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A signal processing methodology for assessing the performance of ASTM standard test methods for GPR systems

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ABSTRACT

Ground penetrating radar (GPR) is one of the most promising and effective non-destructive testing techniques (NDTs), particularly for the interpretation of the soil properties. Within the framework of international Agencies dealing with the standardization of NDTs, the American Society for Testing and Materials (ASTM) has published several standard test methods related to GPR, none of which is focused on a detailed analysis of the system performance, particularly in terms of precision and bias of the testing variable under consideration. This work proposes a GPR signal processing methodology, calibrated and validated on the basis of a consistent amount of data collected by means of laboratory-scale tests, to assess the performance of the above standard test methods for GPR systems. The (theoretical) expressions of the bias and variance of the estimation error are here investigated by a reduced Taylor's expansion up to the second order. Therefore, a closed form expression for theoretically tuning the optimal threshold according to a fixed target value of the GPR signal stability is proposed. Finally, the study is extended to GPR systems with different antenna frequencies to analyze the specific relationship between the frequency of investigation, the optimal thresholds, and the signal stability.

1. Introduction

Ground penetrating radar (GPR) is an increasingly popular nondestructive testing (NDT) technique that emits a short pulse of electromagnetic energy into the subsurface [1,2]. When such a pulse strikes an interface between layered materials with different electrical properties, part of the wave reflects back, and the remaining energy continues to the next interface, thereby penetrating in depth before being absorbed. GPR is capable to collect the reflections of the electromagnetic waves at the interface between two different dielectric materials. It is relatively easy to recognize a GPR signal, since the return signal is shaped very similar to the emitted one. The depth, shape and electromagnetic properties of the scattering of the reflecting object affect the time delay, as well as the differences in phase, frequency and amplitude. GPR is a technology with a wide flexibility of usage. It is mainly application-oriented, with structure and electronics relatively variable according to the target characteristics, such as type and constituent materials, the environmental context, and the spatial scale of applications. A variety of areas, e.g., civil and environmental engineering [3], geology, archaeology, forensic and public safety [4], planetary sciences [5] are therefore increasingly interested by the application of this tool.

Nevertheless, few recognized international standards exist in the area of GPR, and a certain amount of inhomogeneous recommendations can be encountered in different countries. Moreover, the levels of knowledge, awareness and experience on the use of GPR may vary very considerably across countries. This results in a general need for the GPR users to know the most appropriate good practices to be followed in terms of GPR measurements and the expected quality level of the results. A small number of National and International standards includes general recommendations for performing geophysical surveys of the subsurface. Many of these focus on civil engineering applications, with the area of transport infrastructures being the most regulated. Within the European framework, few GPR-related National and International guidelines have been issued if compared to the widespread usage of this tool. It is worth to mention the Italian contribution within the field of the underground utility detection [6], along with the guidelines released by IDS (Ingegneria dei Sistemi) enterprise [7] and the ASG (Associazione Società di Geofisica) geophysical association [8]. These provide useful theoretical and practical insights on GPR, along with a number of key and application-oriented data processing algorithms. In France, the detection of buried utilities has been thoroughly tackled [9]. In

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Germany, instructions on the use of radar systems for non-destructive testing in civil engineering [10] and for gaining inventory data of road structures [11] are available. In Scandinavia, recommendations were developed within the Mara Nord Project on the use of GPR in several applications, such as the measurement of air voids in asphalt concrete [12], road construction quality controls [13], bridge deck surveys [14], road rehabilitation projects [15] and in-site investigations [16].

Still at the European level, a number of standards and codes introduced by the European Telecommunications Standards Institute (ETSI) regulate the use of GPR and its emissions of electromagnetic radiation. Such documents focus on the common technical requirements [17], the specific conditions for ground and wall probing radar (WPR) applications [18], the main technical characteristics and test methods [19], the levels of compliance [20] with the Radio and Telecommunications Terminal Equipment (RTTE) Directive [21], as well as with one code of practice in respect of the control, use and application of GPR and WPR systems and equipment [22]. On the other hand, three main standards released by the American Society for Testing and Materials (ASTM) guide the use of GPR toward the investigation of the subsurface [23], the evaluation of asphalt-covered concrete bridge decks [24], and the determination of pavement-layer thickness [25]. In more details, according to the ASTM classification on the standard categories, the above documents can be classified into (i) Standard Guides (i.e., [23]), namely, an organized collection of information or series of options that does not recommend a specific course of action, and (ii) Standard Test Methods (i.e., [24] and [25]), wherein specific test procedures for assessing the stability of the GPR signal are discussed, such as the signal-to-noise-ratio (SNR) test.

