Hydrophone-only receiver deghosting using a variable sea surface datum

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Summary

Receiver deghosting algorithms assuming a flat sea surface may be sub-optimal in the case of significant sea surface datum variations. We propose a method that begins by using the seismic data to calculate a sea surface profile. The sea surface profile is then provided to a modified linear Radon inversion scheme to model the receiver ghost. We compare receiver deghosting results using a flat sea surface datum and a variable sea surface datum using a deep water marine dataset. We show that receiver deghosting using a variable sea surface may improve wavefield separation; specifically, the clarity of the shallow reflectors is improved at the higher frequencies.

Introduction

In marine towed-streamer acquisition, receiver ghosts (down-going wavefield) are the reflections which propagate downwards to the sensors after reflection at the sea surface. Receiver ghosts constructively and destructively interfere with the primary (up-going wavefield) recordings at different frequencies giving rise to ghost peaks and ghost notches. For vertical propagation ghost notches occur at frequencies f determined by $f = rc/2z$, where r is the order of the ghost notch, c is the velocity of water and z is the depth of the sensor. For this reason, ghost reflections distort the seismic signal and its associated frequency content leading to a loss in temporal resolution.

Deghosting is the process whereby the source and receiver ghosts are removed from the seismic data. The source ghost can be removed as part of the source designature process (Poole et al., 2013). On the receiver-side, towing variable-depth streamers creates ghost notch diversity, which allows the receiver ghosts to be separated using for example either post migration joint deconvolution (Soubaras, 2010) or pre-migration model-based deghosting (Poole, 2013; Wang et al., 2013). These receiver-side deghosting algorithms assume the sea surface is positioned at the flat sea datum (i.e. z = 0 m). In reality, waves in the ocean will cause the sea surface to vary around this datum. The effect of the sea surface is alleviated by directly combining the hydrophone and particle velocity available from multi-sensor acquisition (Carlson et al., 2007). However, an obliquity correction is required and the particle velocity may introduce noise into the deghosted output.

The sea surface will be affected by waves across a range of spatial wavelengths. Short period waves may cause variations in the sea surface reflectivity away from minus one (Orji et al., 2013). Long period waves, created by weather effects such as wind, may cause datum variation away from the flat sea assumption.

We estimate the variable sea surface datum and show how to include the datum into the deghosting algorithm of Poole (2013). Using a deep water marine dataset, we show a comparison of receiver deghosting using a flat sea surface datum and receiver deghosting using a variable sea surface datum.

Theory and Methodology

Before receiver deghosting is performed, we first estimate the sea surface profile above each sensor. Methods have been proposed to perform this step. Kragh et al. (2002) show that the shape of the sea surface can be derived using very low frequency hydrophone recordings (< 0.5 Hz). This approach requires the low frequencies be correctly calibrated. Orji et al. (2012) attempt to derive the sea surface shape by extrapolating the separated up-going and down-going wavefields (requiring multi-sensor data) towards the sea surface and performing an imaging condition.

In our method we estimate the sea surface datum through a comparison of primary energy and receiver ghost energy. The input primary reflection data is first extrapolated to its mirror datum, assuming a flat sea surface. If the sea surface has a local variation the extrapolated data will not align with the recorded ghost reflection. The time difference implicitly contains information relating to the local variation of the sea surface. The time difference is recovered by cross-correlating the extrapolated primary with the recorded ghost reflection following which it is converted to a sea surface datum in meters. The calculation may be performed in time windows to determine a sea surface profile that varies with time. The very low frequencies from the hydrophone may be used to verify and/or constrain the estimated sea surface datum.

We modify the deghosting algorithm outlined in Poole (2013) to account for the sea surface datum calculations from above. Deghosting is performed by solving the linear Radon equations:

$$d(n) = L(n,m)\,p(m),$$

where $d(n)$ is the input shot where n is the trace number, $p(m)$ is the slowness model where m is the model trace, and $L(n,m)$ is the combined reverse slant and reghosting operator, whose elements are given by,

$$L(n,m) = e^{-2\pi i f \tau_{up}} + R\ e^{-2\pi i f \tau_{dw}} \quad .$$

DOI http://dx.doi.org/10.1190/segam2015-5891123.1

Here, f is the temporal frequency (Hz), R is the sea surface reflectivity (typically minus one) and τ_{up} and τ_{dw} are the time shifts (seconds) of the up-going and down-going components at the sea surface, respectively. The time shift for the up-going component is given by,

