3D full-wavefield tomography: imaging beneath heterogeneous overburden

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Summary

We have developed computer codes and work-flows for 3D acoustic waveform inversion in both the frequency and time domains. We have applied these methods to several 3D field datasets with a variety of acquisition geometries and target depths. 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.

Overview

We have developed computer codes and workflows for 3D acoustic full-wavefield tomography implemented by finite differences in both the frequency and time domains. In 3D, both methods require approximately similar computational resource, and they have largely complementary properties in terms of their effectiveness. We have applied these methods to several 3D field datasets with a variety of acquisition geometries and target depths. These include conventional marine multi-streamer acquisition, multi-azimuth marine OBC, a high-resolution land survey, and deep-water low-fold, 3D, 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. In this paper, we will show these datasets, and outline the main procedures that were used to generate the images.

In the remainder of this abstract, we present the generic steps that are required in order to obtain reliable models from wavefield tomography. We do not explicitly consider anisotropy, anelastic attenuation or elastic effects, although all of these can be important. We assume marine airgun arrays and towed or ocean-bottom hydrophones. We do not explicitly consider cross-hole, VSP, land or multi-component datasets, but much of the workflow will be applicable to these other situations. We also do not discuss the use of composite sources which can speed up tomography significantly. We assume that the primary purpose of the tomography is to obtain an improved p-wave velocity model – both in terms of its spatial resolution and absolute accuracy. It is also implicitly assumed that this velocity model is to be used for pre-stack depth migration of conventional reflection data. Wavefield tomography can be used to obtain a number of other physical parameters, and the resulting models used for a number of purposes including direct imaging via wavefield tomography. However, in all nearly such cases, the quality of the final result depends critically upon first obtaining a high-quality p-wave velocity model.

Wavefield tomography is a technique that seeks to obtain a high-resolution high-fidelity model of seismic velocity in the subsurface by linearised least-squares inversion from a starting model, minimising the misfit between observed and predicted seismic wavefields. The potential benefits of wavefield tomography have been extensively demonstrated using 2D synthetic examples. However the widespread adoption of the technique has been limited by the computational expense of working in 3D, the non-linearities associated with uncertainties in the starting model, and the difficulty of applying the technique meaningfully to conventional reflection data.

The first of these problems has been overcome recently with advances in hardware and algorithms, and several groups have now demonstrated acoustic wavefield tomography in 3D. The second problem is serious; a potential solution is discussed in a companion paper (Shah et al, 2010). The third problem is also serious though its implications are perhaps less widely realised; a partial solution was presented by Hicks & Pratt (2001), but a full solution is still lacking.

The key elements to successful waveform inversion are:

1. Choose a problem that it is likely that wavefield tomography can usefully solve, acquiring or selecting a dataset that has sufficient offset and sufficiently low frequencies.
2. Pre-process the data to remove the direct water wave and the effects of the free surface while retaining low-frequencies and wide-angle arrivals. Remove all other arrivals from the data that will not be modelled within the tomography. Extract a source function from the data.
3. Devise a smooth but accurate starting velocity (and perhaps attenuation) model. Generate time-domain synthetics to check the appropriateness of the velocity model and source, check for phase skipping on the major arrivals at the lowest frequencies, improve the starting model if required and/or adopt a staged inversion strategy (Shah et al., 2010).
4. Refine the parameterisation for the tomography. Begin by using realistic synthetic data, in 2D then 3D, tuning the parameterisation to improve recovery of the known model. If the acquisition geometry allows, optimise the parameterisation and pre-processing by testing on the field data in 2D. Ensure that the target is recoverable, at least in principle, using the chosen parameterisation.

5. Perform the full 3D tomography, proceeding from low to high frequencies, by successive layer stripping, and by recovering the longer spatial wavelengths using only wide-angle transmitted arrivals before attempting to recover shorter spatial wavelengths using sub-critical reflections.
6. Check the quality of the final velocity model by generating time and frequency-domain synthetics. Check especially for cycle skipping between the synthetic and field data, and check that depth migration of deeper events beneath the recovered velocity model improves.
7. Use a perturbation analysis to constrain resolution and sensitivity at target depths.

The key steps within this workflow are data selection, generation of the starting model, and appropriate parameterisation and data selection within the tomographic iteration. The current level of understanding of how to apply wavefield tomography optimally in 3D is sufficiently limited that careful quality control and parameter testing is an absolute requirement at each stage of the inversion. Figure 1 shows an example of applying this approach to a 3D high-resolution multi-azimuth dataset.

