Surface-Related Multiple Elimination for Variable-Depth Seismic Streamer Acquisition

Roald van Borselen, PGS

Summary

In this paper, a method is presented to compute 3D surface-related multiples using multi-component sensor data that have been acquired with streamers at variable depth. An equivalent for single sensor streamer is also presented. Results are shown for a 2D dual-sensor synthetic example, designed to highlight the potential of the method presented.

Introduction

In recent years, new acquisition systems have been introduced to marine seismic acquisition to increase the bandwidth and the resolution of the recorded data. These methods all aim to remove the so called "ghost" reflections that have been generated by the free-surface. The free surface reflects the seismic energy back into the water layer such that any seismic event is recorded twice: first as an up-going wavefield that has been reflected by the subsurface, and secondly as a ghost, which is the down-going field that has been reflected by the free-surface. This receiver ghost has the opposite polarity from the up-going wavefield, causing peaks and notches in the amplitude spectrum of the recorded data, due to the interference of the up-going and down-going wavefields. As a result of these receiver ghosts, the temporal resolution of the data is reduced.

In multi-component acquisition, the problem of receiver ghost events is overcome through the utilization of streamers where hydrophones and velocity sensors are collocated at the same depth. Because the velocity sensors are directional, the down-going velocity wavefield, being phase reversed by reflection at the free-surface is measured as having the same polarity to the up-going velocity wavefield. As a result, the receiver ghost notches for the pressure and particle velocity sensors are exactly interleaved in the frequency domain. When signals from the two sensors are properly combined, the ghost reflection cancels and the bandwidth of the recorded data is significantly increased (Tenghamn et al. 2009).

Another approach to address the receiver ghosts is to measure the data using a single pressure sensors at variable depths (Soubaras and Dowle 2010). As the interference patterns are directly dependent on the depth where the measurements are taken, the ghost notches will have a more diverse character which can reduce the impact of the notches in the seismic spectrum of the recorded data.

It is also possible to combine these two strategies and use variable depth multi-component streamers.

The utilization of variable-depth streamer acquisition does have implications for some processing techniques that are likely to be applied to the data. One of such techniques is Surface-Related Multiple Elimination, also known as SRME. In SRME, multiples are predicted through the convolution of source- and receiver gathers, where the depths of the sources and receivers need to be equal in order to predict the correct arrival times of the multiples. As this condition is certainly not full-filled using depth-varying streamers, the SRME method needs to incorporate steps that aim to correct for these differences in depths.

In this abstract, a modified SRME method is presented that is suitable to remove surface-related multiples for both single and multi-component variable-depth measurements. The method is explained further in the next section, after which a synthetic data example is presented.

Methodology

In SRME, surface-related multiples are predicted through a convolution of the upgoing pressure wavefield with the downgoing vertical component of the particle velocity wavefield (Van Borselen et al., 2011).

For multi-component sensor data acquired with streamers that are assumed to be flat, methods to decompose the measured seismic wavefields into up-going and down-going wavefield constituents are well established (Fokkema and Van den Berg, 1993, and Van Borselen et al., 2013). Once the up-going and down-going wavefield components have been computed, the computation of the surface-related multiples is straightforward. In this computation, it is important that the convolution of the upgoing pressure wavefield and the downgoing vertical component of the particle velocity wavefield occurs at the correct depths. The relevant process is illustrated in Figure 1. The upgoing wavefield generated by an impulsive source located at depth level x_3^S and measured at receiver depth x_3^R, is to be convolved with the vertical component of the particle velocity field generated by a source at depth level x_3^S and measured at source level x_3^S. This means that the downgoing particle velocity wavefield has to be propagated backwards from the original recording level x_3^R to depth level x_3^S. The back propagation of up-going and down-going wavefields is well understood in the literature (see for example Fokkema and van der Berg, 1993, Chapter 10).