$$\tau_{up} = s(m)(h(n) + \Delta h(n,m)) - \Delta\tau(n,m)\ ,$$

where $s(m)$ is the slowness of the m^{th} model trace, $h(n)$ is the offset of the n^{th} trace in the shot record and $\Delta h(n,m)$ and $\Delta\tau(n,m)$ are the offset and time between the plane wave at the sensor and its position at the sea surface, respectively (Figure 1). The incidence angle θ is given by $\sin\theta = s(m)c$ where c is the water velocity. The offset $\Delta h(n,m)$ is defined as $\Delta h(n,m) = z(n)\tan\theta$, where $z(n)$ is the depth of the sensor. The time $\Delta\tau(n,m)$ is defined as,

$$\Delta\tau(n,m) = \frac{\sqrt{z(n)^2 + \Delta h(n,m)^2}}{c}\ .$$

The time delay for the down-going component is given by,

$$\tau_{dw} = s(m)(h(n) - \Delta h(n,m) - \Delta h(n,m)_{sea}) + \Delta\tau(n,m) + 2\Delta\tau(n,m)_{sea}$$

where $\Delta h(n,m)_{sea}$ and $\Delta\tau(n,m)_{sea}$ are the offset and time between the plane wave at the flat sea surface and its measured position on the variable sea surface, respectively, as shown in Figure 1. The offset $\Delta h(n,m)_{sea}$ is defined as $\Delta h(n,m)_{sea} = z_{sea}\tan\theta$, where z_{sea} is the height of the sea surface above zero measured in the previous step and the time $\Delta\tau(n,m)_{sea}$ is given by

$$\Delta\tau(n,m)_{sea} = \frac{\sqrt{z_{sea}^2 + \Delta h(n,m)_{sea}^2}}{c}\ .$$

By setting z_{sea} equal to zero in the equations above, the deghosting algorithm assumes a flat sea surface and is equivalent to that outlined in Poole (2013). Least squares inversion, using conjugate gradients or other solvers, is used to find the model p. The tau-p model p is reversed transformed using the down-going operator to estimate the ghost which is subsequently subtracted from the input data. Note that the implementation described above can be extended to 3D hydrophone-only deghosting (Wang et al., 2014) or data acquired using multi-sensor streamers (Poole, 2014).

There may be inaccuracies in the first estimate of the wave height. For this reason the sea surface profile may be refined in a second iteration using the procedure described above to compensate for errors introduced, for example by 2D extrapolation and other factors.

Data Example

Receiver deghosting was performed on variable-depth streamer data from a deep water marine survey. Figures 2a and 2b show a common shot gather and common channel

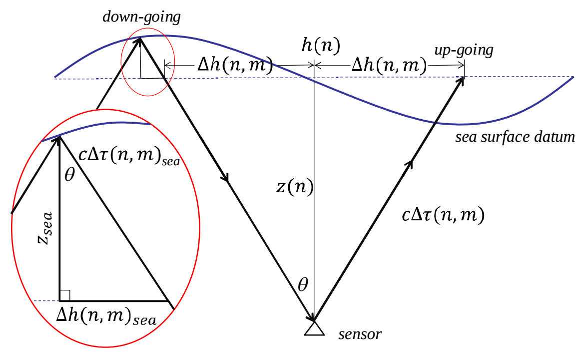

Figure 1: 2D geometry of plane wave propagation

gather at 355 m offset before receiver deghosting. The water-bottom primary reflection is highlighted by the black arrows. The white arrows highlight the ghost reflection following the primary reflection. The variable sea surface caused the ghost reflection to deviate from a hyperbolic traveltime (white arrow in Figure 2a). Figures 2c-2f show the corresponding gathers after receiver deghosting using a flat sea surface datum and after receiver deghosting using a variable sea surface datum, respectively. The sea surface profile in meters is shown above Figure 2a and 2b. Maximum wave height and spatial wavelengths were in the order of ±3 m and 100 m, respectively. It is clear from Figures 2c and 2d that the true character of the ghost was not modelled accurately. This was observed by the presence of ghost residual in the deghosted output (orange arrows). Less ghost residual (orange arrows) and reduced ringing artifacts (yellow arrows) were observed when deghosting was performed using a variable sea surface. Figure 3 shows the amplitude spectrum of the common channel. The red line is the spectrum before deghosting, the blue line is the spectrum after deghosting using a flat sea surface and the green line is the spectrum after deghosting using a variable sea surface, respectively. Both deghosting results show that energy in the ghost notches was recovered. The overall spectra for both strategies were very similar.

