginary parts of a complex number. In order to carry out the Inverse Fourier Transform correctly, both the real and imaginary parts of the frequency domain signal must be known. The simple schematic of a FMCW system as shown above, cannot supply the complete information required.

As the repetition frequency decreases, then the frequency difference between the sinusoids of the Fourier Transform becomes smaller until, in the limit when there is only a single occurrence of the signal, the frequency spectrum becomes continuous. The diagram below shows a single occurrence of a real time domain signal, together with its Fourier Transform. Note that the time domain signal illustrated has a DC component, and the spectrum of the output of the Fourier Transform is distributed about zero frequency. With radar pulses, there would be no DC component and the spectrum of the Fourier Transform would be distributed about the centre frequency of the radar system (Figs. 6 and 7).

To obtain the correct Inverse Fourier Transform, both the real and imaginary components of the frequency domain version must be used in the calculation, as shown below. The general case is that, in principle, the time domain signal may also have real and imaginary parts.

The above has implications for the design of a FMCW radar system, because an extra channel of information is needed so that both real and imaginary parts (or amplitude and phase) of the frequency domain signal can be captured. To achieve this, the Local Oscillator output is divided into two signals which differ in phase by 90°, and each is applied to its own mixer. The signal from the receive antenna is also divided, with no relative phase shift. These are mixed with the two LO signals to generate the real and imaginary parts. They are more usually known as the ‘In-Phase’ (I) and ‘Quadrature’ (Q) components.

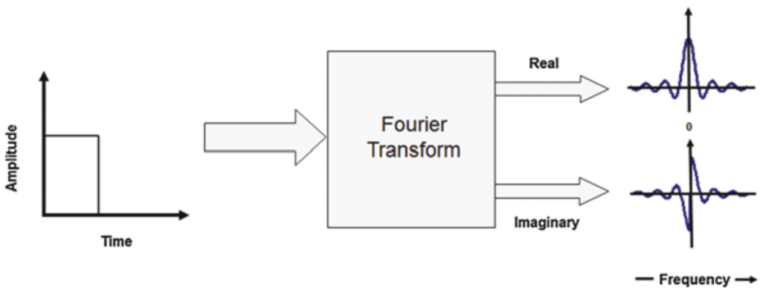

Fig. 6 Fourier transform concept

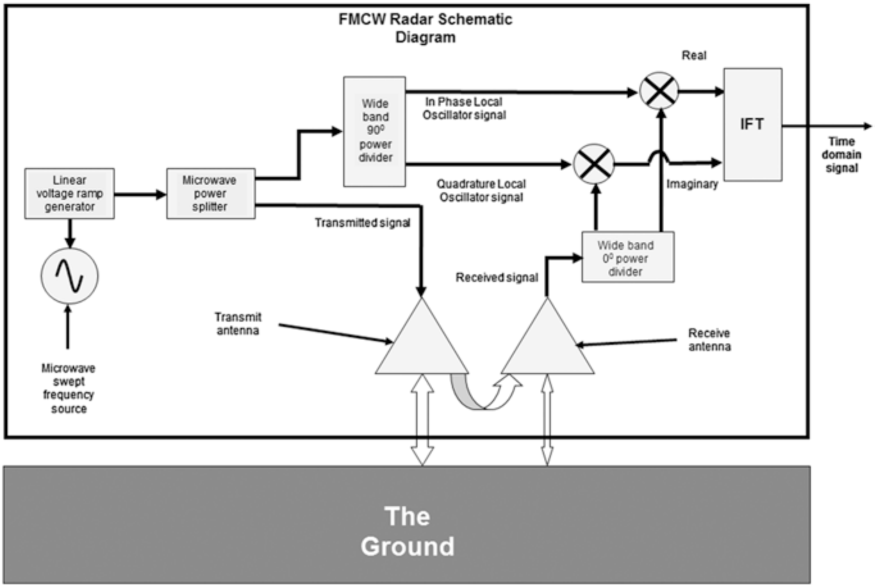

Fig. 7 FMCW radar with I and Q outputs schematic diagram

2.3.3 Stepped Frequency Continuous Wave Systems

Thus far, the microwave source has been described as a voltage controlled swept frequency generator where the output frequency is continuously variable; the main advantages and disadvantages of such a system have been outlined above.

