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Int. J. Electron. Commun. (AEÜ) 59 (2005) 329 – 336
International Journal AEÜ of Electronics and Communications
www.elsevier.de/aeue

Linear tomographic inversion of stepped-frequency GPR data: experimental results on two test-sites

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Received 25 November 2003; received in revised form 30 August 2004

Abstract

This paper deals with the tomographic inversion of experimental data acquired by a stepped-frequency ground penetrating radar (SFGPR).

The experimental SFGPR has been designed for archaeological prospecting and makes it possible to exploit a multi-view/multi-static/multi-frequency configuration. The tomographic algorithm is based on a linear model of the electromagnetic scattering to reconstruct the shape of strongly scattering targets. It has been already validated against experimental data for objects in free-space and synthetic data for buried scatterers.

Here, we present experimental results for buried objects starting from measurements collected at two test-sites. The first one has been a dedicated outdoor test facility which has allowed to test the experimental setup and the inversion algorithm in controlled conditions; the second one has been an archeological test-site.

Keywords: Microwave tomography; Ground penetrating radar; Stepped-frequency; Experimental data

1. Introduction

Ground penetrating radar (GPR) techniques [1] had a strong impulse to develop and improve in the last decade due to the large amount of possible applications covering, for example, archaeology [2–5], civil engineering [6] and geophysics [7].

Although GPR applications share a common theoretical background, they in general require, for different applications, different probing frequencies and thus different hardware equipments. In this paper, we will focus our attention on archaeological applications and we will present a tomographic inversion of data acquired by an experimental stepped-frequency GPR (SFGPR) build-up in the framework of the "ARCHEO" project [8], an Italian national research project funded by the (former) Italian Ministry for University and Scientific and Technological Research—MURST—(now Ministry for University and Research—MIUR). This 3-year program has aimed at developing advanced devices and techniques to be used

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1434-8411/$ - see front matter
doi:10.1016/j.aeue.2004.11.043

for characterization of archaeological zones and detection and recovery of findings.

The GPR system has been realized by the Italian Consortium on Advanced Remote Sensing Systems (CO.RI.S.T.A.) having in mind for the hardware two main innovative features for the archaeological prospecting [8]. The first one has regarded the development of a SFGPR system from scratch. Even though the SF technology is known since a long time [9], it is up to now still not widespread and, at our knowledge, the system realized in the framework of the ARCHEO project has been the first SFGPR in archaeological applications ever setup in Italy. A stepped frequency GPR provides several technological advantages as compared to the traditional impulsive GPR systems, spacing from the dynamic range, to the low power consumption, and to the higher signal-to-noise ratio (SNR) due to the narrower band required about each excitation frequency [10]. Furthermore, it is also possible to relax the band requirements on the adopted ADC converter, because it needs a much lower sampling ratio than that required by an impulsive system.

A second innovative significant feature concerned the acquisition modalities based on the simultaneous exploitation of the diversity in the transmission and the reception allowing to achieve a full multi-view/multi-static/multi-frequency measurement scheme, as it will be described in the following.

A third innovative feature of the ARCHEO project, which is of main concern for this paper, has regarded the processing modalities of the acquired data, where the GPR has been employed as a tool for imaging instead of simply detecting and locating buried scatterers [11–16]. To reach this goal, SFGPR data must be processed by inverse scattering techniques rather than to perform the classical detection of echoes by means of "synthetic" pulses. Reconstructions of test objects by these techniques has been already successfully performed on experimental equipments, but they are very few [13]. The tomographic processing of the measurements has been performed at the Second University of Naples by means of a linear inversion algorithm suited for subsurface purposes [16].

The structure of the paper is as follows. In Section 2, brief descriptions of the employed inversion algorithm and of the SFGPR system are provided. In Section 3, the results of the tomographic processing of the data, collected at two test-sites, are shown. Finally, in Section 4, we discuss the results and directions for possible improvements.

2. Reconstruction algorithm and experimental setup

In this section, we briefly recall the employed inversion algorithm and the SFGPR. We quote [11,12,16–18] for relevant papers about the former and [8] for a description of the technical characteristics of the latter.

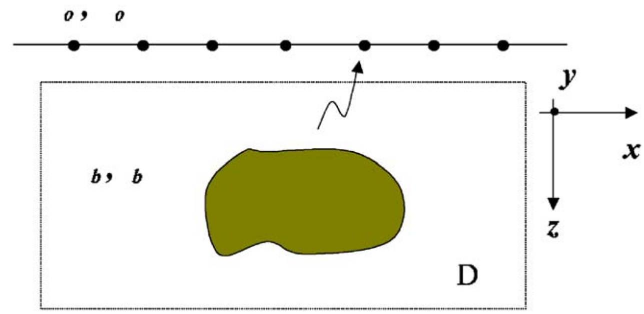

Fig. 1. The geometry dealt with by the inversion algorithm.

2.1. The reconstruction algorithm

The geometry dealt with by the exploited inversion algorithm [16] is depicted in Fig. 1. It consists of two half-spaces; the upper half-space is air with the dielectric permittivity equal to that of the vacuum, the lower half-space is soil assumed as a homogeneous medium with a known relative dielectric permittivity ε_{b} and conductivity σ_{b}. It is a 2-D geometry where objects are assumed infinitely long and invariant along the y-axis and located within a rectangular investigation domain D completely embedded within the soil. The incident field is supposed to be radiated by an infinitely long y-invariant filamentary current, so that a TM polarization results with the electric field directed along the y-axis. This further simplifies the problem by making it a scalar one. Finally, the available inversion algorithm deals with scattered field measurements collected inside a finite bandwidth in the frequency domain, so that it fits the SF acquisition strategy.

The objects of interest for this paper are assumed not penetrable; this holds without any approximation in the case of perfectly conducting objects and is a good approximation for objects whose dielectric properties are very different from those of the host medium. Accordingly, the only information about the objects that the algorithm expects to retrieve concerns their shape which thus becomes the unknown of the problem [16,18].

Our algorithm is based on an approximated model of the electromagnetic scattering, namely on the *physical optics or Kirchhoff approximation* [16,18], leading to a linear inverse problem [19]. The algorithm permits a partial reconstruction of the scatterers' shape due to the limitedness of the viewing angles of the subsurface measurement configuration considered in this paper and to the non-penetrability of the targets [16]. The mathematical tool used to perform the linear inversion is the singular value decomposition (SVD) of the unknown-data link. More in detail, the truncated SVD (TSVD) [19] of the matrix arising form the discretization of the integral relationship between the data and the unknown is employed. The unknown is represented according to a Fourier series involving N_x terms for the spatial variations along the x-axis and N_z rectangular pulses for the spatial variations along the z-axis.