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Application of time-reversal-based processing techniques to enhance detection of GPR targets

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A B S T R A C T

In this paper we analyze the performance of time-reversal (TR) techniques in conjunction with various Ground Penetrating Radar (GPR) pre-processing methods aimed at improving detection of subsurface targets. TR techniques were first developed for ultrasound applications and, by exploiting the invariance of the wave equation under time reversal, can yield features such as superresolution and statistical stability. The TR method was examined here using both synthetic and actual GPR field data under four different pre-processing strategies on the raw data, namely: mean background removal, eigenvalue background removal, a sliding-window space-frequency technique, and a noise-robust spatial differentiator along the scan direction. Depending on the acquisition mode, it was possible to determine with good precision the position and depth of the studied targets as well as, in some cases, to differentiate the targets from nearby clutter such as localized geological anomalies. The proposed methodology has the potential to be useful when applied to GPR data for the detection of buried targets.

1. Introduction

Ground penetrating radar (GPR) is widely used for mapping and identification of buried targets, such as concrete tubes, metallic and plastic drums, pipes, etc. However, conventional data processing methods for target detection do not always yield satisfactory results in field applications due to the presence of ground clutter, ground losses, and geological anomalies that often obscure the target response and create ambiguities. In a typical GPR deployment, a transmitter (or set of transmitters) located above ground sends a waveform into the subsurface and the resulting scattered signal by the target(s) and geological anomalies within the subsurface is collected by a receiver (or set of receivers) above ground. Since the wave equation governing propagation of the waveforms is invariant under time-reversal (TR) in stationary and lossless media and approximately so in low-loss media, this implies that the data collected by the receivers can be time-reversed and used to recreate wavefields that would "backpropagate" into the subsurface and automatically focus on reflective targets and/or anomalies.[1] In general, TR invariance can be exploited for detection and localization of obscured targets in noisy and rich-scattering environments, with high resolution. Time-reversal (TR) techniques were first developed for acoustics (Fink et al., 1989) (Fink, 1992), being later successfully used in several applications including non-destructive testing and evaluation (Liu et al., 2014), sound quality enhancement (Lin and Too, 2014), atmospherics studies (Mora et al., 2012), subsurface geophysics (Fink, 2006; Leuschen and Plumb, 2001; Saillard et al., 2004; Cresp et al., 2008; Artman et al., 2010; Foroozan and Asif, 2010; Yavuz et al., 2014; Chen et al., 2016; Santos and Texeira, 2017), microwave remote sensing (Reyes-Rodríguez et al., 2014), wireless communications (Fouda et al., 2012) and medicine (Thomas and Fink, 1996; Tanter et al., 1996). The basic TR algorithm can be modified in a number of ways; for example, it can be applied iteratively in sequence to automatically focus on the most reflective target immersed in a scattering medium (Prada et al., 1993). Variants on the basic TR algorithm exist which allow for selective focusing on well-resolved secondary (weaker) targets (Saillard et al., 2004; Yavuz and Teixeira, 2006) and tracking of obscured moving targets as well (Fouda and Teixeira, 2012).

In this paper, we compare the results of the TR algorithm when combined with four preprocessing techniques for GPR data, to determine the most effective combination thereof: Background removal (Daniels, 2007), eigenvalues background removal (Khan and Al-Nuaimy, 2009), a sliding-window space-frequency technique (Yavuz et al., 2014) and a noise-robust spatial differentiator along the scan direction (Holoborodko, 2008). The comparative analysis is performed using both simulation results based on the Finite-Difference Time-Domain (FDTD) algorithm and field data from actual measurements. Consideration of actual field data

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[1] Backpropagation can be effected either physically by transmitting the time-reversed signals into the original medium, or synthetically by means of a forward simulation engine, such as the finite-difference time-domain (FDTD) method. Synthetic backpropagation is done for imaging purposes, as considered here.

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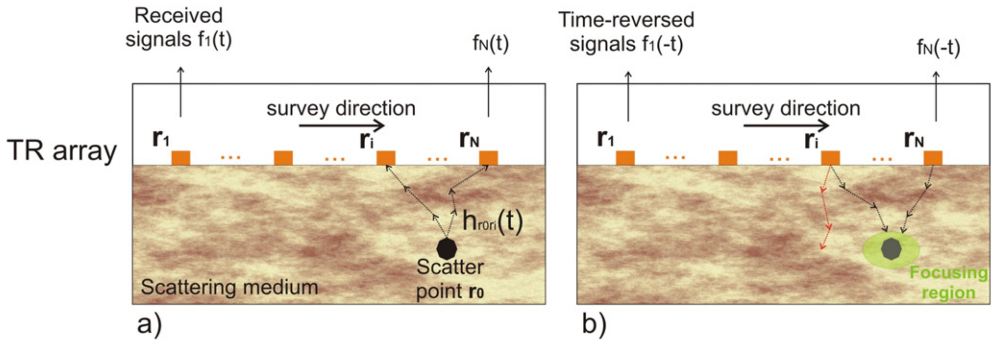

Fig. 1. Basic time-reversal procedure. a) Physical scattering from a buried target after the forward propagation of the GPR signal. b) Synthetic back-propagation of time-reversed signals.

allows for assessing the performance under typical signal-noise ratio found in practice. Consideration of simulation data allows for a better control and subsequent assessment of the variables affecting the algorithm performance. Both types of data can suggest ways to improve these methods in practice. The results obtained here can provide tools for improving GPR data interpretation and may assist in future applications of GPR in geotechnical and environmental studies.

