Comparison of methods for rough sea-surface estimation

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Summary

Marine seismic data acquired in rough sea conditions present a challenge to successful processing due to the time- and space-dependent perturbations introduced at the source and the relative timing of the ghost at the receivers. It is possible to partially correct for these perturbations via stochastic treatments based on an assumed sea-state, but a more complete deterministic correction requires that we obtain the height profile of wind-driven waves at the surface or some approximation to it. Here we make a comparison of known methods for the estimation of such a profile and discuss some of the practical aspects and limitations in the context of receiver-side de-ghosting. We derive surfaces from a 3D shot record via ghost interference and via low-frequency signal and use these to de-ghost the data. We find generally good correlation between surfaces and in both cases there is uplift in de-ghosting quality when comparing to a flat-sea assumption. The interference method gives greatest improvement at the event from which it is derived but is not suited to generalizing for all times and offsets. The low-frequency method has the advantage in this respect. We propose a hybrid methodology to overcome some of the limitations identified.

Introduction

Marine seismic data acquired in rough sea conditions present a challenge to successful processing due to the time- and space-dependent perturbations introduced at the source and the relative timing of the ghost at the receivers. It is possible to partially correct for these perturbations via stochastic treatments based on an assumed sea-state (e.g. Jovanovich 1983), but a more complete deterministic correction requires that we obtain the height profile of wind-driven waves at the surface or some approximation to it. Here we make a comparison of known methods for the estimation of such a profile and discuss some of the practical aspects and limitations, followed by a suggestion for a hybrid methodology to overcome some of the limitations identified.

Estimation of a sea-surface profile via features in the ghost spectrum surrounding an event and using operators that incorporate this information has been shown to provide uplift in the quality of de-ghosting (e.g. Grion *et al*. 2016). However this approach is not easily generalized for all events, since the sea-surface profile evolves with time and position and estimation can become difficult for far offsets, shallow water surveys and where the geology surrounding the event is complex. The low-frequency signal may be used to overcome some of these difficulties, since it encodes the surface wave height. Kragh *et al.* (2004) pointed to the potential of such an approach and made use of a surface derived this way but independent verification of the surface and comparison of its use in de-ghosting versus the flat-sea assumption were not available.

Explicit estimation of rough-sea corrections

In principle, with the time-dependent sea-surface profile known above the hydrophones, it is possible to completely correct for the rough sea effect on the ghost and make any static corrections to the source position. A number of methodologies have been described to estimate the required rough-sea timing corrections and also the explicit form of the surface profile:

- Ghosted spectrum: using the deviation in the frequency of the ghost notch(es) in the amplitude spectrum of the seismic data. (e.g. Hardwick et al. 2015, Grion *et al.* 2016).
- Cross-correlation: for primary and re-datumed ghost event (King and Poole, 2015)
- Low frequency signal: use signal recorded directly due to the passage of waves over the hydrophone (Cavaleri 1980, Kragh *et al.* 2002 and Laws and Kragh 2006). This is the most direct method to estimation of the surface profile.
- Kurtosis maximisation: data-adaptive search for optimum time delay based on a statistical objective function (Grion *et al.* 2015). Identifies timing corrections to apply (either to *x-t* or τ-*p* traces stabilised over a window), enabling a rough-sea surface profile to be inferred.

We focus our attention on the spectral notch and low frequency signal to examine correspondence, robustness of estimation and to understand better the limitations of each approach.

Ghosted spectrum

In rough sea conditions the ghosted *f-x* spectrum taken over a short window surrounding an isolated picked event (usually the water-bottom) will show interference nulls that deviate from the frequency expected for a flat sea. This frequency, f_{flat}, is estimated from the angle of arrival, θ (e.g. calculated from the derivative of picked two-way-time) and the reported receiver depth. The frequency deviation can be attributed to a variation in the surface wave amplitude:

$$S_z = \frac{c}{2\cos\theta}\left(1/f - 1/f_{flat}\right) \qquad (1)$$

This approach can be further refined and stabilised by a tomographic update to take account of non-vertical propagation (since the delta recorded at a particular channel may not be due to the height change directly above the streamer), joint picking of 1st and higher-order interference nulls as available and joint picking of the interference null and turning-point in the phase spectrum (Grion *et al*. 2016).

