

Derivation of Statistical Sea-surface Information from Dual-sensor Towed Streamer Data

T. Klüver* (PGS Geophysical AS) & H. Tabti (PGS Geophysical AS)

SUMMARY

Multi-component towed streamer data allow for separation of the up-going and down-going wavefields and, thus, sea-surface independent removal of the receiver side ghost. To achieve deghosting of conventional (pressure-only) data, assumptions about the sea-surface state have to be made in order to describe the deghosting operator. Typically, a flat free sea-surface with a reflection coefficient of -1 is assumed. Since wavefield separation from multi-component seismic towed streamer recordings can be performed independently of the sea-surface state, the latter can be inferred from the data. In this paper, we show a method to derive statistical information about the sea-surface state from separated wavefields. We will extract the statistical ghost operator from the data and derive parameter values fitting a sea-surface model. The extracted statistical ghost operator will be compared to actual ghost operators found in the data.

Introduction

The introduction of multi-component towed streamer acquisition allows for separation of the up-going and down-going wavefields and, thus, removal of the receiver side ghost from towed streamer data. This separation is independent of the sea-surface state in contrast to deghosting single-component (typically pressure) recordings. To achieve the latter, assumptions about the sea-surface state have to be made in order to describe the deghosting operator. Typically, a flat free sea-surface with a reflection coefficient of -1 is assumed. Since wavefield separation from multi-component seismic towed streamer recordings can be performed independently of the sea-surface state, the latter can be inferred from the data. Orji et al (2010) have shown how to derive the actual sea-surface state for every shot record using an imaging technique. In this paper, we show a method to derive statistical information about the sea-surface state from separated wavefields. We will extract the statistical ghost operator from the data and derive parameter values fitting a sea-surface model.

Method

The method is based on deconvolving the up-going wavefield from the total wavefield and averaging the resulting ghost operators over a range of seismic records. The deconvolution is not performed for entire records but restricted to short time windows covering a couple of events. Since there is no need to consider a range of offsets to derive statistical information about the sea-surface, the following description of the method is made for a single near-offset. We use a dataset acquired in deep water with 20 m streamer depth to outline the methodology and we consider the sea-floor reflection event. Since the water depth (more than two seconds two-way time) is very much greater than the offset, the reflected wavefield from the sea-floor emerges at the receiver very close to vertically. To extract statistical information about the sea-surface, we use extracted wavelets obtained by aligning the sea-floor reflection event for a range of shots and stacking the aligned traces. Wavefield separation is performed using the extracted wavelets from collocated pressure and vertical particle velocity recordings.

In the first step, the up-going part of the reflection event is aligned for a range of shots. Since all sea-surface effects are recorded in the down-going part, the up-going part will sum constructively in the wavelet extraction process whereas sea-surface variations lead to partially destructive summation for the down-going part.

The alignment is done in two steps:

1. Align the centre between the up- and down-going parts for all traces by determining appropriate time shifts from cross-correlating all traces with a chosen reference trace. The cross-correlation is performed for a window containing both the up- and down-going parts of the selected event.
2. Align the up-going parts for all traces in the same way as in step 1 but using a restricted window containing only the up-going part of the selected event.

Obviously, this alignment could be performed in one step. However, the extracted time shifts for step 2 provide independent information about the sea-surface since they are equal to half of the change in ghost period from the chosen reference trace. There is an ambiguity between sea-surface variations and variations in receiver depth which have identical effects on the ghost period. The navigation information in the data used for this paper does not suggest any rapid streamer depth variations causing time variations as large as observed in the data. These time shifts are therefore attributed mainly to sea-surface variations. Figure 1 shows details of the sea-floor reflection event in the pressure data after aligning the up-going part.

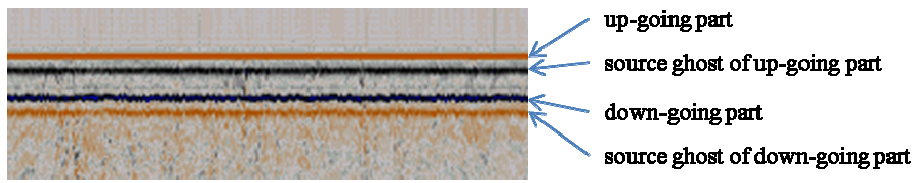


Figure 1: The sea-floor reflection event aligned for the up-going part of the wavefield. The fluctuations in the down-going part are primarily due to changes in the sea-surface elevation.