2. TR technique: fundamentals

To make the discussion here more self-contained, we next briefly describe the basic principles of the TR technique. More details can be found in Fink (2006). Although it has been developed originally for acoustic waves, the TR technique can be equally applied to electromagnetic waves (Yavuz and Teixeira, 2009). This process is akin to Reverse Time

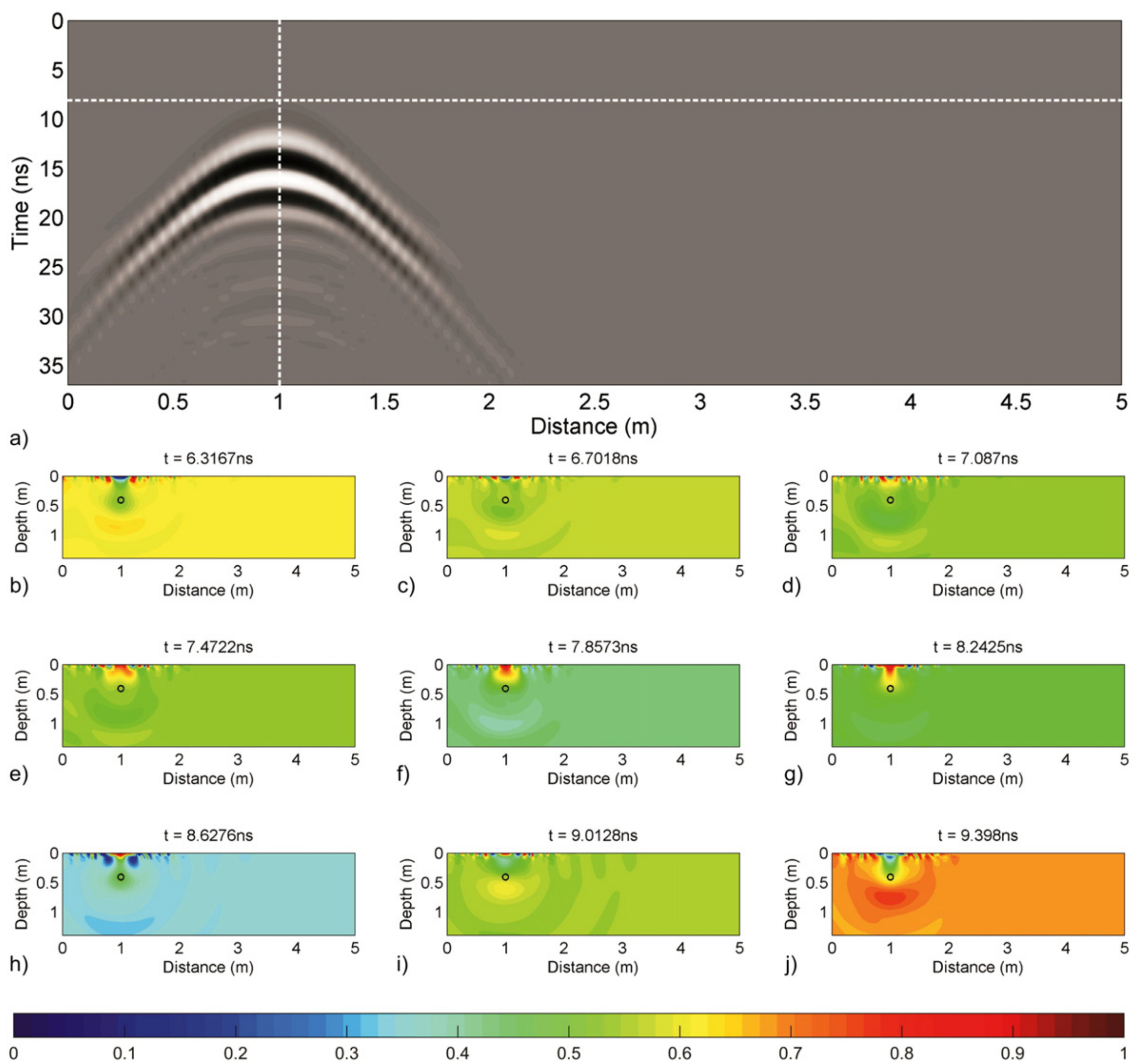

Fig. 2. a) Synthetic GPR data for buried plastic pipe. b) to j) Different time-steps from TR results applied to GPR data.