Low frequency signal

The low frequency signal in the raw data may be used to infer wave height using the linear theory of deep-water surface waves (Kinsman 1965). Cavaleri (1980) discusses estimation of wave height using pressure recordings at a depth below the surface and Kragh and co-authors (2002, 2006) apply this method to a seismic streamer spread composed of many hydrophones. The departure from mean hydrostatic pressure that is measured at the hydrophone due to the presence of a wave overhead (ignoring the constant components due to cyclical x and z particle velocities and translational x particle velocity) is given by:

$$\Delta p = \rho g S_z e^{-kz} \cos(kx - \omega t) \qquad (2)$$

Where k is the wavenumber, z is the depth below the mean sea-level of the hydrophone and S_z is the amplitude of the sea-surface wave height. Deep water waves are described by the dispersion relation: $\omega^2 = gk$. The recorded pressure due to the surface waves decreases exponentially with depth and will decay more rapidly for larger k (smaller wavelengths), so although it is possible to unwrap *Sz* from the data, we will reach the noise floor more quickly for short wavelengths and deep cables. To sample the low frequency signal properly it is important to use a long time record e.g. concatenating a few shot records made from a continuous recording.

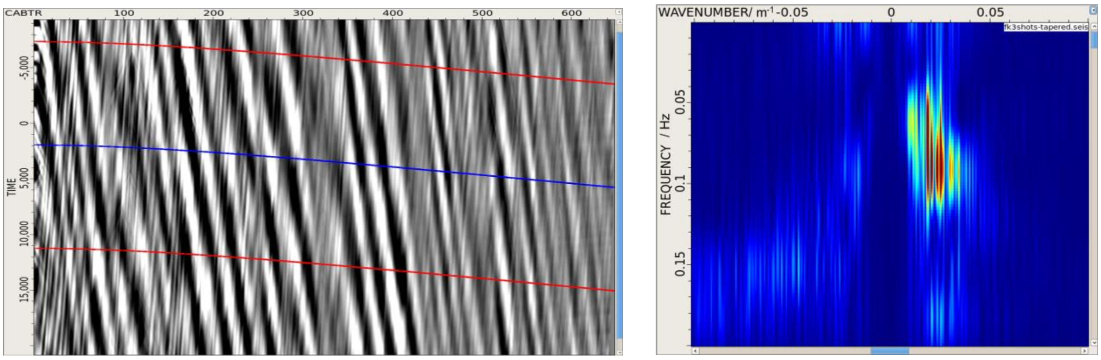

Figure 1 *Three consecutive shots records (central cable) (left) showing dominant swell noise. The blue curve is the timing of the water bottom for the central shot used to extract the wave amplitudes. The corresponding f-k spectrum (right) shows the waves energy peaks in the range 0.07-0.1 Hz.*

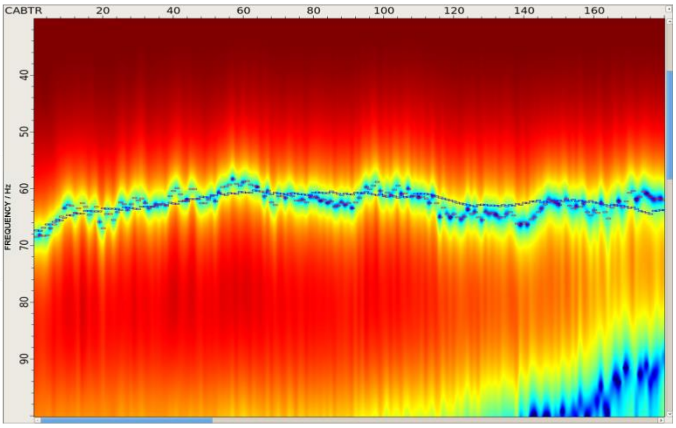

Figure 2 *Ghosted f-x spectrum around the water-bottom of the central of the three shots showing picked and reference (flat-sea) interference nulls. The deviation of notch from the reference line is used to calculate a depth deviation using equation (1) which is attributed as the wave height.*