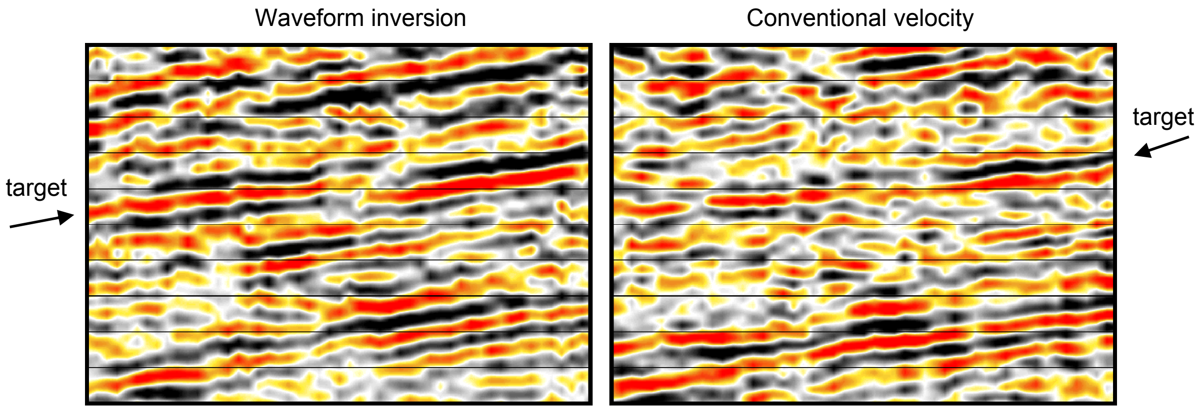

Figure 1 *A vertical slice through a multi-azimuth 3D dataset following two different processing routes – one processed using a velocity model recovered using waveform inversion, and the other processed using a conventional velocity model for migration and statics determination. The target is the main reflector lying about a third of the way down the section. This horizon is cut by a sequence of small-offset, steep, reverse faults – these can be identified clearly on the left-hand section but not on the right. The continuity and signal-to-noise ratio is also much improved following waveform inversion. The principal contribution of the method in this instance is in resolving velocity heterogeneity in shallow overburden – this is treated dynamically by waveform inversion, but is treated as a statics plus migration problem in conventional processing. The advantages of the former are clear.*

Problem and data selection

The present state of the art is such that wavefield tomography only really works usefully for field data where transmitted energy is available to constrain the longer-wavelength features of the velocity model. For surface data, imaging using transmitted energy is normally only possible where wide-angle, long-offset, post-critical arrivals ("refractions") are recorded that have penetrated to at least the depth of the velocity target. It is helpful if this energy is recorded as a first or near-first arrival, but that is not essential. Wavefield tomography also performs optimally when there is significant azimuthal coverage at all mid-points at all offsets.

The offset that is required in order to record appropriate wide-angle arrivals depends upon the velocity model, but it is often three to six times the depth to the velocity target. The smaller value is typical for shallow water, shallow targets; the larger value is more typical in deeper water, with deeper targets. Tomography becomes more technically difficult, and the requirement for a good starting model becomes more demanding, as path length increases and the target becomes deeper. Problems that involve shallow heterogeneity that distorts the migrated image of a deeper reservoir are easiest to attack. Approaches that seek to image a deep reservoir directly, or where conventional p-wave imaging performs poorly for reasons other than velocity heterogeneity, are not likely to be easy wins.

The key wide-angle arrivals for wavefield tomography are those that are typically removed using a front-end mute and/or dip-filter during reflection processing. The frequencies at which we will endeavour to work are also typically below those used in reflection processing, and the offsets that we seek to use are also unusually large. Consequently, early pre-processing of seismic data for reflection imaging often does not properly preserve the phase, amplitude, dip or even the existence of the data and offsets that we seek to use. Problems can occur with low-cut filters, swell-noise removal, wavelet adjustments, f-k and radon filters, free-surface multiple suppression, deghosting, regularisation, datuming and amplitude compensation – plus of course simple muting. Some of these processes happen early in a processing sequence, consequently it vital that the data for wavefield tomography are either obtained prior to any of these processes, or that they are undertaken in a way that honours and preserves wide-angle arrivals. The latter is usually straightforward to achieve, but it will not normally be the default behaviour in reflection processing, and so it requires special attention.

If they were available, we would want to start the tomography from frequencies below 1 Hz. In normal datasets, such very low frequencies are not available. In this case, we still wish to start as low as possible. Consequently, the acquisition system should have no low-cut filter, and in surface-streamer data, we will likely aim for a low end in the range 4 to 6 Hz. If there is nothing useable below about 8 Hz, then tomography will be difficult; if there is nothing below about 12 Hz, then it will likely be impossible; frequencies above about 15 Hz are typically not useful. This limited high-end bandwidth means that the computational effort of wavefield tomography is often less than that of reverse-time migration at full bandwidth despite the iterative nature of the former.