Surface-Related Multiple Elimination for Variable-Depth Streamer Acquisition

In the case of depth-varying streamers, the convolutions can no longer be made in a straightforward manner, as the recording depths now are spatially dependent. Here, the following is proposed: For multi-component streamer measurements, the approach can be adopted by computing the downgoing vertical constituent of particle velocity recorded at source depth x_3^S, and computing the upgoing pressure wavefield at a receiver depth of choice $x_3^{R\prime}$. Using the two extrapolated wavefields, multiples belonging to upgoing pressure wavefield can be predicted at constant receiver depth of choice, as depicted in Figure 2. The predicted multiples can then be subtracted from the computed upgoing pressure wavefield at receiver depth of choice $x_3^{R\prime}$.

To compute the upgoing constituent of the pressure wavefield at an arbitrary constant depth level, established equations can be utilized that expresses this field as a function of measurements of pressure and the normal component of the particle velocity fields at an arbitrary (i.e. depth varying) interface (Fokkema and Van den Berg, 1993, chapter 10, and Van Borselen et al., 2013). To compute a similar equation for the downgoing vertical constituent of particle velocity at an arbitrary constant depth level, the downgoing pressure wavefield is computed by extrapolating the upgoing wavefield up to depth level $x_3 = 0$ and noting that at this depth level the sum of the up- and downgoing pressure wavefields is zero. After a forward extrapolating of the downgoing pressure wavefield to depth level $x_3 = x_3^R$, the downgoing vertical constituent of particle velocity can be computed in a straightforward fashion. It is remarked that a flat sea surface assumption is used in these computations.

Once the upgoing pressure wavefield $\hat{p}^{up}(x_1, x_1, x_3^{R\prime} | x_1, x_1, x_3^S, s)$ and the downgoing component of the particle velocity $\hat{v}_3^{down}(x_1, x_1, x_3^S | x_1, x_1, x_3^S, s)$ are computed, the corresponding surface-related multiples are computed through:

$$\hat{M}\left(x_1^R, x_2^R, x_3^{R\prime} | x_1^S, x_2^S, x_3^S, s\right)$$
$$= \int_{(x_1, x_2) \in \mathfrak{R}^2} \hat{P}^{up}\left(x_1^R, x_2^R, x_3^{R\prime} | x_1^\prime, x_2^\prime, x_3^S, s\right)$$
$$. v_3^{down}(x_1^\prime, x_2^\prime, x_3^S | x_1^S, x_2^S, x_3^S, s) \, dA. \ (1)$$

In the method described so far, multiples are predicted for the upgoing pressure wavefield at constant depth of choice $x_3^{R\prime}$. However, in SRME processing, it is common practice to predict multiples for the total scattered pressure wavefield, containing both the up- and downgoing ray-path constituents, depicted in Figure 3a-b. The reasoning behind this is that it may be preferred to subtract the multiples from data that has undergone as little pre-processing as possible. To accomplish this, multiples need to be predicted at the original variable streamer depths, and they need to contain both up- and downgoing constituents.

The upgoing ray-path constituent of the multiple shown in Figure 3a is obtained by carrying out the decomposition as described above up to a chosen depth $x_3^{R\prime}$ and extrapolating this upgoing multiple pressure field back to the original variable streamer depths. This back propagation is accomplished through:

$$\hat{P}^{up}(x_1, x_2, x_3^R | x^S, s) = F^{-1}\{\tilde{p}^{up}(js\alpha, js\beta, x_3^{R\prime} | x^S, s) \ (2)$$

$$. \exp(+s\Gamma(x_3^R(x_1, x_2) - x_3^{R\prime}). F\{\hat{P}^{up}(x_1, x_2, x_3^{R\prime} | x^S, s)\}\},$$

where $\{F, F^{-1}\}$ are the forward and backward transformation to the spectral domain, and $s\Gamma$ denotes the well-known vertical propagation coefficient. Note that upgoing multiple pressure field will be backward propagated over a distance $(x_3^R(x_1, x_2) - x_3^{R\prime})$, where $x_3^{R\prime}$ is chosen such that $x_3^R(x_1^R, x_2^R) > x_3^{R\prime}$.

