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Wavefield tomography in three dimensions: application to field data in the absence of a realistic starting model

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Wavefield tomography (AKA full waveform inversion) is a method of inverting geophysical field data that seeks to find a quantitative model of physical properties in the subsurface that can be used to generate synthetic data that match field data "wiggle-for-wiggle". It is most often applied to active-source seismic data, but it can also be applied to passive seismic data and to controlled-source electro-magnetic data. The method has significantly higher spatial resolution and fidelity than can be achieved using conventional imaging methods. The first practical methods were developed in 2D, mostly in the frequency domain. Here we report recent algorithmic developments which, coupled with hardware advances, make these methods tractable in three dimensions.

We have implemented finite-difference computer codes for 3D acoustic and elastic wavefield tomography by explicit time-stepping in the time-domain, and for visco-acoustic tomography by iterative solution of the implicit matrix equations in the frequency-domain. Unlike the situation in two dimensions, where frequency-domain methods have proven to be far more efficient, in three dimensions both methods require approximately similar computational resource, and have largely complementary properties in terms of their effectiveness.

We have applied these methods to a variety of synthetic and real-world problems taken from petroleum, mining and academic field datasets with a variety of 3D acquisition geometries and target depths. These include conventional marine multi-streamer acquisition, multi-azimuth marine OBC, high-resolution land surveys, and deep-ocean single-streamer acquisition. In each case, wavefield tomography was able to obtain a high-resolution high-fidelity velocity model of the heterogeneous overburden, and consequently to improve subsequent depth imaging of an underlying target.

One of the serious practical limitations on the wider applicability of wavefield tomography is the necessity to have low-frequencies in the field data coupled with high-accuracy in the low-wavenumber starting velocity model. When these conditions are not met, linearised local wavefield inversion schemes are unable to deal with cycle-skipped starting data, and they invariably fall into the nearest local minimum of the objective function, from which they do not subsequently recover.

We have developed a scheme that is able to overcome this limitation, and that consequently opens up the range of problems, datasets and depths to which wavefield inversion techniques may be successfully applied. This scheme uses the unwrapped phase of both the field data and starting data at the lowest useful frequency. We use these to generate a new intermediate dataset that has an unwrapped phase that lies between the two, and that is not cycle skipped. We use this intermediate dataset to begin the inversion. After several iterations, we switch to the true field dataset, and continue inverting. This approach is able to invert datasets successfully that are otherwise entirely intractable.