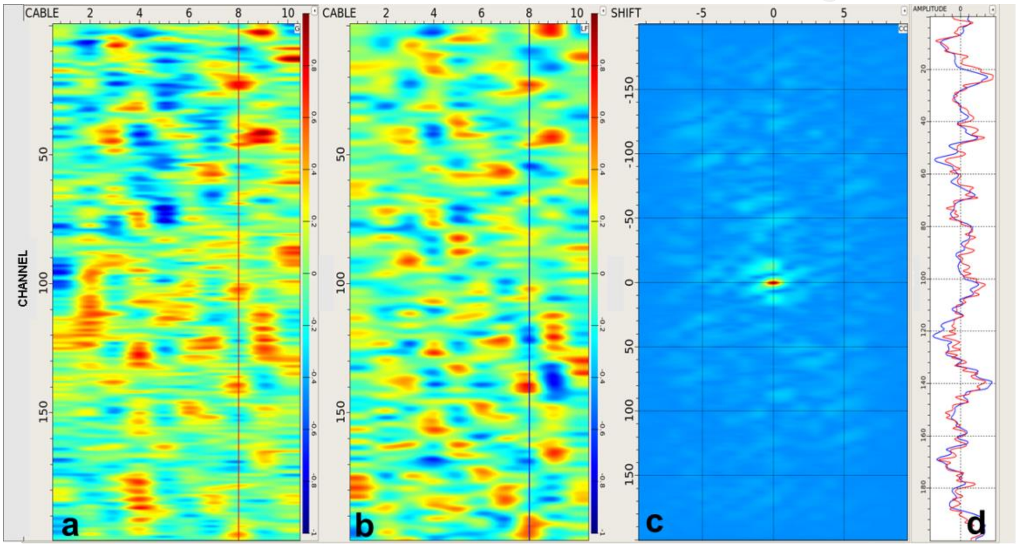

Figure 3 *Estimated sea-surface heights in metres obtained via ghost (a), via low-frequency signal using equation 2 (b) and their 2D cross-correlation (c), together with an amplitude slice of the surface (d) for cable 8 where the blue line is from low-frequency signal and red from ghost interference. Only the first 200 channels are shown here for clarity and the aspect ratio is chosen to be approximately 1:1 for distance.*

Data example

The data are from a 3D acquisition, with 10 cables, spacing 150 m, each with 648 grouped channels, 12.5 m group spacing and receiver depth slanting linearly over 12-28 m. To sample the low-frequency signal we used a rolling gather of three consecutive shot records at a time, corresponding to 30 s duration. Receiver motion correction was applied and the 2 Hz analogue first-order high-pass was backed-off. We then derived surfaces and de-ghosted the data. Figure 1 shows the group of three shot records and the corresponding *f*-*k* spectrum indicating a peak in the surface wave energy around 0.08 Hz and wavenumber 0.02 m^{-1}, corresponding to a wavelengths around 300 m. Figure 2 shows the *f*-*x* spectrum for a 100 ms window around the water-bottom on the central shot record after low-cut filtering to reveal the seismic signal. The surface profile from the low-frequency signal is extracted at the water-bottom time for comparison with the profiles derived via the ghosted spectrum.