The downgoing ray-path constituent is obtained by considering receivers to be located at the mirror positions of the true receivers, shown in Figure 4. This field can be obtained by forward propagating the upgoing multiple pressure wavefield from the constant (arbitrary) depth $x_3^{R\prime}$ to these mirror locations and accounting for the free-surface reflection coefficient. Note that in order to do this, a flat-sea surface assumption is used.

The forward propagation is accomplished through:

$$\hat{P}^{down}(x_1, x_2, x_3^R | x^S, s)$$
$$= -F^{-1}\{\tilde{p}^{up}(js\alpha, js\beta, x_3^{R\prime} | x^S, s) \ (3)$$

$$. \exp(-s\Gamma(x_3^R(x_1, x_2) + x_3^{R\prime}). F\{\hat{P}^{up}(x_1, x_2, x_3^{R\prime} | x^S, s)\}\},$$

where it is noted that the upgoing multiple pressure field will be forward propagated over a distance $(x_3^R(x_1, x_2) + x_3^{R\prime})$. Summing the up- and downgoing multiple ray-path constituents leads to the multiples for the total scattered pressure wavefield. These multiples are then ready to be subtracted from the measured scattered pressure wavefield at variable streamer depths.

When only pressure measurements are available, the computation of upgoing and downgoing wavefield constituents is not straightforward due to singularities in the wavefield decomposition operator for certain combinations. One way to circumvent the numerical instabilities is to take measurements of the scattered pressure wavefield at variable depth, where the depth of the receiver depends on the offset between the source and the receivers. In such case, the notches in the measured spectra may pose less of a problem, as the measured scattered pressure wavefield in the transformed domain will no longer be zero anymore, because of the diversity of receiver depths utilized. In other words, the notches in the transformed domain may display a more diverse character (Van Borselen et al., 2013).

To decompose the measured pressure wavefield in its up- and downgoing wavefield constituents, it is possible to adopt the approach taken by Riyanti et al (2009), where an

Surface-Related Multiple Elimination for Variable-Depth Streamer Acquisition

inversion-based approach is utilized to compute the upgoing pressure wavefield at arbitrary and constant depth $x_3^{R'}$. However, it is remarked that such methods may break down in the presence of significant noise levels in the measured pressure wavefield data (Van Borselen et *al.*, 2013).

Once the upgoing pressure wavefield $\hat{p}^{up}(x_1, x_1, x_3^{R'} | x^S, s)$ has been computed at a constant arbitrary receiver depth, the downgoing constituent of the particle velocity wavefield can be computed using a flat sea surface assumption, as discussed. Subsequently, the upgoing multiple pressure wavefield can be predicted again according to Figure 2.

It is again possible to predict the multiples belonging to the total scattered wavefield at variable streamer depth. To this end, again receivers on both sides of the free-surface are considered, and the predicted upgoing multiple pressure wavefield is extrapolated backwards and forwards to the original variable streamer depths and mirror locations, similar as described for multi-component streamers. After summation, the predicted multiples for the total scattered wavefield can be subtracted from the measured pressure wavefield recorded at variable streamer depths.

Finally, it is remarked that any errors made in the computation of the upgoing wavefield using only single sensor data may not have a significant impact on the end result for two reasons: Any errors made may stack out after the convolutions over many different traces carried out to predict the multiples, and secondly, errors made may be accounted for during the adaptive subtraction of the multiples from the raw, measured total scattered wavefield.

A Synthetic Data Example

The numerical data example is chosen to be simplistic to allow for a straightforward qualitative analysis of the results.

We consider the case where dual sensor measurements are made using a recording streamer where the receiver depth is dependent on the distance between source and receiver. A single shot gather is considered, with a point source located at a 5-m depth, and receivers are located behind the source with a receiver distance of 5 m, where the first receiver is at a 10-m depth, where the receiver depth is linearly increasing with offset (distance between the source and receiver) up to a 35-m depth at an offset of 1250 m. The temporal sampling is 2 ms, and the recording length is 1000 ms. The model consists of two layers: the first layer extends from the free surface to a depth of 250 m, the second layer from 250 m to an infinite depth.

