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FWT2D: A massively parallel program for frequency-domain full-waveform tomography of wide-aperture seismic data—Part 2 Numerical examples and scalability analysis ☆

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ABSTRACT

This is the second paper in a two-part series that describes a massively parallel code that performs 2D full-waveform inversion of wide-aperture seismic data for imaging complex structures. We present several numerical validation of the full-waveform inversion code with both canonical and realistic synthetic examples. We illustrate how different multiscale strategies can be applied by either successive mono-frequency inversions or simultaneous multifrequency inversions and their impact on the convergence and the robustness of the inversion. We present a scalability analysis using a real marine data set recorded by a dense array of ocean bottom seismometers to image the crustal structure of a subduction zone. We obtained a speedup of 20 when using 50 processes on a PC cluster which allowed us to iteratively invert 13 frequencies of the full data set in less than 2 days. This computational performance will allow in the future more extensive analysis of full-waveform tomography methods when applied to representative case studies or when considering 3D geometries.

1. Introduction

Frequency-domain full-waveform tomography (FWT) has prompted renewed interest during last decade since the pioneering work of Pratt and collaborators in the nineties. The frequency-domain formulation of FWT has been shown to be an efficient imaging tool to build velocity models from seismic data e.g. (Pratt et al., 1996; Ravaut et al., 2004; Brenders and Pratt, 2007b). Frequency-domain FWT was originally developed for cross-hole acquisition geometries which involve a broad range of propagation angles. Such acquisition geometries lead to a redundant coverage of the wavenumbers in the model space thanks to the redundant control of temporal frequencies and aperture angles on the resolution of the imaging. This redundancy can be mitigated by limiting the inversion to few discrete frequencies (Sirgue and Pratt, 2004). These few frequency components can be inverted successively rather than simultaneously to design a multiscale approach which helps to mitigate the non-linearity of the inverse problem (Pratt, 1999). Modelling of one frequency component reduces to the resolution of a large sparse system of linear equations which is classically

☆ Code available at http://seiscope.unice.fr/opendownload.php.

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performed with a direct solver for 2D applications to compute efficiently solutions for multiple right-hand sides (i.e., sources) (Marfurt, 1984; Jo et al., 1996).

Since the first applications to cross-hole data, frequency-domain FWT has been assessed for different surface acquisition design and exploration scales. Hicks and Pratt (2001) applied FWT to multichannel seismic reflection data to estimate P-wave velocities and attenuation over a gas sand deposit. Ravaut et al. (2004) and Operto et al. (2004) presented an application to onshore wide-angle data to image a thrust belt in the southern Apennines. Operto et al. (2006) presented the first application to a real dense ocean bottom seismometer (OBS) data set to image the deep crustal structure of the eastern-Nankai subduction zone. Brenders and Pratt (2007a, b) inverted synthetic onshore elastic data using the acoustic approximation for lithospheric imaging in the frame of a blind test and assessed the sensitivity of the inversion to the starting frequency and the acquisition geometry. Bleibinhaus et al. (2007) applied frequency-domain FWT to image the San Andreas Fault from seismic refraction data down to a maximum depth of 5 km. Jaiswal et al. (2008) applied FWT to onshore seismic reflection data to image a shallow target of the Naga thrust and fold belt (India) where prestack depth migration failed to provide a clear image of the structure. At a smaller scale, frequency-domain FWT was also applied to VSP-surface data set to image a groundwater contamination site (Gao et al., 2006). While frequency-domain FWT was originally developed as a tool to build high-resolution velocity models from acquisition geometries involving wide-angle propagations such as cross-hole or refraction experiments, frequency-domain FWT was also appraised as quantitative prestack-depth migration of multichannel seismic reflection data. In this context, all frequencies are generally simultaneously inverted (Plessix and Mulder, 2004; Shin et al., 2001).

This is the second paper in a two-part series that documents the practice of the massively parallel code FWT2D that performs 2D full-waveform inversion of wide-aperture seismic data. In the previous paper (this issue) (hereinafter referred to as paper 1), we presented a detailed description of the parallel algorithm. We explained how the main tasks performed by the FWT algorithm (i.e., calculation of the gradient of the objective function and its scaling provided by the diagonal terms of the approximate Hessian) can be easily parallelized thanks to a parallel direct solver which returns the multiple solutions of the forward problem distributed over the processors following a domain decomposition driven by the LU factorization. In this paper, we illustrate the main functionalities of the FWT2D software and assess its scalability.

All the results presented in this paper are limited to the 2D acoustic case. Preliminary applications of the 3D extension of the FWT algorithm are presented in Operto et al. (2007) and Ben Hadj Ali et al. (2008). The memory and time complexity of direct solvers as well as their limited scalability will probably prevent the use of direct solver to solve very large 2D elastic or 3D high-frequency acoustic problems. Especially, the memory and time complexities of direct solver dramatically increase from the 2D case to the 3D one, i.e., from $\mathcal{O}(n^2 \operatorname{Log}_2 n)$ and $\mathcal{O}(n^3)$ in 2D to $\mathcal{O}(n^4)$ and $\mathcal{O}(n^6)$ in 3D for the memory and time complexities, respectively (George and Liu, 1981; Ashcraft and Liu, 1998). Here, n denotes the dimension of a 2D square and 3D cubic grid, respectively. This prompted several authors to perform wave modelling in the frequency domain using iterative solvers (Riyanti et al., 2007; Plessix, 2007; Warner et al., 2007; Stekl et al., 2007) or in the time domain from which the frequency response is extracted for frequency-domain FWT (Nihei and Li, 2007; Sirgue et al., 2008). The main advantage of the iterative or the time-domain approach is their lower memory requirement which allows to perform simulation in large 3D models and their good scalability for both 2D and 3D problems. The main drawback may be the time requirement to perform multiple-shot simulations in the frame of waveform tomography since the time complexity of these approaches linearly increases with the number of sources. The time and memory complexity of 3D acoustic full-waveform modelling and inversion based on the MUMPS direct solver are quantified in Operto et al. (2007), Ben Hadj Ali et al. (2008) who showed that representative problems can be addressed at low frequencies. At the resolution scale provided by frequencies smaller than 7 Hz the velocity models developed by 3D FWT can be conceived as macromodel for prestack depth migration.

In this paper, we first illustrate how different frequency-domain inversion strategies can be easily tested with the FWT2D software. These strategies consist of successive mono-frequency inversions following the classical multiscale frequency-domain approach, of simultaneous multi-frequency inversion and of successive inversions of overlapping frequency groups of increasing frequency content. We illustrate with two different case studies the footprint of these strategies on the robustness and convergence behaviour of the inversion. We illustrate with a canonical test how the inversion converges differently depending whether the frequencies are inverted successively or simultaneously. We also illustrate how the source spectrum acts as a weighting operator in the data space during simultaneous multi-frequency inversion. The inversion is also applied to the imaging of a dip section of the overthrust model. We tested two multiscale frequency-domain strategies and illustrated how one of the approach remove some inaccuracies in the inversion at the expense of the computational time.

In the second part of the paper, we present a scalability analysis of the FWT2D software. We first assessed the scalability of the forward problem to verify that the memory and CPU-time complexities of the MUMPS direct solver are consistent with theoretical complexities of LU factorization applied to sparse matrices. Second, we performed a scalability analysis of the FWT2D software based upon an application to a real dense OBS data set collected in the eastern-Nankai subduction zone. We show that frequency-domain acoustic full-waveform inversion of a dense OBS data set for imaging a 2D crustal velocity model of dimension $105 \times 25\,\text{km}^2$ can be performed in less than 2 days using 36 processors of a PC