A strong correlation peak is observed suggesting good agreement between the two derived surfaces. Both surfaces improve the de-ghosting with respect to the flat-sea approximation. However, the surface derived via the ghosted spectrum provides greatest uplift (Figure 4) appearing to capture finer wave structure or other features of the propagation process. The surface is derived from a reflection and interference process and the Fresnel zone at the surface (i.e. those points that correspond to a distance from the hydrophone approximately within a quarter wavelength of each other) is some 28 m in diameter at normal incidence for 60 Hz signal and 12.5 m hydrophone depth, so some spatial averaging of the waves will inevitably take place. This approach will also capture uncertainties in the underwater propagation environment close to the streamer which may affect de-ghosting, and which are not fully captured in the low-frequency signal. Local sound speed is influenced by temperature and salinity fluctuations, which can be significant in some environments and reported receiver depth (usually a time-averaged reading) may be in error due to transient motion of the cable. The surface derived via low-frequency signal has a noise floor associated with turbulent water motion in the vicinity of the streamer and appears subject to greater temporal averaging, missing some of the fine-structure in the waves pertinent to de-ghosting.

Conclusions

There is good agreement between the surface profiles derived via two very different approaches and both provide some uplift when compared to de-ghosting under the assumption of a flat-sea-surface. A potential advantage of using the low frequency signal is that it overcomes issues inherent in the ghost spectrum method i.e. it can be generalized for all times and can be applied when there is a lack of clear, isolated reflection events e.g. shallow water.

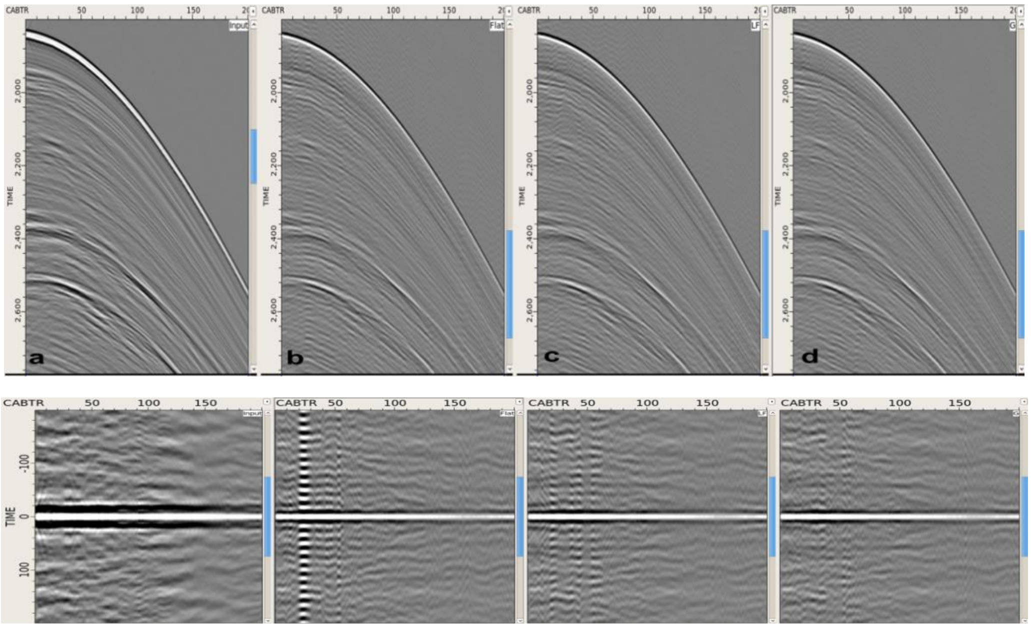

Figure 4 *Input (a), de-ghosted assuming flat sea-surface (b), using low-frequency-derived surface (c) and using ghost-derived sea-surface (d). The figures underneath show the respective autocorrelations.*

The downside is the apparently slightly poorer resolution in describing the reflection surface. A potentially fruitful hybrid approach would be to use the low frequency signal as a guide for stabilising and reducing the search range in a data-adaptive method such as kurtosis maximization (Grion *et al.* 2015). With such a guide it could be performed on a trace-by-trace basis instead of over shot-averaged windows and since it is applicable to overlapping time windows down the trace it does not suffer the limitations of methods using single picked events.

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