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Recent Advances in Hydrophone-Only Receiver Deghosting

G. Poole* (CGG), S. King (CGG), J. Cooper (CGG)

Summary

Many hydrophone-only receiver deghosting approaches assume a stationary free surface profile, or that the data may be represented by linear events within a small spatial aperture. In this paper we propose methods to address these limitations. Firstly, we describe a data-driven methodology to estimate a time-variant free surface profile which may be used in combination with a modified receiver deghosting formulation. Secondly, we propose the use of a tilted hyperboloidal model of the data, which better represents travel-time moveout at short offsets in shallow water regions. Both methods are illustrated on real datasets and demonstrate more effective deghosting than conventional approaches.

Introduction

Free surface ghosts limit the bandwidth of seismic data by introducing notches into recorded amplitude spectra. In recent years, strategies to recover the bandwidth by attenuating free surface ghosts have transformed the market. At the source, multi-level airgun arrays have created diversity in the frequency of the ghost notches (Siliqi et al., 2013). At the receiver, several acquisition approaches have been proposed; for example, dual-level streamers (Sønneland et al., 1986), variable depth streamers (Soubaras, 2010), and dual-sensor streamers (Carlson et al., 2007). Many processing approaches have also been developed, used either in combination with the acquisition schemes outlined above, or with conventional hydrophone-only, horizontal tow measurements. Among others, two assumptions often made in hydrophone-only receiver deghosting may degrade results; firstly, that the free surface datum is stationary in time, and secondly, that the wavefield travel-time varies approximately linearly with local changes in offset. This paper addresses these assumptions and shows that receiver deghosting results may be improved by incorporating a time-variant sea surface, and by allowing wavefield travel-times to increase hyperbolically with offset.

Time-variant sea surface

Many receiver deghosting algorithms assume that the free surface is horizontal (Poole, 2013; Wang et al., 2014a). While this assumption may be valid in good weather conditions or at low frequencies, in other cases, significant variations in the sea surface datum are observed. This can compromise deghosting algorithms, leading to signal damage and residual ghost energy in the output. Although the free surface profile may be estimated from very low frequency data (Kragh et al., 2002; Telling and Grion, 2017), in many cases, such recordings will be unreliable due to noise contamination. King and Poole (2015) proposed a data-driven response to this problem. The first step estimated a spatially varying free surface profile using mirror wavefield extrapolation, followed by cross-correlation picking. The second step incorporated the free surface profile into a modified deghosting algorithm. We extend the approach to consider a sea surface profile varying in both space and time.

The proposed approach begins by repeating the cross-correlation step described by King and Poole (2015) but using a sliding cross-correlation time window. Figure 1a shows a shot gather acquired offshore Ireland using 14 streamers separated by 100 m and towed at a 12 m depth. Figure 1b shows the corresponding raw wave heights using the sliding window approach; while this captures variations in ghost timing, the measurements are reliable only where the signal-to-noise ratio is high. Hence, wave heights relating to data with a low signal-to-noise ratio are reconstructed from wave heights relating to data with a high signal-to-noise ratio, as shown in Figure 1c. Kragh et al. (2002) demonstrated that sea surface profiles can be derived from very low frequency hydrophone recordings, and we note that the reconstructed wave height profile shown in Figure 1c is consistent with the recorded data below 0.5 Hz shown in Figure 1d.

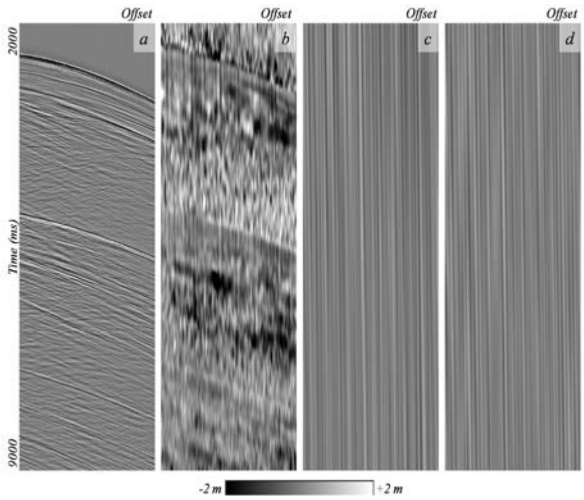

Figure 1 *Time-variant wave height calculations: a) input data, b) raw wave height profile, c) reconstructed wave height profile, and d) very low frequency data (below 0.5 Hz).*