Another class of microwave sources is available where the frequency can be changed in discrete, highly repeatable and stable, steps. In this case, 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, as described for the continuous wave source, 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. However, it is not possible to apply a filter to the data, so the Nyquist requirement that the sampling rate provides a range of twice that to the most distant target to be detected (whether that target is below or above ground) must be strictly observed.

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. Also, the accuracy of the frequencies provides an extremely linear sweep, which eliminates one of the principal weaknesses of FMCW sources.

3 Ground Penetrating Radar Antennas

The purpose of the antenna system is to illuminate the target and to collect the resulting scattered energy from the environment. Two main types of system are used:

- Monostatic.
- Bistatic.

Monostatic systems use a common radiating element for transmitting and receiving the signal; most GPRs use bistatic antennas with the transmitter and receiver hosted in the same enclosure.

The key requirements for the antennas are:

- An ability to radiate a wide range of frequencies, typically over the range 100–1000 MHz or more.
- Linear phase characteristics over the operating frequency range.
- Predictable (and, preferably, constant) polarisation characteristics over the operating frequency range.

The key design objectives for a GPR antenna are to achieve

- a high degree of isolation between transmit and receive antennas;
- a low return loss from the feed point to minimise ringing and thus clutter generation;
- a good immunity from radio frequency interference.

Two general types of antenna have been used so far; dispersive and non-dispersive. In dispersive antennas different frequencies are radiated at different times, usually with high frequencies being radiated first followed by the low frequencies. This type of waveform is sometimes known as a “chirp”. Although some antennas are classed as non-dispersive, in fact all antennas are dispersive to some degree. Examples of these classes of antennas are:

- Dispersive—Spirals (logarithmic, exponential and Archimedean), exponential slot, Vivaldi.
- Non-dispersive—TEM horn, biconical, bow tie, resistive lumped element loaded, resistive continuously loaded.

The design of the antenna system is influenced by the nature of the required targets. All targets tend to depolarise electromagnetic waves incident upon them, the most extreme example of this being long, thin (in terms of wavelength) objects. If the long thin object is metallic then the reflected wave's polarisation is parallel to its axis; if it is non-metallic, then the reflected polarisation is orthogonal to its axis (Roberts and Daniels 1996).

In the case of radar systems designed to locate pipes and cables, this is a very useful property that can, in principle, be used to improve the response to the required target. A complete knowledge of the depolarisation characteristics of targets in general, particularly how they behave over a range of frequencies, can be a powerful aid in target detection and classification. There are many descriptions in the literature of antenna configurations specifically designed to extract polarisation information.

3.1 Array of Antennas

Optimum GPR system performance, particularly for high resolution detection of shallow objects, is obtained when the whole of the system is designed around a specific target type or geometry.

For example, whenever a high density of utilities is expected in several orientations (e.g. in an inner city road junction), a single antenna GPR must be scanned over a dense orthogonal grid (i.e. along two directions at right angles to each other) with a step no larger than say 0.5 m; using a larger step might be adequate when trying to trace a single pipeline across a field where the approximate entry and exit points are known, but is totally inadequate when mapping a complex layout of underground assets.

Thus, when the collection of data requires the execution of a large number of profiles, the use of an array of antennas lined up in the transversal direction with respect to the direction of movement, and operating simultaneously, will provide the most efficient method.

This architecture enables another advantage in respect to the analysis of collected data; in a certain sense, an array GPR implements a scheme very similar to the one used by "double threshold detection" radar.

