

High-resolution seismic imaging of the subsurface with MUMPS: Solving the time-harmonic wave equation with multiple sparse right-hand sides in large computational meshes

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Abstract

High resolution imaging of the constitutive properties of a medium from acoustic waves has many applications in civil engineering, oil exploration, earthquake seismology, medical imaging, non destructive control testing, ... The so-called Full Waveform Inversion (FWI) has become the baseline imaging method in many application domains with the development of new acquisition technologies and the continuous advances of high-performance computing. FWI relies on simple principles: FWI aims at estimating the constitutive parameters of a medium contained in the coefficients of the wave equation by minimizing a distance between recorded waves by an array of sensors and the numerically simulated counterparts. As such it is a partial-differential equation (PDE) constrained optimization problem, which is solved with iterative gradient-based methods. At each iteration, building the gradient of the misfit function with the adjoint-state method requires to compute the incident wavefields triggered by each source of the experiment and the so-called adjoint wavefields by propagating the data residuals backward in time from the sensors. The wave equation is classically solved with numerical methods such as finite difference or finite element schemes to exploit the full information content in the data. Moreover, the wave equation can be solved either in the time-space or in the frequency-space domain. In the former case, solving the wave equation is an initial condition evolution problem, which can be solved with explicit (matrix-free) schemes. In the later case, solving the time-harmonic wave equation for each source of the experiment is a boundary value problem requiring the solution of a large and sparse complex-valued linear system with multiple sparse right-hand sides. These systems can be solved with direct or iterative methods. Here, we implement FWI in the frequency domain, where the Helmholtz equation is solved with a finite difference method and the MUMPS solver. We develop frequency-domain FWI for geophysical applications where we seek to image a geological medium containing several tens to hundreds of millions of unknowns after discretization while the seismic experiment involves hundreds to thousands of seismic sources (right-hand sides). In this framework, we take advantage of two key ingredients of MUMPS to design computationally-efficient algorithms: block-low rank factorization with mixed-precision arithmetic to mitigate memory and computational time of both the LU factorization and solution step and efficient block processing of a large number of sparse right-hand sides. We illustrate the performance of MUMPS with an industrial seabed case study from the North-West continental shelf, Australia, and discuss the perspective of these applications.