Full waveform inversion of broadband data: beyond high resolution reflectivity images, towards 3D multi-parameter characterization of the subsurface

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Full waveform inversion (FWI) is now a standard step of the seismic imaging workflow in the hydrocarbon exploration industry (i.e. Stopin et al., 2014). It is based on the exploitation of the full seismic data by the solution of a data-fitting inverse problem. From an initial model of the subsurface mechanical parameters, FWI generates a series of models which iteratively minimize the misfit between the recorded seismic data and synthetic data calculated through 3D wave propagation modeling (Virieux et al., 2017).

FWI is in general used to improve the resolution of velocity models conventionally estimated through travel-time tomography techniques. The higher resolution (potentially half-wavelength) output velocity model is subsequently used as input to migration, to improve the focusing of reflectivity images for interpretation. However, since the past few years, thanks to the increased capacities of high performance computing platforms, FWI has been used to invert seismic data in frequency bands usually reserved for migration. Taking vertical derivatives of the resulting high resolution velocity models directly yields reflectivity images. This makes it possible to bypass the migration step and associated data pre-processing, henceforth reducing the overall time from acquisition to interpretation (Huang et al., 2021).

This is a remarkable progress. However, when FWI is coupled with dense, broadband seismic data, its potential for reconstruction of the subsurface models is much higher than generating reflectivity models only. Indeed, the mathematical framework of this method makes it possible to invert any of the subsurface parameters involved in the partial differential equations chosen to describe the wave propagation and to which waves are sensitive: for instance, in the visco-acoustic approximation, it is possible to reconstruct the models of P-wave velocity, density and quality factor describing the attenuation. What usually prevents FWI to recover the latter secondary parameters (density and quality factor) is a lack of sensitivity of the data to these parameters. This lack of sensitivity is itself related to the generally narrow frequency band used to filter the FWI input data together with a possible lack of diversity of the recorded events in terms of transmitted and reflected energy.

The chosen frequency band results in general from a trade-off between the expected resolution of the output velocity model and the computational cost. The broader the frequency band, the higher the computation cost, the algorithmic complexity of the FWI algorithm scaling with the power 4 of the maximum frequency. In a narrow frequency band, the seismic data is mostly sensitive to velocities, with potentially important trade-offs with other secondary parameters.

This paradigm changes when FWI is applied to broadband data. Opening the bandwidth provides sufficient information to better decouple the effect of velocities and secondary parameters. This is what we highlight in the presented study, in an application to a 3D North Sea Ocean Bottom Cable (OBC) data which we invert up to 22.5 Hz. We design a fully scalable FWI algorithm, relying on three levels of parallelism: a first MPI level over shot distribution, a second MPI level over domain decomposition, and an inner OpenMP level on each domain. The final models we reconstruct are defined on a 17.5 m 3D Cartesian mesh, involving more than 120 millions discrete unknowns per parameter, using up to 50,000 CPU simultaneously on the French National machine ADASTRA, at CINES, Montpellier. We simultaneously reconstruct the P-wave velocity model, the density and the quality factor. As expected, broadband FWI yields a high resolution reflectivity image as a by-product of the inverted P-wave velocity and density (Fig.1, top). However, what we highlight, is that it also makes possible the quantitative estimation of density in the target region, down to 2.5 km, as can be seen from the fit to the density log (Fig.1, bottom).

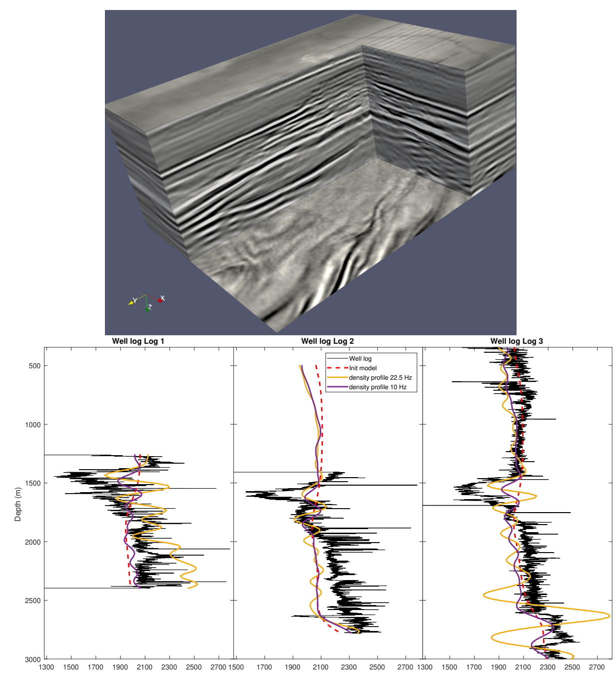

Figure 1: Top: reflectivity model obtained as the vertical derivative of the reconstructed acoustic impedance (velocity and density product) at 22.5 Hz. Bottom: comparison of 3 density logs with the initial density (Gardner's law from the initial velocity mdoel), the density estimated at 10 Hz (purple) and at 22.5 Hz (orange).