Non-array GPRs are examples of, "single threshold detection radars", where the operator decides whether a target is present on the basis of one "peak detection decision"; in other words, the output of the receiver is compared to a threshold or bias level.

This bias level, which is dependent upon the sensitivity of the display and the human operator's visual perception, affects the probability of generating a false alarm and of missing a genuine target; in other words, when a received signal component that has been generated by noise or clutter exceeds the bias level, it can be mistaken for a return from a genuine target and there is a "false alarm". On the other hand, when a signal received from a genuine target is interpreted as a noise pulse or clutter (which occurs when the signal return is below the bias level), there is a "missed detection".

Missed detection and false alarm rates are subject to trade-off; it means that the number of false alarms (missed detection) may be decreased (increased) as the bias level is raised, and vice versa; therefore bias level is a primary parameter in the radar's design.

For solving problems related to the human operator, "double threshold detection" radars have been introduced. Such systems impose detection criteria whereby there must be several occurrences of the threshold of detection being exceeded in a defined period of time before a target is confirmed; therefore, the performance of these equipment are less vulnerable to the sensitivity of human operators.

Analogously, in GPR operations, the use of antenna arrays improves the detection of buried utilities because elongated targets (e.g. pipes or reinforcement bars in concrete) produce echoes (in the form of hyperbolae) in the same position in most (ideally in all) of the data windows; therefore, the operator can easily distinguish this category of target from those that are concentrated (e.g. a stone), and performance, in terms of probability of detection, is improved.

A further benefit of this array based architecture is the possibility of using advanced signal processing techniques; data collected with the array are geometrically coordinated and can be stored as a three-dimensional data set that may be displayed as slices in vertical or horizontal planes. These are effectively microwave images, and image-processing techniques may be applied to enhance wanted features; in this respect, as the target sought has identifiable properties (a pipe is long and thin), then this may be taken into account in the processing by the application of appropriate filters, such as line finding algorithms.

Finally, the latest developments in GPR are tending towards providing the capability of generating real-time 3D high resolution images of surveyed areas. This objective is achievable by having a complete, very dense, coverage of the surveyed area, in the form of a 3D data set.

This could be achieved, albeit less efficiently, by performing hundreds of 2D profiles, very close to each other, with a single antenna GPR. However, since this data collection procedure is very time consuming, several dense arrays have been developed with the capability of producing 3D data volumes with a single scan.

4 Data Processing and Analysis

The processing of GPR data, with its several aspects both theoretical and practical, could form a "chapter" in its own right. At first sight, it appears that the mathematical ill-posedness of the problem (Colton and Kress 1992) makes it impossible to retrieve any details of the buried scenario. This should not make us unnecessarily pessimistic. However, this means that, whether the exploited processing algorithm, there will be a finite resolution and a finite quantity of information extractable from the data. Consequently, it is illusory to think that gathering an indefinitely growing number of data will achieve an increasingly precise image, and it is even harmful to think of prolonging indefinitely the processing in order to improve the achieved results. This over-processing is the equivalent of squeezing a lemon in an attempt to extract more juice than it contains.

That being said, several categories of processing can be identified, depending upon whether a 1D, 2D or (more rarely) a 3D approach is taken and depending upon whether the problem is treated by a linear or (more rarely) nonlinear method. Within each approach, the configuration of the antennas has also to be taken into account (Persico et al. 2005), as well as the height of the measurement line (Persico 2006), the frequency band (Sala and Linford 2012) and the a priori information available in relationship with the case history at hand. In particular, if reliable a priori information is available, that is if the nature of underground targets are already presumed, and only some of their geometrical features are looked for, then a forward modelling technique may be exploited (Daniels 2004; Utsi 2012).

4.1 One-Dimensional Processing

Proceeding in order of increasing complexity, and taking for granted the preliminary step of the zero timing, 1-D processing is, in general, a technique where GPR traces (gathered at any fixed measurement point and presented either in time or frequency domains), are processed independently from each other. This can be done if a one-dimensional scenario is scanned so that a 1-D model of the propagation can be exploited (Persico and Soldovieri 2004; Pieraccini et al. 2006), or the interest is in equalizing the deformation of the signal when it is reflected by the targets of interest.

