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FWT2D: A massively parallel program for frequency-domain full-waveform tomography of wide-aperture seismic data—Part 1 Algorithm ☆

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This is the first paper in a two-part series that describes a massively parallel code that performs 2D frequency-domain full-waveform inversion of wide-aperture seismic data for imaging complex structures. Full-waveform inversion methods, namely quantitative seismic imaging methods based on the resolution of the full wave equation, are computationally expensive. Therefore, designing efficient algorithms which take advantage of parallel computing facilities is critical for the appraisal of these approaches when applied to representative case studies and for further improvements. Full-waveform modelling requires the resolution of a large sparse system of linear equations which is performed with the massively parallel direct solver MUMPS for efficient multiple-shot simulations. Efficiency of the multiple-shot solution phase (forward/backward substitutions) is improved by using the BLAS3 library. The inverse problem relies on a classic local optimization approach implemented with a gradient method. The direct solver returns the multiple-shot wavefield solutions distributed over the processors according to a domain decomposition driven by the distribution of the LU factors. The domain decomposition of the wavefield solutions is used to compute in parallel the gradient of the objective function and the diagonal Hessian, this latter providing a suitable scaling of the gradient. The algorithm allows one to test different strategies for multiscale frequency inversion ranging from successive mono-frequency inversion to simultaneous multifrequency inversion. These different inversion strategies will be illustrated in the following companion paper. The parallel efficiency and the scalability of the code will also be quantified.

1. Introduction

Seismic imaging has widespread applications including civil engineering, seismic hazards, hydrocarbon exploration and crustal-scale imaging for more fundamental applications. Among seismic imaging methods, full-waveform inversion (e.g., Tarantola, 1984) is that with the greatest potential in terms of resolution power and

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

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quantification of the material properties since the whole information contained in the recorded wavefields is theoretically exploited thanks to the complete resolution of the full wave equation embedded in the optimization process. However, the number of convincing applications of full-waveform inversion to real data case studies has remained extremely limited due to the computational cost of these methods and their sensitivity to several source of errors and limitations such as the inaccuracy of the starting model in the frame of local optimization approaches, incomplete modelling of the wave propagation physics, noise, lack of low frequencies source and limited-aperture acquisition systems. In order to improve full-waveform inversion schemes and to appraise their relevance on representative case studies, it is critical to design optimized algorithms which take advantage of parallel computing facilities. This is the main aim of this paper which presents a massively parallel algorithm which performs 2D frequency-domain full-waveform inversion of wide-aperture seismic data.

The frequency-domain formulation of full-waveform inversion or tomography (FWT) has prompted renewed interest during last decade to build accurate velocity models of complex structures from dense global offset (or wide-aperture) acquisition geometries (Pratt et al., 1996; Ravaut et al., 2004; Brenders and Pratt, 2007). Global offset acquisition means geometries providing sufficiently long source–receiver offset so that both refracted and reflected waves can be recorded. These acquisitions are generally carried out with dense network of multicomponent stations both on land or at sea. One of the main interests of FWT is the extensive use of the full aperture range spanned by global offset geometries for the reconstruction of broad and continuous range of wavelengths in the medium including large to medium wavelengths. In these high-resolution velocity models, theoretical resolution limit is half the minimum propagated wavelength. Resolution analysis of FWT reveals that both temporal frequency and aperture angle control the spatial resolution of the imaging (Wu and Töksoz, 1987; Sirgue and Pratt, 2004). Therefore, the more the acquisition geometry illuminates a broad range of aperture angles, the more the seismic imaging can resolve a broad and continuous spectrum of wavenumbers. When applied to wide-aperture data, the frequency-domain approach of FWT has been shown to be efficient for three main reasons: first, only few discrete frequencies are necessary to develop a reliable image of the medium by decimating the wave number redundancy provided by multiaperture geometries (Sirgue and Pratt, 2004; Pratt and Worthington, 1990; Pratt, 1999). Second, proceeding sequentially from the low to the high frequencies defines a multiscale imaging framework which helps to mitigate the non-linearity of the inverse problem. Indeed, the low frequencies are less sensitive to cycle-skipping artefacts than the higher ones for a given starting model. A third criteria is related to the forward modelling problem. Frequency-domain modelling reduces to the resolution of a large sparse system of linear equations per frequency whose right-hand side (RHS) term is the source and the solution is the monochromatic wavefield. For 2D acoustic problems, the few frequencies involved in the inverse problem can be efficiently modelled in the frequency domain for a large number of sources if a direct solver is used for solving the linear system. Indeed, the matrix factorization is independent of the RHS terms and the solution for multiple shots can be obtained efficiently by substitutions once the matrix has been factorized once (Marfurt, 1984). Furthermore, attenuation effects using complex velocity (Toksöz and Johnston, 1981) can be easily implemented in the frequency domain as well as unsplit perfectly matched layers (PMLs) (Berenger, 1994; Hustedt et al., 2004) and 45° paraxial (Clayton and Engquist, 1977) absorbing boundary conditions. For all these reasons, the frequency-domain approach of FWT is more computationally efficient than the time-domain counterpart to tackle 2D acoustic problems. Moreover, the frequency domain provides a more natural framework than the time domain to design a multiscale approach by successive inversion of increasing frequencies which mitigates the risk of convergence towards a local minimum of the objective function (see Bunks et al., 1995 for a multiscale FWT in the time domain). Although the frequency-domain formulation of FWT has shown to be very attractive, its computational cost remains high. A crustal-scale application was presented by Operto et al. (2006) for which only the LU factorization was performed in parallel using 12 processes. For a computational grid of 4.4 millions of nodes, the FWT took 20 days to perform 20 iterations of 13 frequency inversions. Therefore, it is critical that FWT algorithms take advantage of recent advances in high-performance computing as that provided by large Beowulf clusters.

This is the first paper in a two-part series that describes a massively parallel code that performs 2D FWT in the frequency domain. In this paper, we focus on the description of the parallel algorithm. In the companion paper (hereinafter referred to as paper 2), we shall validate the FWT program with synthetic examples of increasing complexity and present a scalability analysis of the algorithm thanks to a real data case study. Our code is written in Fortran 90 and uses the message passing interface (MPI) for parallelism. Although the models are parametrized by heterogeneous P-wave velocity, density and attenuation for wave propagation modelling, only the P-wave velocity is currently reconstructed in the inversion. The inverse problem is solved by an iterative local optimization approach based on a steepest-descent (or gradient) method (Tarantola, 1987; Pratt et al., 1998). The gradient of the objective function is computed using the adjoint method which allows to avoid the explicit computation of the sensitivity matrix. The inversion is iterated non-linearly, which means that the final model of the current iteration is used as the starting model for the subsequent iteration. The algorithm can perform either successive mono-frequency inversions or simultaneous inversion of multiple frequencies. Full-waveform modelling is performed by a finite-difference (FD) frequency-domain method (Jo et al., 1996; Hustedt et al., 2004). For solving the discrete linear system of equations resulting from the FD discretization of the forward problem, we use the MUltifrontal Massively Parallel direct Solver (MUMPS)