Pre-processing and source extraction

Pre-processing involves removal of any parts of the data that are not to be included within the tomography or that are not represented within the forward modelling code. These include free-surface multiples, ghosts, water-wave direct arrivals, elastic effects, and other sources of noise. They may also include sub-critical reflection events and wide-angle arrivals from particular depths. The data geometry need not be regularised, nor need missing shots or receivers be interpolated – the tomography uses the true geometry of the survey.

In principle, it is possible to run wavefield tomography by including free-surface multiples and ghosts within the input data and including a free surface at the top of the model. In practice, including multiples within the inversion increases dramatically the degree of non-linearity within the problem. Consequently, it is usually appropriate to proceed by removing the multiples from the input data, replacing the free-surface within the model by an absorbing upper boundary. However, care must be taken to ensure that multiple removal does not damage wide-angle arrivals with dips close to that of the water wave. Surface ghosts can either be incorporated into the source, or can be included explicitly in the modelling using virtual sources and receivers. Normally it will be necessary to remove direct water-wave arrivals from both the model and field data since these seldom match well.

Starting velocity model

Together with the existence of long offsets and low frequencies, obtaining an adequate starting velocity model is the principal requirement for effective wavefield tomography. The higher the lowest frequency, and the longer the maximum path length from source to receiver, then the greater the accuracy required for the starting model. If the starting model produces significant cycle skipping between model and field data, wavefield tomography will fail. Staged inversion may circumvent this.

Ideally we would build a starting model using travel-time tomography based upon all the arrivals that are used to drive the wavefield tomography – these are principally the wide-angle arrivals not the reflections. When applying travel-time tomography, high-frequency arrivals should be used to maximise the temporal accuracy of the travel-time picks; ideally, we would like the diameter of the

Fresnel zone for the *highest-frequency* arrivals used in the travel-time tomography to be approximately equal to the wavelength of the *lowest frequencies* used for the wavefield tomography. If this condition is met, then the resolution of the two velocity models will be similar. The starting model should be smoothed spatially so that it contains no structure with a wavelength shorter than the wavelength of the lowest frequency used in the wavefield tomography, except that a sharp seafloor may appear in the velocity model if we have confidence in its location and reflectivity.

Parameterisation and strategy

Parameterisation of 3D wavefield tomography codes is not yet a matter of routine. A period of pre-testing will be required to optimise for specific problem types and datasets. This is most readily done by working from realistic synthetic testing in 2D and 3D, testing in 2D with field data, to final testing in full 3D with a subset of the field data. The lowest frequency for the tomography will be set by the field data. The highest frequency will be set by the grid spacing and the lowest velocity in the model – usually the water layer. For a typical grid spacing of 25 m, the maximum frequency will be in the range 12 to 14 Hz. Around ten frequencies is normally adequate, spaced in approximately equal ratios between the lowest and highest, and typically we will want to iterate about ten times per frequency. If the data are noisy, the use of several frequencies simultaneously can improve results.

A typical inversion scheme would proceed as follows – with detailed QC at each step:

- Initially work to improve the near-seafloor portion of the model – mute or weight in time, restrict the offset range, and pre-process the data to remove sub-critical reflections and deeper arrivals.
- Open up the data window to allow shallow short-offset reflections into the tomography.
- Hold the shallow portion of the velocity model fixed, change the mutes, offset range and pre-processing to open up the data window so that it includes wide-angle data from deeper within the model, and work to improve intermediate depths within the model.
- If the data and model quality warrant it, open up the data window to allow intermediate-depth short-offset reflections into the tomography.
- Hold the shallow and intermediate parts of the velocity model fixed, opening up the data windows further to include the deepest data, but continue to suppress short-offset deep reflections; work to improve the model at target depths.
- Finally, if the data and model quality warrant it, open up the data window to allow deeper reflections into the tomography.

The wavefield tomography is driven by both amplitude and phase. Typically we would use only phase early in the tomography, introducing amplitudes, if at all, late in the process. Since amplitudes can be affected significantly by source directivity and anelastic attenuation, these need proper attention if amplitudes are used extensively. It would be difficult to overemphasise the importance of careful quality control throughout in order to obtain useful inversion results from field data.

The final step should be to constrain the resolution and sensitivity of the recovered model. This can be done by perturbing the final model, generating synthetics, and attempting to recover the perturbations using the same geometry and parameterisation as were used in the field tomography. Such testing will not reveal that there are problems with effects that have not been modelled – anisotropy for example – or with a poor starting model. But it will reveal the degree to which certain types of features are recoverable from the data, the degree to which they are resolved spatially, and the degree to which their absolute amplitudes are reliable.

References

Hicks J and RG Pratt (2001) Reflection waveform inversion using local descent methods. Geophysics, 66, 598–612.

Shah N, M Warner, L Guasch, I Stekl, A Umpleby (2010) A Strategy for waveform inversion without an accurate starting model. EAGE Barcelona 2010.