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Inversion of crosshole seismic data in heterogeneous environments: Comparison of waveform and ray-based approaches

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ABSTRACT

High-resolution tomographic imaging of the shallow subsurface is becoming increasingly important for a wide range of environmental, hydrological and engineering applications. Because of their superior resolution power, their sensitivity to pertinent petrophysical parameters, and their far reaching complementarities, both seismic and georadar crosshole imaging are of particular importance. To date, corresponding approaches have largely relied on asymptotic, ray-based approaches, which only account for a very small part of the observed wavefields, inherently suffer from a limited resolution, and in complex environments may prove to be inadequate. These problems can potentially be alleviated through waveform inversion. We have developed an acoustic waveform inversion approach for crosshole seismic data whose kernel is based on a finite-difference time-domain (FDTD) solution of the 2-D acoustic wave equations. This algorithm is tested on and applied to synthetic data from seismic velocity models of increasing complexity and realism and the results are compared to those obtained using state-of-the-art ray-based traveltime tomography. Regardless of the heterogeneity of the underlying models, the waveform inversion approach has the potential of reliably resolving both the geometry and the acoustic properties of features of the size of less than half a dominant wavelength. Our results do, however, also indicate that, within their inherent resolution limits, ray-based approaches provide an effective and efficient means to obtain satisfactory tomographic reconstructions of the seismic velocity structure in the presence of mild to moderate heterogeneity and in absence of strong scattering. Conversely, the excess effort of waveform inversion provides the greatest benefits for the most heterogeneous, and arguably most realistic, environments where multiple scattering effects tend to be prevalent and ray-based methods lose most of their effectiveness.

1. Introduction

The structure of the shallow subsurface is in general complex and high-resolution crosshole seismic and georadar methods have arguably the greatest potential of resolving it. Moreover, these methods are critically sensitive to some of the most interesting and pertinent petrophysical parameters for environmental and engineering applications. Velocities of both seismic and georadar waves are highly sensitive to porosity and water content (e.g., Schoen, 1996). During the last two decades, acquisition technologies as well as modelling and inversion algorithms for high-resolution seismic and georadar data have seen immense technological and methodological progress. Whereas the innovations in instrumentation and data acquisition have been readily embraced by the wider community of practitioners, this is not the case for the corresponding innovations in inversion methodologies.

To date, most tomographic inversions of shallow crosshole seismic and georadar data still rely on traditional ray-theoretical approaches. These approaches are based on asymptotic high-frequency approximations and therefore only exploit a small fraction of the total recorded wavefields, such as the first arrival traveltimes, and thus result in an inherently sub-optimal resolution of the probed region (e.g., Wielandt, 1987). This is clearly problematic as the shallow subsurface is generally characterized by particularly strong heterogeneity and many, if not most, engineering, environmental and hydrological problems require detailed knowledge of the local geological and geophysical structure. This problem can potentially be alleviated through waveform-based tomographic inversion approaches, which, at least in principle, are capable of exploiting the full information contained in the entire recorded wavefield (e.g., Tarantola, 1984, 1986, 2005). As a rule of thumb, we can assume that the spatial resolution of ray-based inversion methods scales with the diameter of the first Fresnel zone, or $\sqrt{\lambda L}$ with λ and L denoting the dominant wavelength and path length, respectively (e.g., Williamson, 1991; Williamson and Worthington, 1993), whereas the resolution of waveform approaches is of the order of half a dominant wavelength or even better (e.g., Wu and Toksoz, 1987; Dickens, 1994).

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For a typical 10-m-by-20-m 100–200 MHz near-surface crosshole georadar survey or an equivalent 1–3 kHz seismic survey (e.g., Hubbard et al., 2001; Paasche et al., 2006) the potential improvement in resolution when using waveform-based inversion approaches is thus in the range of one order-of-magnitude, and the spatial resolution of waveform-based inversions is close to that of common downhole logging methods (e.g., Song et al., 1995; Pratt and Shipp, 1999; Dessa and Pascal, 2003; Ernst et al., 2007a,b).

Although Tarantola's (1984) seminal work laid the foundations of seismic waveform inversion more than two decades ago and a number of corresponding algorithms have been developed and published, waveform-based inversions of seismic and georadar data are still rather uncommon (e.g., Gauthier et al., 1986; Pratt and Worthington, 1990; Pratt, 1990a,b, 1999; Pratt and Shipp, 1999; Zhou and Greenhalgh, 2003; Ernst et al., 2007a,b; Wapenaar, 2007; Poot et al., 2008). Moreover, their potential advantages and limitations with regard to conventional ray-based tomographic inversions for imaging strongly heterogeneous surficial velocity structures have not yet been fully assessed. In this study, we seek to address this objective. To this end we have developed a waveform inversion algorithm for seismic crosshole data based on a finite-difference time-domain (FDTD) solution of the acoustic wave equations. After a brief description of the underlying methodology, this algorithm is tested on and applied to a suite of synthetic datasets for seismic velocity models of increasing complexity and realism and the resulting tomographic images are compared with those obtained using a state-of-art ray-based tomographic inversion algorithm.

