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Target-Oriented Inversion of Time-Lapse Seismic Waveform Data

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Abstract. Full waveform inversion of time-lapse seismic data can be used as a means of estimating the reservoir changes due to the production. Since the repeated computations for the monitor surveys lead to a large computational cost, time-lapse full waveform inversion is still considered to be a challenging task. To address this problem, we present an efficient target-oriented inversion scheme for time-lapse seismic data using an integral equation formulation with Gaussian beam based Green's function approach. The proposed time-lapse approach allows one to perform a local inversion within a small region of interest (e.g. a reservoir under production) for the monitor survey. We have verified that the T-matrix approach is indeed naturally target-oriented, which was mentioned by Jakobsen and Ursin [24] and allows one to reduce the computational cost of time-lapse inversion by focusing the inversion on the target-area only. This method is based on a new version of the distorted Born iterative T-matrix inverse scattering method. The Gaussian beam and T-matrix are used in this approach to perform the wavefield computation for the time-lapse inversion in the baseline model from the survey surface to the target region. We have provided target-oriented inversion results of the synthetic time-lapse waveform data, which shows that the proposed scheme reduces the computational cost significantly.

AMS subject classifications: 81U40, 74J25, 74J20, 45Dxx

Key words: Waveform inversion, time-lapse seismic, seismic inverse scattering, target-oriented inversion, Gaussian beam based Green's function.

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1 Introduction

Full waveform inversion (FWI) is a powerful tool for reconstructing the subsurface structure and estimating the physical parameters, e.g. P- and S- wave velocities in the subsurface [1]. Advances in full waveform inversion make it possible to do the time-lapse seismic full waveform inversion. Time-lapse seismic is a widely used tool for the dynamic reservoir monitoring and assessing the reservoir changes due to production [2–4]. Recent studies have shown the applicability of the full waveform inversion for the time-lapse seismic problem [5–10].

Essentially, the seismic full waveform inversion can be viewed as a seismic inverse scattering problem since the scattering theory provides the relations between the model parameter perturbation and the seismic waveform [1, 11–14]. Seismic scattering method is an important technique for seismic data processing, in which the scattered wavefield results from a medium perturbation. The perturbation property of the seismic scattering theory renders it useful not only for seismic forward modeling but also for seismic inversion [15–17]. Since the 1980s, the direct inversion approach based on the linearized wave equation using the seismic scattering method has been widely used [18–23].

Jakobsen and Ursin [24] developed the distorted Born iterative T-matrix method (DBIT) for full waveform inversion based on integral equation methods. The underlying idea of this method is to reduce a nonlinear inverse scattering problem to a sequence of linear inverse scattering problems. For this method, there are several important features: (1) the sensitivity matrix is expressed explicitly in terms of the Green's functions, which is helpful to reduce the computational cost [24, 25]; (2) this method can be applied to the cases with multiple sources; (3) the computational cost and convergence problems can be addressed by the T-matrix approach by domain decomposition and renormalization methods [24, 27–29, 61]. These features make the distorted Born iterative T-matrix method more applicable to seismic full waveform inversion. Additional works on this method can be found in Jakobsen and Wu [29, 31] and Wang et al. [32]. Recently, the integral equation formulations were applied to the time-lapse seismic data and to estimate the uncertainty [33]. However, a major limitation of the time-lapse full waveform inversion is that the computational cost is expensive.

The main purpose of this paper is to develop a fast waveform inversion scheme for the time-lapse inversion. We develop a target-oriented inversion method, which is based on the idea of local inversion. Thus, if we develop a fast repeat-inversion scheme, which is only for a small region, the computational cost can be significantly reduced. It makes sense because the effects of the production on the reservoir changes are considered as small perturbations of the earth model [34]. Several studies on the localized full waveform inversion have been proposed to approach this topic. Borisov et al. [35] used the finite-difference injection method to develop an efficient 3-D time-lapse full waveform inversion. Willemsen et al. [36] derive a local solver for full waveform inversion of a small region of interest. Malcolm and Willemsen [37] have developed local solvers for