Attenuation of water-layer-related multiples
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Summary

We present a method for modeling and separation of water-layer-related multiples in towed streamer acquisitions. Our method models accurately the kinematics of multiples with bounces in the water layer, both on the source and receiver sides, and extends the capabilities of previous methods in particular for the cases with complex topography on the sea bed. We illustrate the method with synthetic data and with field data from a shallow-water 3D towed-streamers marine survey.

Introduction

Water-layer-related multiples are free-surface multiples, that have a bounce in the water-layer on the source or receiver side. Typically, the water-layer-related multiples have large amplitudes because of the strong contrasts in material properties at the air/water (free surface) and at the water/sediments interfaces.

Deconvolution, initially, and later wavefield extrapolation methods were developed to attenuate such water-layer-related multiples. The development of 3D surface-related multiple elimination (SRME) and wave-equation modeling methods, which predict all free-surface multiples, led to redefining the applications for water-layer-related multiples removal. The preferred application cases of the latter technique are now in shallow-water surveys; sea-bed surveys, or other surveys that don’t meet some of the requirements for 3D SRME methods; or, used in combination with imaging methods extracting information from the multiples.

Here, we extend the deterministic water-layer demultiple (DWD) method of Moore and Bisley (2006) to handle complex topography on the near water-bottom multiple-generating reflectors by using the modeling approach described by Verschuur (2006). After presenting a brief outline of our method, we illustrate the method with synthetic data examples, indicate directions for further developments in modeling, and apply our method in a case study with data from a shallow-water survey acquired offshore Canada.

Theory and Method

It is well established that multiples with bounces on the source side or on the receiver side have different raypaths and attributes, and, therefore both types of multiples should be modeled. Figure 1 illustrates the definition of source-side and receiver-side water-layer-related multiples. Note that in a horizontally-layered medium, source-side and receiver-side multiples would be the same (ignoring differences due to source array directivity, for instance). However, traveltime differences between source-side and receiver-side multiples exist even in presence of a horizontal water bottom due to the interaction with deeper non-horizontal reflectors. When both the sea bottom and the deeper structures are non-horizontal, such traveltime differences increase in particular with the number of bounces in the water layer.

The equations for prediction of all water-layer-related multiples by wavefield extrapolation are given by Lokshtanov (2001) and by Verschuur (2006). Following Verschuur (2006), the equation for the model of water-layer-related multiples is

\[ M = W_R \ast D + (D - D_w) \ast W_S - W_R \ast D \ast W_S , \]  

where notations as follows: M is the model of multiples; D is data; D_w is the water bottom reflection; and W_R and W_S wavefield extrapolation operators acting respectively on common shot and common receiver gathers. The \( \ast \) denotes the wavefield extrapolation of the data, performed by multi-dimensional convolution with a (vertical derivative of) Green’s function for the water layer. Implicitly, all the wavefields are functions of temporal frequency and spatial coordinates of the sources and receivers.

To reduce the number of multi-dimensional convolutions, one can group the terms in equation (1) as in Moore (2004),

\[ M_R = W_R \ast D , \]  

(2)

\[ M = M_R + (D - D_w - f \ast M_R) \ast W_S , \]  

(3)
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where \( f \) is a linear filter, determined by matching the model \( M_R \) to the data.

Within this modelling framework, the next steps are the choice of a Green’s function for the wavefield extrapolation, implementation of a method for computing efficiently and accurately the Green’s function, and the pre-conditioning of the data as needed for the wavefield extrapolation.

In current practice, wavefield extrapolation operators are computed as approximations to Green functions in acoustic media, implicitly focusing on matching the kinematics of pre-critical reflections in the data (Wiggins, 1988; Spadavecchia et al., 2013; Wang et al., 2014). Here, we follow this practice and compute wavefield extrapolation operators using constant, angle-independent sea-bed reflectivity, as in the wave-equation modeling of all free-surface multiples (Stork et al., 2006), except that the reflectivity model consists of the sea-bed reflection, or near-sea-bed reflections, only.

The multi-dimensional convolutions involved in the wavefield extrapolation are the same as in the data-driven prediction of surface multiples by 3D SRME methods (Dragoset et al., 2010). Similarly to 3D SRME, the data need to be adequately sampled, either in acquisition, or in pre-processing in order to compute the multi-dimensional convolutions. In our work, we use the efficient on-the-fly interpolation developed as part of the general surface multiple prediction (GSMP) method (Moore and Dragoset, 2008), combined when necessary with interpolation prior to the prediction of water-layer-related multiples.