In particular, it can be the case that incident waves may characteristically be scattered by some targets, allowing them to be recognised and, possibly, distinguished from other objects that may be geometrically similar, but of a different nature. This procedure is called deconvolution (Daniels 2004; Jol 2009), and is sometimes exploited where such an identification is particularly important, as e.g. in de-mining operations (Daniels 2004).

The predominant characteristic of GPR data is that it diminishes in amplitude as a function of time. This is caused by the geometrical spreading of the radiated (and scattered) energy plus the electrical losses usually present in the soil. These effects combine to make the echoes from the deepest targets possibly much weaker than those from shallower targets. By applying an increase in gain versus time along the received signal, it is possible to compensate for this attenuation and make those targets visible.

It should be noted that varying the gain as a function of depth is a non-stationary processing step, which can cause a spurious enlargement of the spectrum of the traces, causing a deterioration of the image. This enlargement of the band is theoretically easily explained by the fact that a variable gain is equivalent to a multiplication of the time domain trace by a monotonically increasing function.

In the frequency domain, this is equivalent to the convolution product of the two spectra that, in general, leads to an enlargement of the band.

This effect can, usually, satisfactorily be mitigated by means of a further 1-D processing procedure consisting of filtering the traces to limit their spectra to be within the original band. This can be done via software making use of an ideal filter (the causality requirement is not essential because the GPR post-processing is not a real time operation) or an algorithm imitating a physically realisable filter, as e.g. a Butterworth filter (Di Lorenzo 2013). Any choice has its pros and cons. In particular, an ideal filtering process can, theoretically, anticipate the depth of the target whereas a "real filter" might add some further distortion in the band (in any case, both of these effects are usually negligible).

Variable gain and 1-D filtering procedures are usually contained in the routines available in commercial codes for GPR data processing, as e.g. the Reflexw (Sandmeier 2003) or the GPRslice (Goodman and Piro 2013). It is worth noting that variable gain and 1-D filtering are also usually exploited within the processing chain performed in 2-D or 3-D contexts. In other words, 1-D processing steps can be (and in practice are) mixed with 2-D or 3-D processing steps. To summarise with a final formula the 1-D filtering, let $\hat{T}(\omega)$ represent the spectrum of a trace $T(t)$.[1]

A 1-D filter is the multiplication of $\hat{T}(\omega)$ by an established filtering function $H(\omega)$, so to achieve a filtered spectrum $\hat{T}_F(\omega)$ given by:

$$\hat{T}_F(\omega) = H(\omega)\hat{T}(\omega). \tag{4.1}$$

4.2 Two-Dimensional Processing

The most common forms of 2-D processing are spatial filtering and migration. The difference between 1-D and 2-D filtering is that, in the second case, several traces are treated and combined together in some manner to produce a comprehensive representation known as a B-scan. The most common 2-D spatial filters are implemented by multiplying the spectrum of the data by a 2-D filtering function.

More precisely, labelling the 2-D Fourier transform of the datum as $d(x, t)$ with respect to the measurement abscissa and to the time as $\hat{\hat{D}}(k, \omega)$, the most common 2-D filter is implemented by multiplying this spectrum by an established filtering function $H(k, \omega)$ to produce the filtered spectrum of the data $\hat{\hat{D}}_F(k, \omega)$, given by

$$\hat{\hat{D}}_F(k, \omega) = H(k, \omega)\hat{\hat{D}}(k, \omega) \tag{4.2}$$

Included in this category is the FK filter, which aims to reject the effect of possible reflection from targets in air (Chan and Stewart 1994) and the Background

[1] The data may be gathered either with a pulsed or a swept frequency GPR, in the latter case $T(t)$ is meant as an equivalent trace in the "synthetic" time domain.