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Early-stage leaking pipes GPR monitoring via microwave tomographic inversion

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ABSTRACT

Ground penetrating radar (GPR) is one of the most suitable technological solutions for timely detection of damage and leakage from pipelines, an issue of extreme importance both environmentally and from an economic perspective. However, for GPR to be effective, there is the need of designing appropriate imaging strategies such to provide reliable information. In this paper, we address the problem of imaging leaking pipes from single-fold, multi-receiver GPR data by means of a novel microwave tomographic method based on a 2D "distorted" scattering model which incorporates the available knowledge on the investigated scenario (i.e., pipe position and size). In order to properly design the features of the approach and test its capabilities in controlled but realistic conditions, we exploit an advanced, full-wave, 2.5D Finite-Difference Time-Domain forward modeling solver capable of accurately simulating real-world GPR scenarios in electromagnetically dispersive materials. By means of this latter approach, we show that the imaging procedure is reliable, allows us to detect the presence of a leakage already in its first stages of development, is robust against uncertainties and provides information which cannot be inferred from raw-data radargrams or "conventional" tomographic methods based on a half-space background.

1. Introduction

With the cost of servicing underground water, sewage and fuel services rising dramatically over the past decade, there is a growing demand for improved utility location, inspection, characterization and monitoring technologies. In this framework, non-invasive "geophysical" imaging techniques are therefore increasingly important investigation tools. In particular, the early detection of leaking pipes (predominantly water) is one of the key areas of commercial concern, as political pressure is applied to utility companies to improve their leak detection rates and service efficiency in the light of public concerns over climate change and energy usage (Desilva et al., 2005).

Amongst all the geophysical methods, surveys based on ground penetrating radar (GPR) appear to be the most promising as they may, in principle, lead to the "above-surface" characterization of pipeline status whilst being low-cost and operator efficient (Stampolidis et al., 2003; Nakhkash and Mahmood-Zadeh, 2004; Takahashi and Sato, 2006; Crocco et al., 2007). However, the large survey areas usually associated with utility work, and the cost/time demands of commercial data collection, means that it is commonplace to find surveys being conducted by non-expert users and interpreted in "real time". This is true for many geophysical techniques and for GPR in particular. In addition, the complex nature of the near-surface urban and industrial environment makes the interpretation of utility-based geophysical surveys extremely difficult, particularly when services are over 50 years old and unmapped.

In an ideal world, data collection with advanced processing and interpretational tools would provide users (both non-expert and expert) with an "on-demand" assessment of a particular target's properties shape, depth and extent. Nowadays, advances in portable computational facilities has brought this ideal one stage closer, as it has now become possible to run sophisticated and computationally demanding inversion and modeling algorithms in realistic times (Cassidy, 2007). Also, recent advancements in reliable microwave tomographic techniques for GPR applications (Leone and Soldovieri, 2003; Catapano et al., 2004, 2006) have opened the way to improved imaging tools, which can provide more detailed information on the surveyed area when compared to standard GPR processing techniques.

Within this framework, this paper deals with the problem of detecting the water leakage from a metallic pipeline, possibly in its early stage, and imaging its temporal evolution from a single-fold, multi-receiver GPR survey. To this aim, we exploit and thoroughly analyze a specifically designed 2D tomographic approach, whose original concept and preliminary tests were reported in Crocco et al. (2007). In order to successfully tackle the problem at hand, in this approach the mathematical model is formulated by taking into explicit account the available knowledge on the monitored scenario (i.e., the location, size and electric characteristics of the pipeline).

In the inverse scattering literature, this kind of approaches are known as "distorted" wave models and are exploited to reduce the complexity and the difficulty of the problem (Chew, 1995). In this respect, the use of "distorted" models in GPR imaging approaches

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opens new and interesting perspectives. As a matter of fact, "conventional" microwave tomographic techniques for GPR applications are based on a reference scenario made of two homogeneous half-spaces (Leone and Soldovieri, 2003; Catapano et al., 2004, 2006; Soldovieri et al., 2007a), that may be inadequate in several applications. Monitoring leaking pipes is indeed one of these, as the response of the pipeline is expected to hide that of the leakage, unless this latter is large, thus precluding timely detection. In addition, the particular model considered in this paper, in which a "cooperative" target is part of the reference scenario, is to our knowledge an original contribution itself.

To assess and analyze the proposed tomographic approach, we make use of an accurate, 2.5D Finite-Difference Time-Domain (FDTD) forward modeling scheme (Cassidy, 2007) to independently simulate realistic data collected over a leaking, metal water pipe. By doing so, we not only achieve reliable (yet controlled) data to investigate the features of the inversion methodology, but also show that the result in the raw-data radargrams are unsuitable for extracting information on the nature of "leak scenario", thus further supporting the claim for more advanced processing strategies. As a matter of fact, a simple comparison of the radargrams in the different conditions does not supply meaningful information, due to the coupling between the pipe and leak, that gives rise to interferences that depend in a complex fashion on kind of soil, the liquid that is filling the pipe, the frequency, the relative position, etc. Moreover, as the leak is usually located below the pipe, its presence, especially in the first stages of development, results in a very small perturbation of the radargram. The paper is organized as follows. In Section 2, we present the methodology of the FDTD-based modeling scheme and the simulation of three realistic 'leaking pipe' scenarios. In Section 3, we recall the "conventional" GPR tomographic approach and show its inadequacy for this specific problem. In Section 4, we describe the "distorted" tomographic approach and detail its mathematical model. Finally, the numerical analysis (Section 5) assesses the improved capability of the proposed approach compared to the "conventional" one and its robustness to uncertainties on the a-priori knowledge exploited in the definition of the "distorted" model. Conclusions follow.