Figures 4a-4f show filter panels of the common channel in Figure 2 (blue box) before deghosting, after deghosting using a flat sea surface datum, and after deghosting using a variable sea surface, respectively. The left-hand panel shows frequencies below 40 Hz. The right-hand panel shows frequencies between 40 Hz and 250 Hz. By comparison, the deghosting results were very similar below 40 Hz. Above 40 Hz however, there was less ghost residual present when deghosting was performed using a variable sea surface (orange arrows).

Figures 5a-5c show a stacked section zoom before receiver deghosting, after receiver deghosting using a flat sea surface datum, and after receiver deghosting using a variable sea surface datum, respectively. Figure 5d shows a

DOI http://dx.doi.org/10.1190/segam2015-5891123.1

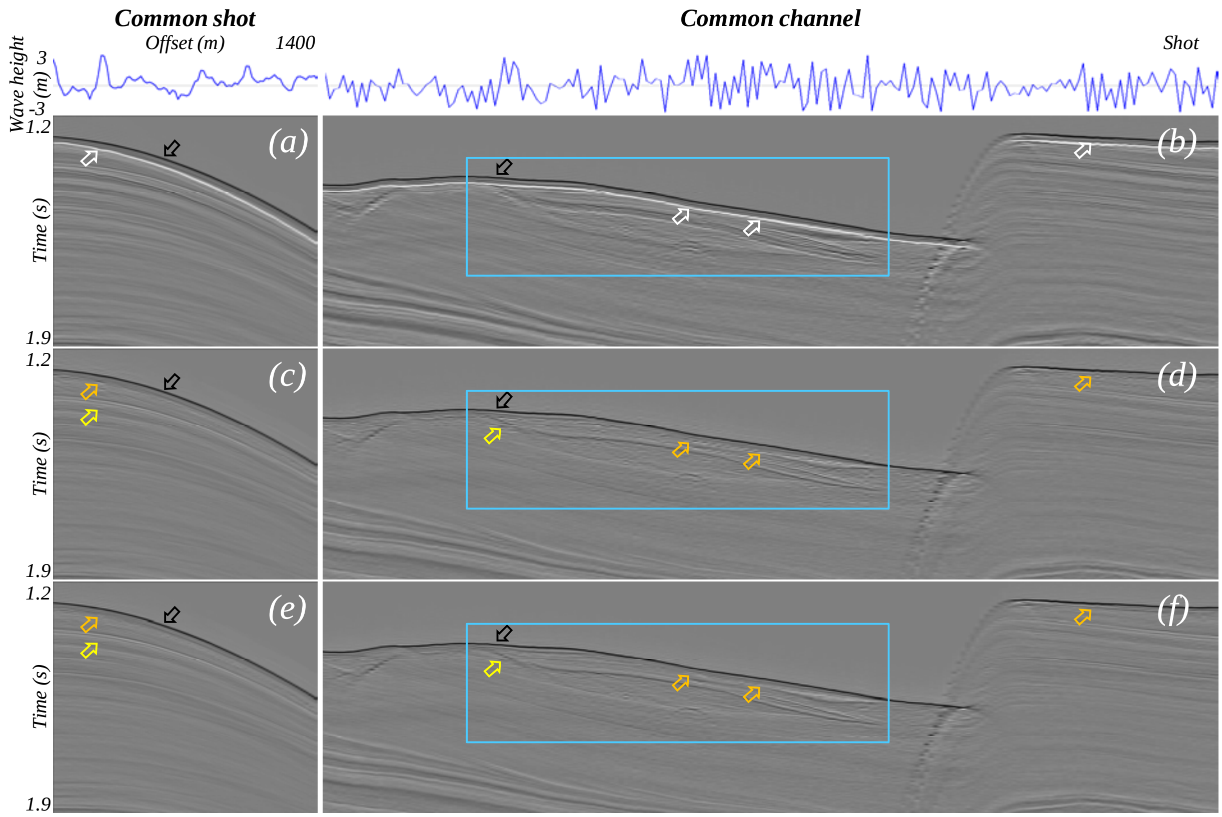

Figure 2: Common shot gather and common channel gather (a) and (b) before receiver deghosting, (c) and (d) after receiver deghosting using a flat sea surface datum and (e) and (f) after receiver deghosting using a variable sea surface datum. Sea surface profile used in the modified deghosting is shown at the top of (a) and (b).

stack of the difference in deghosting. We observe less residual ghost by deghosting using a variable sea surface, particularly in the area defined by the yellow ellipse. Furthermore, we achieved an improved temporal resolution of the shallow reflectors allowing for a better structural estimation of the near surface.