In the next step, wavefield separation is performed on the extracted wavelets. In principle, wavefield separation requires plane wave decomposition (Fokkema and v. d. Berg, 1993). However, since the wavefield emerges very close to vertically at the receiver for all shots at the offset considered in this case, and given that we are considering an event with a large propagation distance such that the difference in geometrical spreading between the up-going and down-going parts is negligible, the separation can be performed correctly without plane wave decomposition. Figure 2 shows the up-going and down-going wavelets.

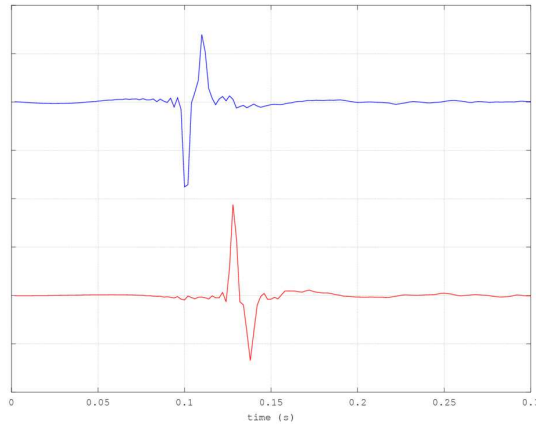


Figure 2: Extracted wavelets after wavefield separation. The up-going wavelet is shown in blue and the down-going wavelet is shown in red.

In the final step, the up-going wavelet is deconvolved from the pressure wavelet. This yields the statistical ghost function (for vertical incidence angle) present in the considered range of shots directly. A chosen model describing the statistical sea-surface can be fitted to the extracted ghost operator which yields values for the parameters describing the sea-surface model. We choose to use the Rayleigh model for the sea-surface reflection coefficient r (Brekhovskikh and Lysanov, 2003) in the description of the ghost operator:

$$r = -e^{-2*(\sigma\omega/c)^2}, \quad (1)$$

where σ is the root-mean-square (RMS) sea-surface height, ω is angular frequency, and c is the wave propagation speed in water. With this frequency dependent sea-surface reflection coefficient the pressure ghost operator for vertical incidence is given by

$$G_p(\omega) = 1 + re^{-i\omega 2z_R/c}, \quad (2)$$

where z_R is receiver depth from mean sea level.

Results

The deconvolution of the up-going wavelet from the total pressure wavelet yields the statistical pressure ghost operator present in the selected range of shots. Its amplitude and phase spectra are

shown in Figure 3. Also shown in Figure 3 is the best fit theoretical ghost operator curve from equation 2.

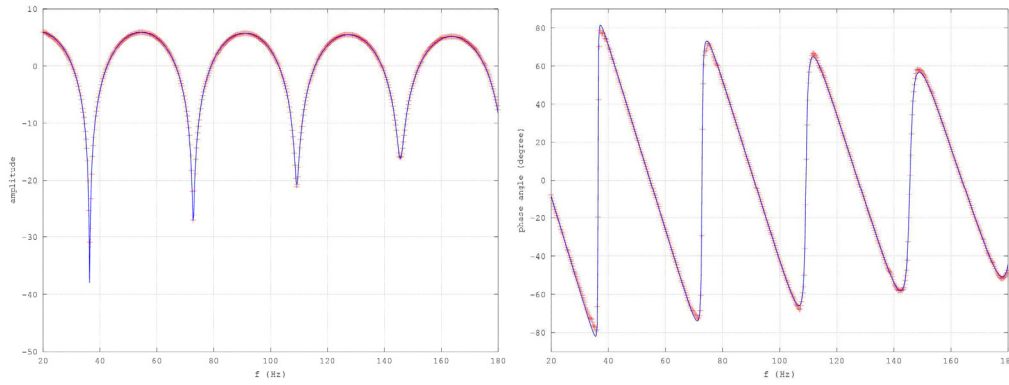


Figure 3: Amplitude (left) and phase (right) spectra of extracted (red +) and fitted (blue) ghost operators.

Figure 3 clearly demonstrates the excellent fit between the statistical ghost operator extracted from the data and the modelled ghost operator following the Rayleigh model for the sea-surface reflection coefficient. This fit was achieved using a RMS sea-surface height of $\sigma = 0.47$ m in the modelling. The corresponding Rayleigh reflection coefficient at the sea-surface is shown in Figure 4.

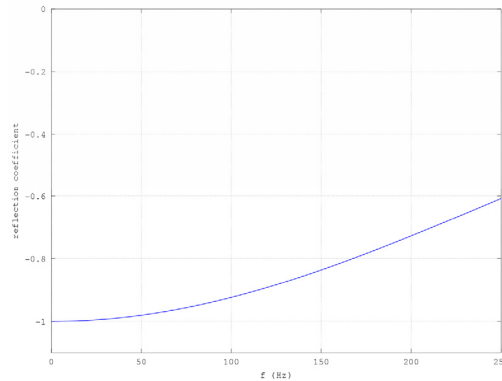


Figure 4: The Rayleigh reflection coefficient as a function of frequency of the sea-surface which yields a best fit ghost operator to the statistical ghost operator extracted from the data.