Notwithstanding the estimate of the SNR is not new to the GPR community, to the best of our knowledge there are no papers related to the SNR test as defined by the ASTM standards. Many works on signal processing procedures for the assessment and improvement of the SNR in GPR investigations can be found in the literature. In [26], the authors propose to enhance the GPR signal with the Karhunen–Loève transform (KLT), whereas the work in [27] aims at improving the SNR of a GPR signal by introducing an enhanced-signal-based method, with the noise variance being estimated by a clustering technique. Furthermore, a novel preprocessing method for GPR signals, based on the minimum gradient method, is discussed in [28]. Within the most established signal processing techniques in the GPR area we can cite time and frequency analyses [29], time varying band-pass filtering [30], deconvolution [31], velocity analysis [32], migration [33] and compressive sensing [34], as well as the attribute analysis and classification [35]. The main purpose of all such techniques is to enhance the SNR of the GPR signal. They commonly focus on the SNR of the received GPR signal, wherein the noise is assumed as the back-scattered noise from the subsurface after carrying out a GPR survey. Conversely, in this paper we are assuming the noise as the amount of clutter that is in the GPR equipment, also known as systematic error. Thereby, we are focusing on the signal stability of a GPR system, during the calibration phase and before an investigation is carried out. The evaluation of this type of internal noise is extremely important to perform automated signal processing by GPR, as it ensures that the quality of the GPR waveforms is suited for purposes. According to this, the ASTM standards [23–25] define some tests to verify the stability of the GPR signal, such as the SNR test, and the (short- and long-term) signal stability tests. Notwithstanding their higher scientific level with respect to similar National and International standards, three main failings in the ASTM standards can be singled out, namely, *i*) how to select the optimal threshold and to which level of signal accuracy (or stability) this threshold corresponds; *ii*) the lacking of a detailed analysis of the system performance, particularly in terms of precision and bias of the testing variable under consideration; and *iii*) the use of a few central frequencies of investigation, which may not allow to supply a comprehensive overview of the results in line with the broader range of central frequencies used in GPR applications. To the best of our knowledge, only one paper [36] can be found in the literature wherein the issues in the ASTM standards are tackled by checking the GPR signal stability versus the systematic error of the GPR system. In particular, the paper by Rial et al. [36] represents an effort to set-up a strategy for verifying the stability of performances in GPR systems in terms of electromagnetic radiated fields. In addition, the paper in [36] focuses on the (short- and long-term) signal stability tests, whereas no discussion has been included about the SNR test. Nevertheless, this activity is definitely relevant as the starting point to develop a methodology for calibrating GPR devices and verifying proper operation.

In line with the above and according to the guidance provided by the mentioned ASTM standards, this paper is (to the best of the authors' knowledge) the first study that focuses on the ASTM SNR test, thereby aiming at providing a detailed analysis of the bias and variance of the testing variable under consideration (i.e. the SNR). In particular, this work proposes a straightforward GPR signal processing procedure (calibrated and validated on the basis of a consistent amount of data collected from laboratory-scale tests), to evaluate the precision and bias of the GPR signal under investigation, by a reduced Taylor's expansion up to the second order. Therefore, we propose a closed form expression for theoretically tuning the optimal threshold, according to a fixed target value of the GPR signal stability. Finally, the study is performed with several GPR systems (i.e. exploiting antennas tuned to frequencies different from 1 GHz), analyzing the specific relationship between the frequency of investigation and the optimal thresholds.

The remainder of this paper is organized as follows. In the first half of Section 2, the GPR working principles as well as its main applications are discussed. The second half of Section 2 illustrates the conventional ASTM standard test methods, highlighting the weaknesses of such methodologies. In Section 3, a signal processing procedure for threshold tuning is provided, as well as a closed form expression for theoretically evaluating the optimal threshold according to a fixed target level of GPR signal accuracy (or stability). Then, a theoretical analysis of the performance of the ASTM test method is developed, in terms of precision and bias of the considered test. The first half of Section 4 describes the laboratory set-up for the GPR measurements, whereas numerical results and comparisons are outlined in the second half of Section 4. Finally, conclusions are briefly drawn in Section 5.

2. Basic framework on GPR principles and reference ASTM standards

2.1. GPR working principles and main applications

The hardware of a GPR system utilized for the measurement of the subsurface conditions usually consists of a transmitter and a receiver antenna, a radar control unit, and suitable data storage and display devices. Measurements can be traditionally performed in two main survey configurations, namely, with ground-coupled or air-coupled antennas, as a function of the main purposes and type of survey.

The working principle of a GPR complies with that of similar electromagnetic devices. It is based on the transmission/reflection of short electromagnetic impulses, with the antenna system being capable to emit and detect them. According to the typical scenario of investigation considered by the ASTM standards analyzed in this

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