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Strategies to Enhance the Model Update in Regions of Weak Sensitivities for Use in Full Waveform Inversion

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Conventional methods of interpreting seismic data rely on filtering and processing limited portions of the recorded wavefield. Typically, either reflections, refractions or surface waves are considered in isolation. Particularly in near-surface engineering and environmental investigations (depths less than, say 100 m), these wave types often overlap in time and are difficult to separate. Full waveform inversion is a technique that seeks to exploit and interpret the full information content of the seismic records without the need for separating events first; it yields models of the subsurface at sub-wavelength resolution.

We use a finite element modelling code to solve the 2D elastic isotropic wave equation in the frequency domain. This code is part of a Gauss-Newton inversion scheme which we employ to invert for the P- and S-wave velocities as well as for density in the subsurface. For shallow surface data the use of an elastic forward solver is essential because surface waves often dominate the seismograms. This leads to high sensitivities (partial derivatives contained in the Jacobian matrix of the Gauss-Newton inversion scheme) and thus large model updates close to the surface. Reflections from deeper structures may also include useful information, but the large sensitivities of the surface waves often preclude this information from being fully exploited. We have developed two methods that balance the sensitivity distributions and thus may help resolve the deeper structures.

The first method includes equilibrating the columns of the Jacobian matrix prior to every inversion step by multiplying them with individual scaling factors. This is expected to also balance the model updates throughout the entire subsurface model. It can be shown that this procedure is mathematically equivalent to balancing the regularization weights of the individual model parameters. A proper choice of the scaling factors required to balance the Jacobian matrix is critical. We decided to normalise the columns of the Jacobian based on their absolute column sum, but defining an upper threshold for the scaling factors. This avoids particularly small and therefore insignificant sensitivities being over-boosted, which would produce unstable results.

The second method proposed includes adjusting the inversion cell size with depth. Multiple cells of the forward modelling grid are merged to form larger inversion cells (typical ratios between forward and inversion cells are in the order of 1:100). The irregular inversion grid is adapted to the expected resolution power of full waveform inversion. Besides stabilizing the inversion, this approach also reduces the number of model parameters to be recovered. Consequently, the computational costs and the memory consumption are reduced significantly. This is particularly critical when Gauss-Newton type inversion schemes are employed.

Extensive tests with synthetic data demonstrated that both methods stabilise the inversion and improve the inversion results. The two methods have some redundancy, which can be seen when both are applied simultaneously, that is, when scaling of the Jacobian matrix is applied to an irregular inversion grid. The calculated scaling factors are quite balanced and span a much smaller range than in the case of a regular inversion grid.