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Global wave propagation in 3-D aspherical Earth models boosted by exploiting wavefield complexity

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The multi-scale nature of Earth's 3-D structure and the availability of broadband global seismic data encourage high-frequency wave propagation in 3-D Earth models. Irrespective of hardware and algorithmic advances, conventional 3-D numerical methods come at a persistently high computational cost that still obliterates any possibility to cover the highest observable frequency ($\sim$1 Hz) with realistic computing resources.

Seismic inversion and geodynamic modelling have revealed a characteristic 3-D picture of Earth's mantle, that is, a predominant 1-D layered structure weakly altered by long-wavelength 3-D inhomogeneity and scattered with probably strong small-scale heterogeneities. Such a characteristic 3-D structure leads to particular spatiotemporal complexity of the resultant wavefield, which can be exploited to diminish the problem scale and thus significantly ease the computability. We take advantage of the azimuthal smoothness of global wavefields and parameterise the azimuthal dimension in Fourier series while describing the other two meridional dimensions with a discretised 2-D mesh. Because the expansion order of the Fourier series can be locally adapted to the azimuthal complexity of wavefields, the computational cost becomes model-dependent and is usually significantly lower than conventional 3-D methods.

Notwithstanding the pseudo-spectral characterisation, our method is a stand-alone and convergent 3-D numerical method for global wave propagation, which allows not only for material heterogeneities such as velocity, density, anisotropy and attenuation, but also for finite undulations on vertical discontinuities, and thereby a variety of aspherical Earth features such as ellipticity, topography and bathymetry, variation of crustal thickness, and core-mantle boundary topography. It also proves robust to localised small-scale heterogeneities with sharp material contrasts. For a period ranging from 10 to 1 s, the speedup of our method with respect to a 3-D spectral element method can reach 2 to 3 orders of magnitude for the state-of-the-art tomographic mantle models and 1 to 2 orders of magnitude for full 3-D Earth models with crustal structures. The observable frequency band (up to 1 Hz) of global seismic data has been covered with affordable computing resources, opening a door to high-frequency body wave studies of the deep Earth. The high-performance C++ code, named AxiSEM3D, is developed taking utmost care of usability (such as streamlined 1-D and 3-D model generation and wave visualisation) and extensibility (such as the introduction of new rheology and multi-physics), available open-source at https://github.com/kuangdai/AxiSEM3D.