Based on the notation of Poole and King (2016), we may implement receiver deghosting of time-space shot domain data, d, for a spatially varying sea surface datum by solving the inversion problem,

$$d = F^{-1} L_{\tau p} F m_{\tau p}, \quad (1)$$

in which the linear operator, $L_{\tau p}$, is defined by:

$$L_{\tau p} = L_{\tau p U} + L_{\tau p D}, \text{ where } L_{\tau p U} = e^{-2\pi i f (x p_x + y p_y - z p_z)} \text{ and } L_{\tau p D} = R e^{-2\pi i f (x p_x + y p_y + (z+w) p_z)}. \quad (2)$$

Here, F is a Fourier transform operator from time to frequency domain, and f is temporal frequency. $L_{\tau p U}$ and $L_{\tau p D}$ are linear operators transforming the frequency domain model to up-going and down-going frequency domain data respectively, and $m_{\tau p}$ is a $\tau - p$ model of up-going energy at constant free surface datum, to be found by inversion. R is free surface reflectivity (we may take $R = -1$, for example), (x, y, z) is the location of a receiver relative to a source, w is the free surface datum for each trace, (p_x, p_y) is $\tau - p$ slowness, and vertical slowness, p_z, may be computed using the expression $\frac{1}{v_w^2} = p_x^2 + p_y^2 + p_z^2$, where v_w is the water velocity.

We modify the formulation of Equation (1) by assigning the time-variant wave height values to a range of wave height bins, b, for example of size equal to 0.1 m. A time-space domain mask operator, $W(b)$, for each wave height bin then selects the time samples for each trace that require a given wave height correction. The masking may then be incorporated into the inversion equation as follows:

$$d = \sum_b W(b) F^{-1} L_{\tau p}(b) F m_{\tau p}. \qquad (3)$$

After the model, $m_{\tau p}$, has been found, we estimate the deghosted data, u, by subtracting the corresponding ghost model from the input data: $u = d - \sum_b W(b) F^{-1} L_{\tau p D}(b) F m_{\tau p}$. The approach may be extended to use model domain sparseness weights, for example as described by Trad et al. (2003). It may also be modified to incorporate multi-sensor streamer recordings, for example following Poole (2014) or Wang et al. (2014b).

Figure 2 compares receiver deghosting results for the data introduced in Figure 1. The upper panels show events at the water-bottom reflection and the lower panels show events at the first-order water-bottom multiple. Figures 2a and 2b show the input data before receiver deghosting, clearly illustrating a wave height effect on the timing of the receiver ghost. Figures 2c and 2d show the deghosting result assuming a horizontal free surface. The artefacts introduced on the output highlight the weakness of the horizontal free surface assumption in this case. Receiver deghosting, incorporating a static wave height correction, suppresses the artefacts around the water-bottom primary (Figure 2e), but not at the multiple (Figure 2f), due to the change in sea surface conditions over time. Figures 2g and 2h show the receiver deghosting results from the proposed method. By incorporating a time-variant sea surface, it is evident that we obtain better clarity and consistency over time, which is highlighted by improved deghosting of the first-order water-bottom multiple (Figure 2h).