Figure 5a and b shows the recorded pressure and vertical component of the particle velocity recorded at variable depth. Figure 5c shows the multiples to be predicted, and Figure 5d shows the predicted multiples after an auto-convolution of the measured scattered wavefield, without correcting for the differences between source and (variable) recording depth. In the computation of the predicted

multiples, the source signature used in the modelling was utilized. Note the significant errors made compared to the true multiples. Figures 5e and 5f show the upgoing pressure wavefield and the downgoing vertical component of the particle velocity field at a chosen reference depth of 10m, both obtained through multi-component wavefield decomposition. Figure 5g shows the predicted multiples for the upgoing pressure wavefield, obtained through Equation 1. Note the good agreement with the modelled multiples, shown in Figure 5h. Finally, Figure 5i shows the multiples for the scattered pressure wavefield, extrapolated back to the variable depths. Note the excellent agreement with the ideal multiples, shown in Figure 5c.

Conclusions

A method has been presented to compute 3D Surface-Related Multiple Prediction (SRMP) multiples using multi-component and single sensor data that have been acquired with depth-varying streamers. Results from a 2D synthetic example show the potential of the proposed methods.

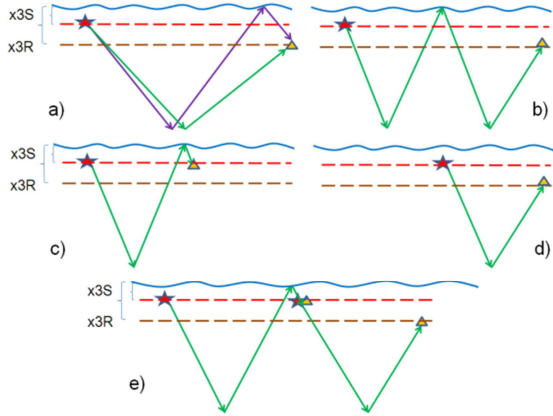# Surface-Related Multiple Elimination for Variable-Depth Streamer Acquisition

Figure 1: a) The ray-path constituents recorded at the streamers (ignoring the source ghost), b) The multiple ray-path constituent to be predicted, present in the upgoing wavefields, c) The downgoing and d) upgoing ray-path constituents, obtained through wavefield decomposition, and e) The upgoing multiple ray-path constituent obtained from convolving (c) and (d). Note that the downgoing wavefield (c) has been back-propagated as it would have been recorded at the source depth. The obtained multiple in (e) is then readily to be subtracted from the computed upgoing wavefield at the receiver depth.
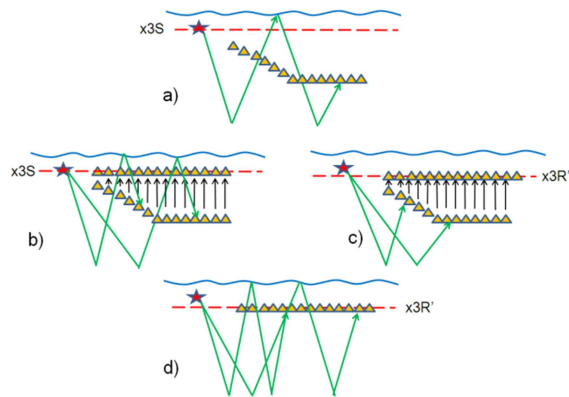
Figure 2: a) The upgoing multiple ray-path constituent to be predicted, b) The downgoing ray-path constituent obtained through wavefield decomposition at the source depth , c) The upgoing ray-path constituent obtained through wavefield decomposition at a constant receiver depth of choice , d) The upgoing multiple ray-path constituent obtained from convolving (b) and (c), at constant receiver depth of choice.
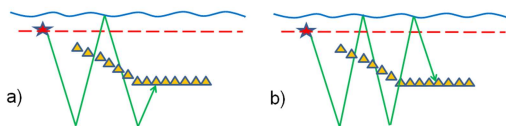

Figure 3: a) The upgoing multiple ray-path constituent to be predicted, b) The downgoing ray-path constituent to be predicted.
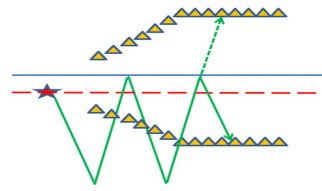