The extracted RMS sea-surface height is confirmed by an analysis of the time shifts extracted while aligning the up-going part of the wavefield. These time shifts, when converted to distance using the acoustic wave propagation speed in water, directly represent the sea-surface elevation as outlined in step 2 in the description of the alignment process. Figure 5 shows a histogram of the extracted elevation values (normalized such that the sum of all bars is one). A subjective fit of a Gaussian function, accommodating both height and width of the histogram, suggests a standard deviation, i.e. RMS sea-surface height, of 0.42 m which is very close to the extracted value of 0.47 m.

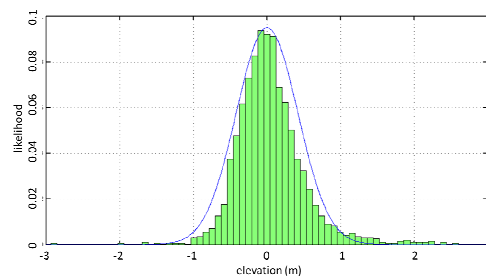


Figure 5: Histogram of extracted time shifts. A Gaussian with a standard deviation of 0.42 m fits the distribution well.

Figure 6 shows some pressure data before extracting a wavelet, i.e. at single trace level. As can be seen, all receiver side notches are deep but the distribution of notch frequencies due to sea-surface variations increases with increasing frequency. This effect causes the decrease in absolute value of the statistical reflection coefficient with increasing frequency and less deep spectral notches in a statistical sense.

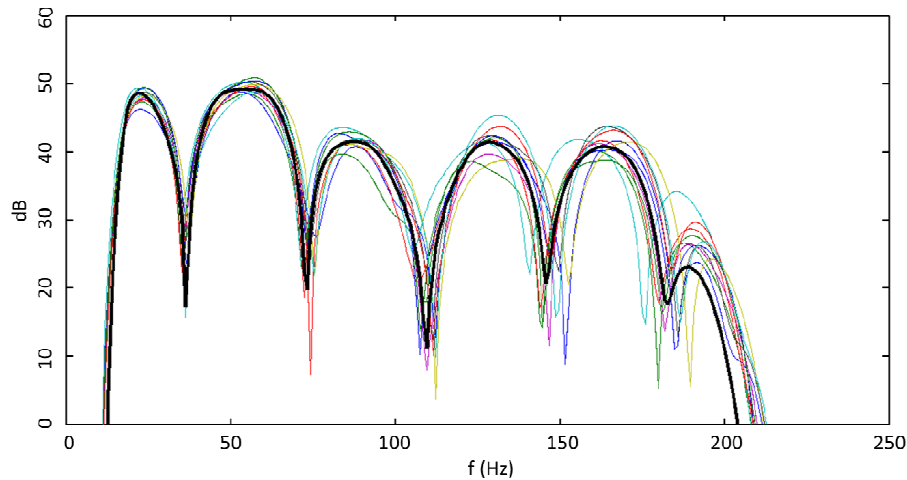


Figure 6: Single trace spectra of selected hydrophone traces. The corresponding average up-going wavefield convolved with the statistical ghost operator is overlaid.

Conclusions

In this paper we presented a method for extracting statistical ghost operators from multi-component towed streamer data. The method uses the fact that the up-going and down-going parts of the wavefield can be separated without assumptions about the sea-surface. Hence, the sea-surface state can directly be inferred from the data. The results indicate a RMS sea-surface height of close to 0.5 m in the example shown. The individual spectral notches in the data, however, are deep. They are distributed over a range of frequencies due to sea-surface variations. This distribution gets larger with increasing frequency resulting in less deep spectral notches in the statistical ghost operator. In this example, even notches in the statistical pressure ghost operator are very deep, which presents a challenge for deghosting pressure-only data across notches.

Acknowledgements

The authors thank PGS for permission to publish this work.

References

Brekhovskikh, L. M. and Lysanov, Yu. P., [2003] *Fundamentals of Ocean Acoustics*, Springer, New York

Orji O. C., W. Söllner and L-J. Gelius [2010] Imaging the sea surface using dual-sensor towed streamer, *Geophysics* 75, V111 – V1118

Fokkema, J. and v. d. Berg, P., [1993] *Seismic Applications of Acoustic Reciprocity*, Elsevier, Amsterdam