Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2018-0199

Vol. **28**, No. 1, pp. 328-341
July 2020

Source-Independent Amplitude-Semblance Full-Waveform Inversion using a Hybrid Time- and Frequency-Domain Approach

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Received 8 August 2018; Accepted (in revised version) 14 January 2019

Abstract. Full-waveform inversion is a promising tool to produce accurate and high-resolution subsurface models. Conventional full-waveform inversion requires an accurate estimation of the source wavelet, and its computational cost is high. We develop a novel source-independent full-waveform inversion method using a hybrid time- and frequency-domain scheme to avoid the requirement of source wavelet estimation and to reduce the computational cost. We employ an amplitude-semblance objective function to not only effectively remove the source wavelet effect on full-waveform inversion, but also to eliminate the impact of the inconsistency of source wavelets among different shot gathers on full-waveform inversion. To reduce the high computational cost of full-waveform inversion in the time domain, we implement our new algorithm using a hybrid time- and frequency-domain approach. The forward and backward wave propagation operations are conducted in the time domain, while the frequency-domain wavefields are obtained during modeling using the discrete-time Fourier transform. The inversion process is conducted in the frequency domain for selected frequencies. We verify our method using synthetic seismic data for the Marmousi model. The results demonstrate that our novel source-independent full-waveform inversion produces accurate velocity models even if the source signature is incorrect. In addition, our method can significantly reduce the computational time using the hybrid time- and frequency-domain approach compared to the conventional full-waveform inversion in the time domain.

AMS subject classifications: 86A15, 86A22

Key words: Amplitude semblance, full-waveform inversion, hybrid time and frequency domain, source independent, source wavelet.

1 Introduction

Full-waveform inversion (FWI) is a highly nonlinear inversion process that inverts seismic data for an optimal subsurface model by minimizing the data misfit between ob-

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served and synthetic data [12, 22, 23]. Studies show that a well estimated source wavelet is one of the most important prerequisites for successful full-waveform inversion. This condition, however, is usually difficult to be satisfied in field data applications because of problems such as noises, imperfect receiver coupling, or unpreserved amplitudes during data processing, etc. Furthermore, when a subsurface model is inaccurate during inversion, it could be difficult to distinguish the contribution of the inaccurate model to the inversion objective function from that of the inaccurate source wavelet. An incorrect source wavelet, even with small-amplitude deviations from the true source wavelet, may yield obvious artifacts in inversion results, and FWI with an incorrect source wavelet can easily converge to a local minimum [17].

The estimation of source wavelet is therefore generally considered as an essential step in FWI but very challenging because of attenuation and noise, among others. In field data applications, the source wavelet can be obtained by extracting the source signature from direct-arrival waves, assuming either zero or minimum phase. However, the fidelity of the estimated wavelet depends greatly on assumptions used. In shallow marine explorations, the extraction of the source wavelet is very challenging when direct-arrival waves interfere with seismic reflections from the shallow water bottom. Another approach is to estimate the source signature by simultaneously inverting for model parameters and the source wavelet [22]. By taking the derivative of the misfit function with respect to the source wavelet, Zhou et al. [28] presented a source inversion in the time domain, while Pratt [11] developed a source inversion algorithm in the frequency domain. Although there have been some successful applications of this strategy [6, 7, 13, 14], an FWI that simultaneously inverts for these two quantities could easily fail to achieve reliable convergence when low-frequency components of data are not available, or the starting model is significantly different from the true model [25]. This is because the source wavelet and the subsurface velocity model are updated simultaneously, and the inaccuracy in both quantities can affect each other during inversion [3].

To alleviate the source wavelet effect on FWI, some source-independent FWI algorithms were developed [2,4,5,8,25–27]. In these methods, they used data convolved with or deconvolved by an optimized reference trace to construct a misfit function, and the influence of an inaccurate source wavelet on FWI can be partially suppressed. A fundamental issue resting in these methods is how to choose a good reference trace. In practice, the preferred reference position would be as close to the shot position as possible, because the anisotropic effects and non-linearity of wavefields increase and the signal-to-noise ratio is also lower in the far-offset data [2, 3]. For deconvolution-type misfit functions, a bad reference trace can devastate the deconvolution process and lead to singular values in the normalization process.

We develop a novel source-independent full-waveform inversion method without using an optimized reference trace. We employ an amplitude-semblance objective function to completely remove the necessity of source wavelet estimation in FWI. The most striking feature of our amplitude-semblance FWI (ASFWI) is that there is no need to manually choose a reference trace. The other obvious advantage of our ASFWI is that