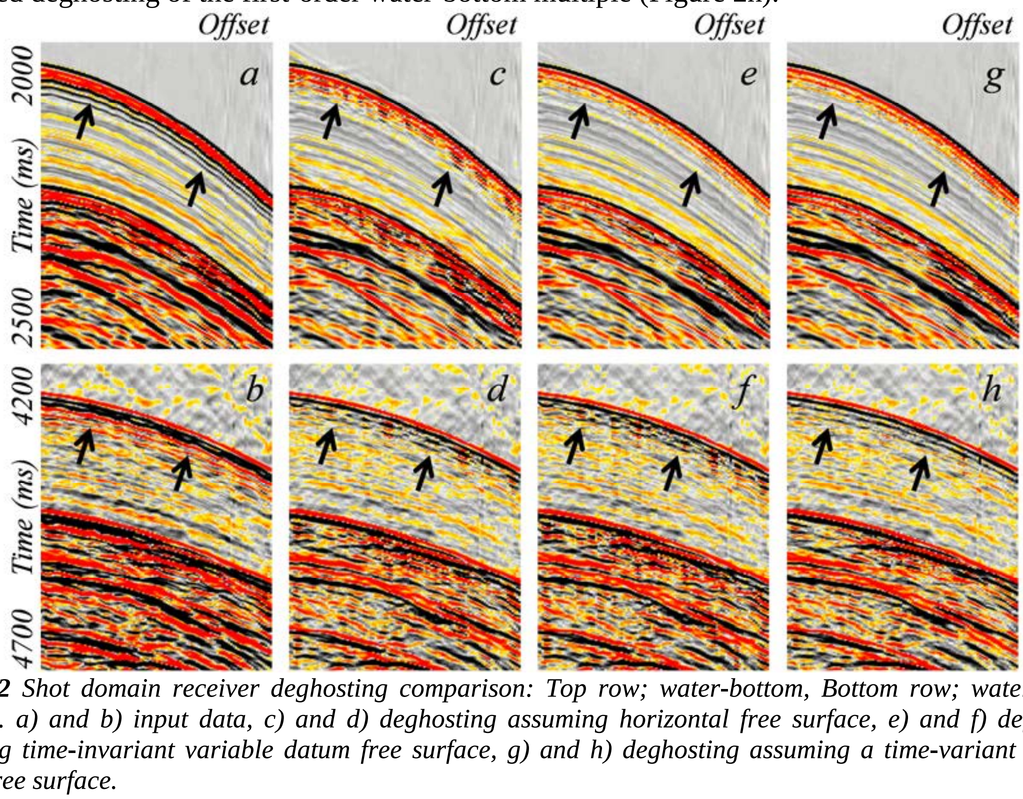

Figure 2 *Shot domain receiver deghosting comparison: Top row; water-bottom, Bottom row; water-bottom multiple. a) and b) input data, c) and d) deghosting assuming horizontal free surface, e) and f) deghosting assuming time-invariant variable datum free surface, g) and h) deghosting assuming a time-variant variable datum free surface.*

Assumption of travel-time linearity

Many multi-channel receiver deghosting approaches make an assumption of travel-time linearity within small spatial windows, for example using $\tau - p$ (Poole, 2013) or $f - k$ representations of the data. While this assumption is reasonable in many cases, deghosting of the highly curved near offsets acquired in shallow water regions may lead to suboptimal results. Consequently, we propose a hyperboloidal model representation, $m_{\tau v p}$, of the data. As hyperbolae support travel-times relating only to a 1D geology, we allow hyperboloids in the model space to tilt, so as to accommodate moderate variations in geology (for example, dipping layers). This means that the proposed model will be a function of time, hyperbolic moveout, and linear slownesses. For a horizontal sea surface, the least squares inversion problem for the proposed approach is given by:

$$d = F^{-1} L_{\tau v p} m_{\tau v p}, \tag{4}$$

where d and F are as in Equation (1) and the linear operator $L_{\tau v p}$ maps time samples from the τ-v-p domain to tilted hyperboloidal events in the space-frequency domain, with phase shifts defined by:

$$L_{\tau v p} = L_{\tau v p U} + L_{\tau v p D} \text{ , where } L_{\tau v p U} = e^{-2\pi i f(\tau_{xy} - \tau_z)} \text{ and } L_{\tau v p D} = R e^{-2\pi i f(\tau_{xy} + \tau_z)}, \tag{5}$$

$$\tau_{xy} = \tau_v + p_x x + p_y y, \text{ where } \tau_v = \sqrt{\tau^2 + \frac{x^2 + y^2}{v^2}}, \text{ and} \tag{6}$$

$$\tau_z = p_z z, \text{ where } \frac{1}{v_w^2} = \left(p_x + \frac{d\tau_v}{dx}\right)^2 + \left(p_y + \frac{d\tau_v}{dy}\right)^2 + p_z^2. \tag{7}$$

τ is the zero offset arrival time, τ_{xy} is the arrival time based on the surface offset (x, y), τ_z is the ghost delay associated with the cable depth, z, and v is RMS velocity. Model domain sparseness weights may be used, for example following Trad et al. (2003). Once the model has been found, deghosted data may be obtained by subtracting the time-space domain ghost model from the input: $u = d - F^{-1} L_{\tau v p D} m_{\tau v p}$. Signal not described by the model (for example, strongly apex-shifted diffractions) may be deghosted with a conventional algorithm (for example Poole, 2013).

Figure 3 compares receiver deghosting results for a near offset common channel gather from a 20 m flat tow acquisition in the Norwegian North Sea. Figure 3a shows the input data, Figures 3b and 3c show 3D deghosting results using a linear model and a tilted hyperboloidal model, respectively. An improvement can be seen using the tilted hyperboloidal model, resulting in better resolution.