Figure 4: The same downgoing ray-path constituent as in Figure 3b, but now as it would have been recorded by receivers located at mirrored positions from the sea surface.
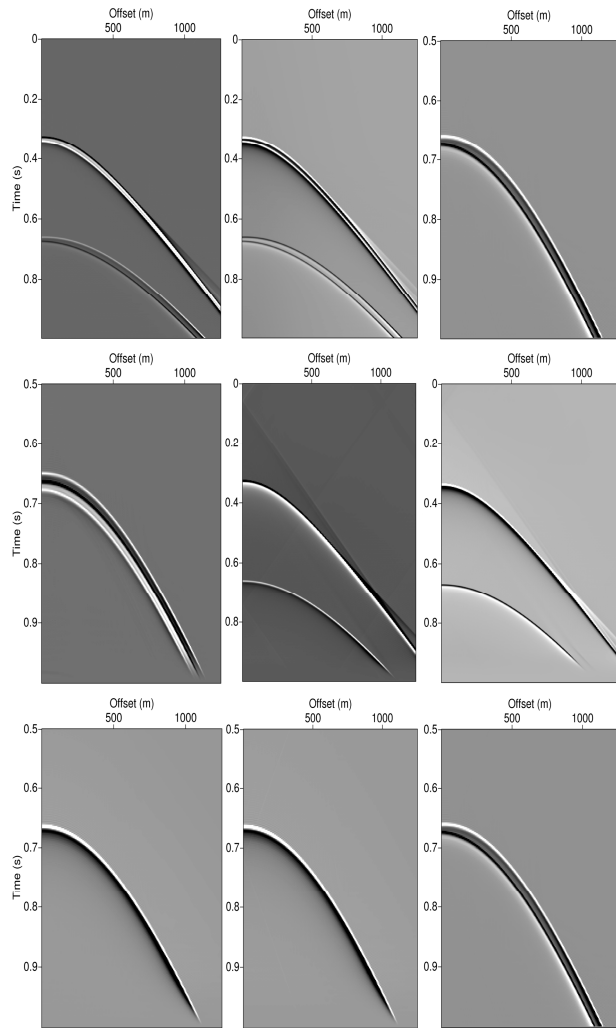

Figure 5: a-b) The modeled scattered pressure and vertical component of the particle velocity wavefield measured with a tilted streamer, c) the corresponding pressure wavefield multiples, d) the result from auto-convolution of the scattered pressure wavefield, e-f) the upgoing pressure wavefield and downgoing vertical component of the particle velocity wavefield measured at the source depth of 10m, g) the predicted multiple obtained from convolution of the results from Figure 5e and 5f, h) the modeled pressure wavefield multiple at reference depth of 10m, i) the predicted multiple scattered pressure wavefield after summing the results after forward and backward propagation of the result from Figure 5g.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2013 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Fokkema, J. T., and P. M. Van den Berg, 1993, Seismic applications of acoustic reciprocity: Elsevier.

Riyanti, C. D., R. G. Van Borselen, J. T. Fokkema, and P. M. Van den Berg, 2009, Method for full-bandwidth deghosting of marine seismic streamer data: U. S. Patent Application 20110110189.

Soubaras, R., and R. Dowle, 2010, Variable-depth streamer — A broadband marine solution: First Break, **28**, 89–96.

Tenghamn, R., and P. E. Dhelie, 2009, GeoStreamer — Increasing the signal-to-noise ratio using a dual-sensor towed streamer: First Break, **27**, 45–51.

Van Borselen, R. G., R. Hegge, T. Martin, S. Barnes, and P. Aaron, 2011, Enhanced demultiple by 3D SRME using dual-sensor measurements: The Leading Edge Aug, **30**, no. 8, 920–926.

Van Borselen, R. G., J. T. Fokkema, and P. M. Van den Berg, 2013, Wavefield decomposition based on acoustic reciprocity: Theory and applications to marine acquisition: Geophysics, **78**, no. 2, WA41–WA54.