2. Forward modeling methodology

For complex electromagnetic wave propagation problems, the FDTD technique has become one of the most popular numerical modeling and simulation tools, particularly with the increase in accessible and inexpensive computational resources. In comparison to integral methods, FDTD has specific advantages for near-surface GPR modeling (Cassidy, 2007), as it:

- uses the direct, time-domain implementation of Maxwell's electromagnetic field equations that are solved with explicit, closed form equations using matrix, parallel or incremental methods;
- provides a "total-field" solution of both the electric (E) and magnetic (H) field vectors in both time and space;
- incorporates a wide range of conductive, lossy and dispersive materials without the need to alter the mathematical description of the scheme;
- can incorporate arbitrary, sub-surface geometries, complex material features and sophisticated antennae design through the use of different sub-gridding schemes and geometric layouts.

The flexibility of the technique has lead to a number of different FDTD formulations (Taflove and Hagness, 2005) and it has been used to successfully model GPR wave propagation in a range of application areas (Nishimoto et al., 2006; Irving and Knight, 2006; Cassidy, 2007).

In the following "leaking pipe" examples, a 3D, staggered, orthogonal, fourth-order in space, centralized FDTD modeling scheme was used to simulate the GPR wave propagation and scattering/reflection responses from each of the leaking pipe scenarios.

The scheme is a total-field, explicit, robust formulation, based on the Yee cell geometry (Yee, 1966) that incorporates realistic antenna configurations, accurate source wavelets and truthful material property descriptions (Cassidy, 2001, 2007). Key to the scheme is the application of distinct "relaxation" or "memory variables" in the FDTD formulation that explicitly accounts for the realistic dispersion behavior of the lossy materials, regardless of their physical loss mechanism (e.g., ionic conductivity losses, etc.) (Cassidy, 2007). As such, the modeling scheme provides high-resolution models of GPR wave velocity and dispersion, without the need for fine spatial sampling and includes a wide range of materials, each having anisotropic and frequency-dependent permittivity, conductivity and, where necessary, a magnetic permeability. The "memory variables" determine the time, and therefore frequency, dependent effect of the materials on the propagating EM wave and the equations for the 1D, 2D and 3D cases of the FDTD scheme can be found in Bergmann et al. (1998) and Cassidy (2001), along with the appropriate stability conditions, error estimates and temporal/spatial sampling criteria, etc.

In the case at hand, since the targets have a leading dimension and the sub-surface is assumed to be invariant in the y-direction, the computational effectiveness of the scheme is improved by exploiting a 2.5D modeling rather than full 3D one (Bergmann et al., 1998; Taflove and Hagness, 2005). According to this approach, in which the 3D features of the source are properly modeled, the overall problem is solved as a suitable superposition of 2D problems, without the loss of relevant Electric (E) and Magnetic (H) field information.

The basic geometry of the "pipe" model, considered in this paper, is illustrated in schematic form in Fig. 1 where a 0.12 m diameter, circular, water-filled metal pipe is buried to a depth of 0.5 m (to its center) in a dry, low-medium loss, uniform sandy soil of relative permittivity, $\epsilon_r \sim 3.5$ and a static conductivity of 10 mS/m. The temporally and spatially varying water leakage is modeled in a realistic way as an early-stage, low-flow, low-pressure, gravity-fed leak that emanates from the base of the pipe and soaks the surrounding sands in an expanding saturation front that moves both laterally and vertically downwards across the modeled volume.

Three phases of the leak propagation have been modeled (phases 1, 2, and 3 in Fig. 1) that represent the temporal evolution of the leak, with the saturated soils having frequency-dependent dielectric properties and a relative permittivity of approximately $\epsilon_r \sim 22$ at 900 MHz. In each simulation, the transmitting antenna is modeled as 900 MHz unshielded, thin-wire dipole element whose long axis is parallel to the pipe (y-axis in the model). An accurate, yet practically realistic, source wavelet function is used to simulate the transmitted pulse that is a modified version of a standard Ricker pulse. It is smooth and continuous in both its first and second derivatives and is designed to match the form of the real GPR wavelets (Cassidy, 2007). The modeled domain is sub-divided into a 2.5D grid of orthogonal Yee field cells (Yee, 1966) with equal sides of 0.005 m. A total of 100 "field

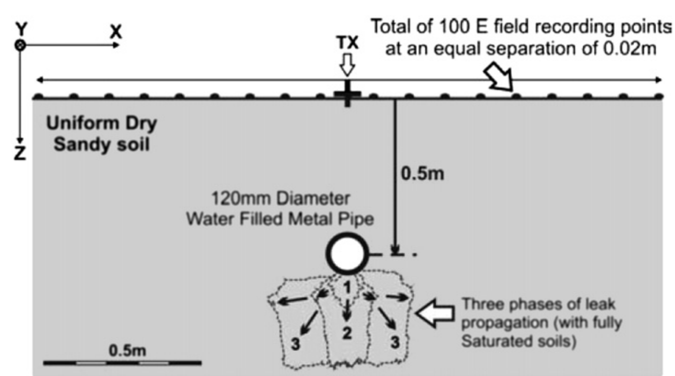

Fig. 1. Base "pipe" FDTD model geometry and form of the spatially expanding water leak.