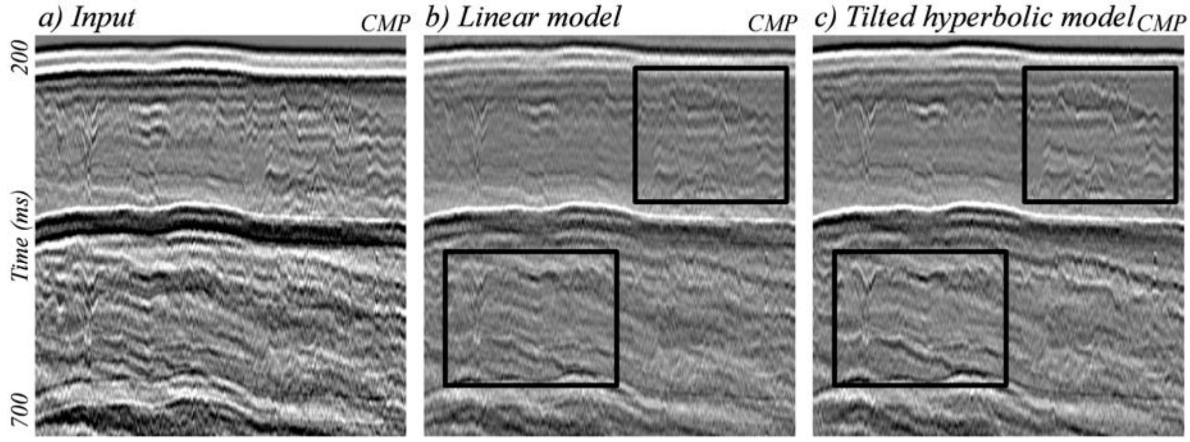

Figure 3 *Near offset receiver deghosting comparison: a) before receiver deghosting, b) 3D receiver deghosting using a linear model, c) 3D receiver deghosting using a tilted hyperboloidal model.*

A second example relates to a dual-vessel acquisition in which the source vessel was placed over the streamer spread to acquire short offset data as well as providing split-spread offsets (Vinje et al., 2017). The variable depth tow resulted in a receiver depth of 35 m beneath the source, giving rise to a longer ghost delay at near offsets than would be observed with conventional acquisition. Figure 4a shows a stacked section before receiver deghosting, Figures 4b and 4c show the corresponding stack after 3D receiver deghosting using a linear and tilted hyperboloidal model, respectively. Significant residual ghost remains when using the linear model, due to the highly curved nature of the pre-stack data at short offsets in this shallow water dataset. The tilted hyperboloidal approximation provides improved results, exhibiting less residual ghost and sharper events with improved continuity.

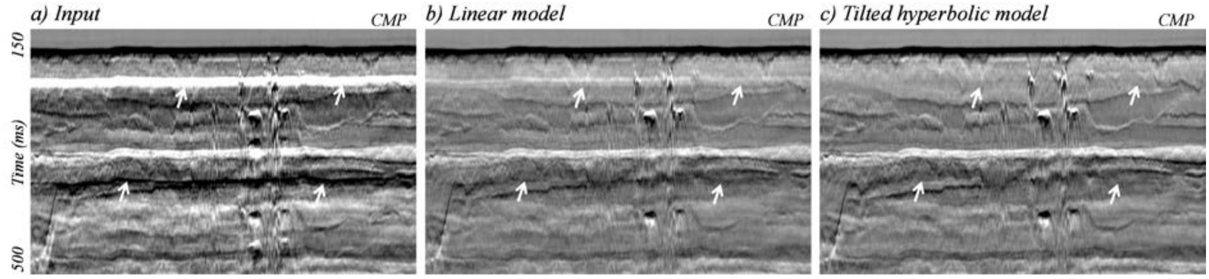

***Figure 4** Receiver deghosting stack comparison a) before receiver deghosting, b) 3D receiver deghosting using a linear model, c) 3D receiver deghosting using a tilted hyperboloidal model.*

Conclusions

Hydrophone-only receiver deghosting relies on knowledge of the ghost delay together with the use of an appropriate model domain. In this paper, we have addressed some of the limitations of existing approaches relating to non-stationary ghost timings resulting from a time-variant free surface profile. In addition, we have proposed the use of a tilted hyperboloidal model domain to respect the moveout of near offset arrivals in shallow water marine data. The proposed methods have been illustrated with real data examples, highlighting their value in producing images with better resolution.

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