2. Methodological background

The seismic inversion algorithm considered in this study is derived from a recently developed waveform inversion algorithm for crosshole georadar data (Ernst et al., 2007a,b) using the electromagnetic-acoustic analogies (e.g., Carcione and Cavallini, 1995; Yuan et al., 1997; Wapenaar, 2007). A substantial benefit of this approach is that all essential results and observations of this study can also be expected to hold true for corresponding georadar studies. In a typical borehole georadar experiment, emitters and receivers correspond to dipole-type antennas that are aligned with the borehole axis, which in turn often corresponds approximately with the z-axis of the local coordinate system (e.g., Sato and Thierbach, 1991). Therefore, borehole georadar surveys are concerned primarily with the component of the transmitted electric field that is parallel to the transmitting and receiving antennas, such that in 2D the so-called transverse electric (TE) form of Maxwell's equation is most appropriate for the purpose of modeling and inversion (e.g., Holliger and Bergmann, 2002; Ernst et al., 2006;2007a,b):

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(-\frac{\partial H_y}{\partial z} - \sigma E_x\right), \tag{1a}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \sigma E_z\right) \tag{1b}$$

and

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} - \sigma^* H_y\right), \tag{1c}$$

where ε is the dielectric permittivity, μ the magnetic permeability, σ the electric conductivity, σ^* the magnetic loss and t the time. E and H denote the electric and magnetic field components, respectively, and x, y, and z refer to the three spatial directions of a three dimensional Cartesian coordinate system. In the georadar regime of electromagnetic wave propagation the quality factor, which corresponds to the number of wavelengths a monochromatic wave of frequency f can travel until its amplitude has been attenuated to $e^{-\pi}$ of its original value, is characterized by (e.g., Nabighian, 1988) $Q = 2\pi f\varepsilon/\sigma >> 1$. For small attenuation (i.e. $Q >> 1$) the phase velocity can be approximated by:

$$c_e \approx \frac{1}{\sqrt{\varepsilon\mu}}. \tag{2}$$

Similarly, acoustic wave propagation in 2-D Cartesian coordinates can be described by

$$\frac{\partial u_x}{\partial t} = \frac{1}{\rho}\left(-\frac{\partial p}{\partial x} - \alpha^* u_x\right), \tag{3a}$$

$$\frac{\partial u_z}{\partial t} = \frac{1}{\rho}\left(-\frac{\partial p}{\partial z} - \alpha^* u_z\right) \tag{3b}$$

and

$$\frac{\partial p}{\partial t} = \frac{1}{\kappa}\left(-\frac{\partial u_x}{\partial x} - \frac{\partial u_z}{\partial z} - \alpha p\right), \tag{3c}$$

where p is the pressure, u_x and u_z are the horizontal and vertical particle velocities, ρ is the density, κ is the compressibility, which corresponds to the inverse of the bulk modulus K, and α and α^* are damping coefficients related to the compressibility and density, respectively (e.g., Yuan et al., 1997). For moderate to small attenuation, as quantified by $Q >> 1$, the phase velocity of acoustic waves is given by:

$$c_a \approx \frac{1}{\sqrt{\rho\kappa}}. \tag{4}$$

Comparison of Eqs. (3a)–(3c) and (1a)–(1c) thus yields the following equivalence between acoustic and high-frequency electromagnetic wave propagation in the TE-mode:

$$\begin{Bmatrix} p \\ u_z \\ u_x \\ \kappa \\ \rho \\ \alpha \\ \alpha^* \end{Bmatrix} \leftrightarrow \begin{Bmatrix} -H_y \\ -E_x \\ E_z \\ \mu \\ \varepsilon \\ \sigma^* \\ \sigma \end{Bmatrix}. \tag{5}$$

In the following, we therefore employ the above equivalences to convert Ernst et al.'s (2007a) numerical forward solver of the Maxwell's equations into a corresponding acoustic algorithm. In doing so, we assume loss-free acoustic wave propagation (i.e., $\sigma = \sigma^* = \alpha = \alpha^* = 0$). The primary reasons for this are that estimating the attenuation of seismic waves is inherently difficult and error prone and that the waveform inversion of S-waves must be regarded as largely unresolved for practical intents and purposes (e.g., Holliger and Bühnemann, 1996; Bourbié et al., 1987; Pratt, 1999; Zhou and Greenhalgh, 2003; Watanabe et al., 2004).

The numerical solution of Eqs. (1a)–(1c) and (3a)–(3c), respectively, is based on a staggered-grid leapfrog finite-difference time-domain (FDTD) approach that is second-order accurate in both time and space (Yee, 1966; Taflove and Hagness, 2000). To minimize artificial reflections from the edges of the computational domain, the models are surrounded by efficient generalized perfectly matched layer (GPML) absorbing boundary conditions (e.g., Fang and Wu, 1996; Lampe et al., 2003). The target parameter of our waveform inversion scheme for acoustic waves is the compressibility κ, while the density ρ is kept constant (e.g., Gauthier et al., 1986). The primary reason for this is that κ has a greater sensitivity to changes in porosity than ρ and that inverting for both parameters also roughly doubles the computational effort. We furthermore assume the time-history of source signal to be known.