**Synthetic Data Example**

Figure 2a displays a synthetic shot gather computed by a finite-differences method in a three-layer acoustic earth model (Figure 2b). The shot gather includes two primary reflections (the two earliest reflections in the figure), free-surface multiples, as well as internal multiples. Even though the dip on the sea bed is small (0.89°), travelt ime differences between source-side and receiver-side multiples (events identified by thick blue arrow in Figure 2a, with raypaths as in Figure 1) are clearly observed for this shot gather computed for frequencies up to 55 Hz.

Figure 2c displays water-layer-related multiples with bounces on the receiver side only. This model of multiples is computed by equation 2. Note that the receiver-side-only model doesn’t contain the split arrival events observed in Figure 2a (compare events pointed by the blue arrows).

The dashed black arrow points to an internal multiple in the input data, whereas the solid black arrow points to a free-surface multiple that is not reflecting on the sea bed and therefore is not included in the model in Figure 2c.

![Figure 2: a) Common shot gather of finite-difference synthetic data; b) Three-layer model used for computing the synthetics with water layer at the top (in blue) and dip on the water-layer bottom of 0.89° (plotted with vertically exaggerated scale). c) Model of multiples with receiver-side bounce in the water layer.](image-url)

We computed synthetic data for shot and receiver locations as in a field survey similar to the one described in the Field Data Example section that follows. The synthetic data are available not only at the locations of acquired data during the survey, but also at locations where data would have been interpolated during processing. Comparing the multiples modeled by finite differences from the acoustic model (Figure 3a) to the multiples predicted by the method described in this paper (equation 1), we note very good agreement for the kinematics of the water-layer-related multiples, including the splitting starting at mid-offsets between the receiver-side and the source-side peg-leg multiples.

**Field Data Example**

To illustrate the approach with field data we use an offshore Canadian survey, acquired in 1997 over the Hebron oil field. The nearly horizontal water bottom (Figure 4) varies in depth from 88 m to 104 m. The particularly hard water bottom makes water-layer-related multiples particularly strong, even for high-order multiples.

The data were acquired with two source arrays each shooting alternately every 50 m in flip-flop mode, and were recorded with 8 streamers, each 4 km long, with receiver group interval of 25 m. The crossline separation between streamers is 100 m.
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The multiple-attenuated data are the result of adaptively subtracting a model of water-layer-related multiples including receiver-side and source-side multiples. The adaptive subtraction workflow includes least-squares matching filters as well as curvelet decomposition and has been optimized for this model, thus removing a significant amount of multiples.

In Figure 7a we display the trace-by-trace crosscorrelations between input stacked data and the model (source and receiver-side bounces). The significant energy at zero-lag indicates a good match between the model and the data. The crosscorrelations between primary events in the data and multiples in the model contribute to negative crosscorrelation times. At positive crosscorrelation times we have cross-talk between multiple events of different orders, not involving the primaries. Figure 7b displays trace-by-trace crosscorrelations between the data without multiples (as in Figure 6) and the model of multiples. Notice the significant reduction of energy at zero and positive crosscorrelation times indicating good attenuation of multiples, whereas significant energy at negative times is preserved and contains contributions from cross-talk between primaries in the data and multiples in the model.

Conclusions

The general wavefield extrapolation operators that we introduced are capable of modeling water-layer multiples interacting with a seafloor of complex geometry. Our predictions of the multiples are kinematically correct which is important in order to use well-constrained adaptive subtraction. The amplitudes of our models are approximate with respect to handling effects due to scattering from the sea floor, source directivity, and residual ghost effects. Such differences in amplitudes are currently compensated by adaptive subtraction. The prediction of more accurate amplitudes for the multiples is a direction for further work in which the main challenges are the accuracy of the available earth models, the significant cost of full solutions of the acoustic or elastic wave equations, and the acquisition geometries required for accurate wavefield extrapolations.
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Our proposed method, illustrated on synthetic and field data, provides accurate predictions of water-layer-related multiples. Use of a model that includes both source- and receiver-side multiples is preferable to use of only a receiver-side model, even in cases of mild structural variations of the seafloor.

Figure 5: Stack section of input data. The rectangles indicate areas of the stack section displayed in Figures 6 and 8.

Figure 6: a) Stack section output, where models of receiver-side and source-side multiples have been subtracted from the input data; b) Stack section of input data with no multiple attenuation. The black arrows indicate locations for comparisons between Figures 6 and 8.

Figure 7: a) Trace-by-trace crosscorrelations between traces from the input stack (Figure 5) and traces from the model with receiver-side and source-side multiples; b) Trace-by-trace crosscorrelations between traces from the output stack (Figure 6) and traces from the model with receiver-side and source-side multiples.

Figure 8: Stack section output, where a model of receiver-side multiples has been matched and subtracted from the input data; b) Stack section of input data with no multiple attenuation. The black arrows indicate locations for comparisons between Figures 6 and 8.

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