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Journal of Computational Physics 208 (2005) 455–468

JOURNAL OF COMPUTATIONAL PHYSICS

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Efficient calculation of the steepest descent direction for source-independent seismic waveform inversion: An amplitude approach ☆

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Received 5 May 2004; received in revised form 2 September 2004; accepted 29 September 2004
Available online 11 May 2005

Abstract

In seismic waveform inversion, if we have no information on source signature, we need to invert seismic data and source signature either simultaneously or successively. In order to avoid the iterative update of the source signature in waveform inversion based on classical, local optimization techniques, we propose two source-independent objective functions using amplitude spectra of Fourier-transformed wavefields. One is constructed by normalizing the amplitude spectra of observed data and modeled data with respect to the respective reference amplitudes. The other is achieved by cross-multiplying the amplitude spectra of observed data and modeled data with the respective reference amplitudes. In the computation of the steepest descent direction, we circumvent explicitly computing the Jacobian by employing a matrix formalism of the wave equation in the frequency domain. Through numerical examples for the Marmousi model, we demonstrate that our inversion algorithms can reproduce the subsurface velocity structure without estimating source signature.

Keywords: Waveform inversion; Source-independent objective function; Steepest descent direction; Local optimization; Jacobian

☆ This work was financially supported by the National Laboratory Project of the Ministry of Science and Technology, and the Brain Korea 21 Project of the Ministry of Education.

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0021-9991/$ - see front matter
doi:10.1016/j.jcp.2004.09.019

1. Introduction

Seismic inversion has been used to delineate the subsurface velocity structure from seismic data. Seismic inversion has been mainly performed by traveltime tomography or waveform inversion. Traveltime tomography of treating refraction or reflection events is performed on the basis of the kinematic property of seismic data [1–3], whereas waveform inversion employs the dynamic property of data [4,5]. Since traveltime tomography is a high-frequency approximation, it cannot always describe the model whose velocity variations are similar to or less than source wavelength [5]. On the other hand, waveform inversion, which is based on wave propagation, gives more refined velocity structures than traveltime tomography, although waveform inversion requires more massive computation than traveltime tomography.

In the beginning, seismic inversion was mainly performed by directly calculating the Jacobian. Since Lailly [6] and Tarantola [7] suggested using the backpropagation algorithm of reverse time migration (e.g., the adjoint state of the wave equation) in seismic inversion, the backpropagation algorithm was extensively used to elegantly compute the steepest descent direction in waveform inversion [4,8–20].

Since full waveform inversion is performed by applying wave equation, we need to know exact source signature to obtain a subsurface velocity structure that is compatible with true velocities. In the case of the exact source wavelet not being known, we iteratively estimate source wavelet in addition to velocity structure in waveform inversion algorithm. Zhou et al. [22] and Pratt [19] suggested methods of estimating source wavelet in waveform inversion algorithm, and found that the iteratively estimated source wavelet is very sensitive to estimated velocity structure. As a solution to this problem, Zhou et al. [22] suggested that successive inversions for source signature and velocity structure should be repeatedly executed until reasonable solutions for both source signature and velocity structure can be obtained. In order to avoid the additional work of inverting source wavelet, Lee and Kim [21] and Zhou and Greenhalgh [5] proposed source-independent waveform inversion algorithms, which are based on the conventional inversion technique directly computing the Jacobian. For the source-independent waveform inversion algorithm, Lee and Kim [21] used the normalized wavefields with respect to a reference wavefield in the frequency domain. The objective function constructed by Zhou and Greenhalgh [5] is similar to that by Lee and Kim [21], except that Zhou and Greenhalgh [5] only used the amplitude spectrum among spectral data obtained by the Fourier transform. Although Zhou and Greenhalgh [5] only used amplitude spectra, they obtained realistic results in the inversion of crosshole data.

In this study, we propose two different source-independent amplitude inversion algorithms. One is constructed by normalizing the amplitudes of modeled data and field data with respect to amplitudes of the respective reference wavefields like the method suggested by Zhou and Greenhalgh [5]. The other is obtained by cross-multiplying the amplitudes of modeled wavefields and field data by the respective reference amplitudes. In the former, the source wavelet is removed by deconvolution; in the latter, the source wavelet is eliminated by convolution. The main characteristic of our waveform inversion techniques is related to the computation of the steepest descent direction. In the following sections, we construct the two source-independent objective functions, and show how to compute the steepest descent direction in the source-independent waveform inversion algorithms. In order to demonstrate our waveform inversion algorithms, we present numerical examples for the Marmousi synthetic data.

2. Theory

2.1. The first source-independent objective function using deconvolution

In the frequency domain, since time series are expressed by the amplitude and phase spectra, we can write the observed data as