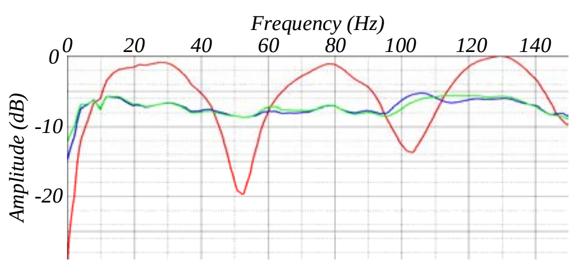

Figure 3: Amplitude spectrum of common channel in Figure 2, (red) before deghosting, (blue) after deghosting using a flat sea surface and (green) after deghosting using a variable sea surface.

Conclusion

We present an extension of hydrophone-only receiver deghosting to incorporate a variable sea surface datum. The method begins by calculating a variable sea surface datum after extrapolation of primary energy to the ghost datum. The sea surface datum is then provided to a modified deghosting algorithm. A field data example demonstrates that deghosting using a variable sea surface exhibits improved wavefield separation over deghosting assuming a flat sea surface. We illustrate that the high frequencies are better recovered and less ringing is observed on the deghosted output. This leads to improved clarity and temporal resolution of the shallow reflectors.

Acknowledgments

We thank CGG marine research for permission to show the data example. We thank CGG management for permission to publish this work.

DOI http://dx.doi.org/10.1190/segam2015-5891123.1

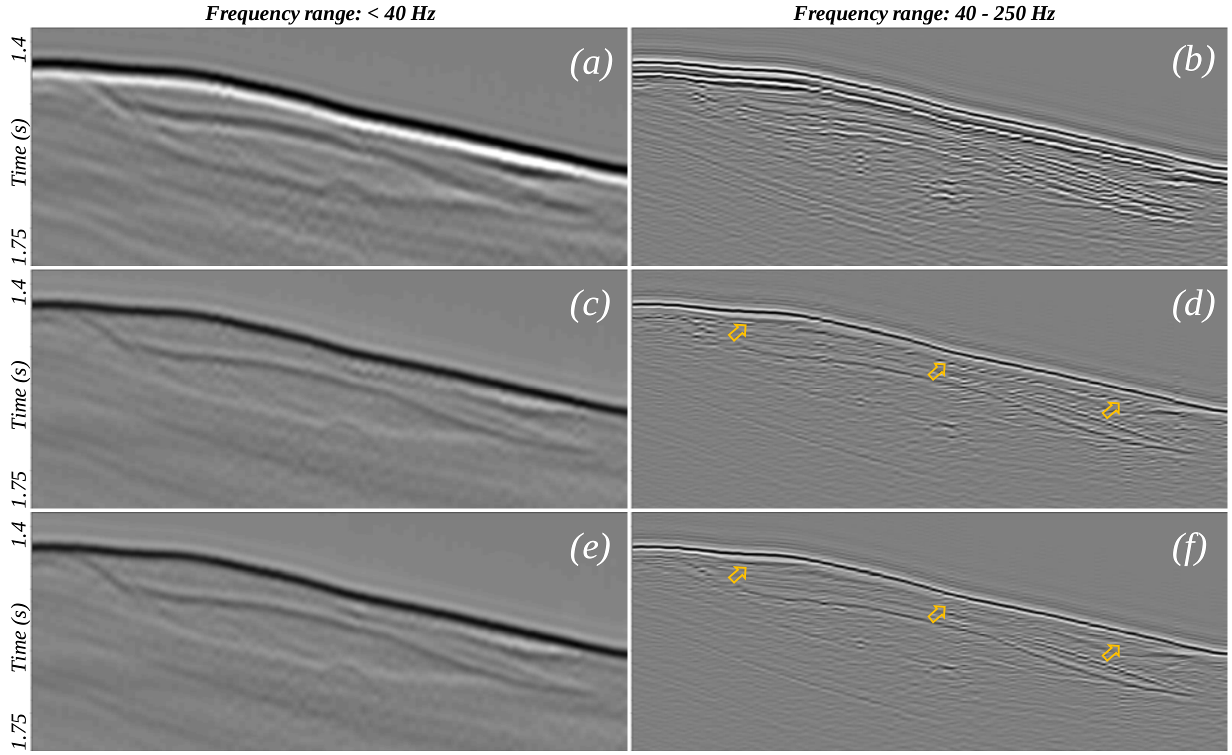

Figure 4: Zoomed filter panels of the common channel gather in Figure 2, (a) and (b) before receiver deghosting, (c) and (d) after receiver deghosting using a flat sea surface datum, and (e) and (f) after receiver deghosting using a variable sea surface datum.

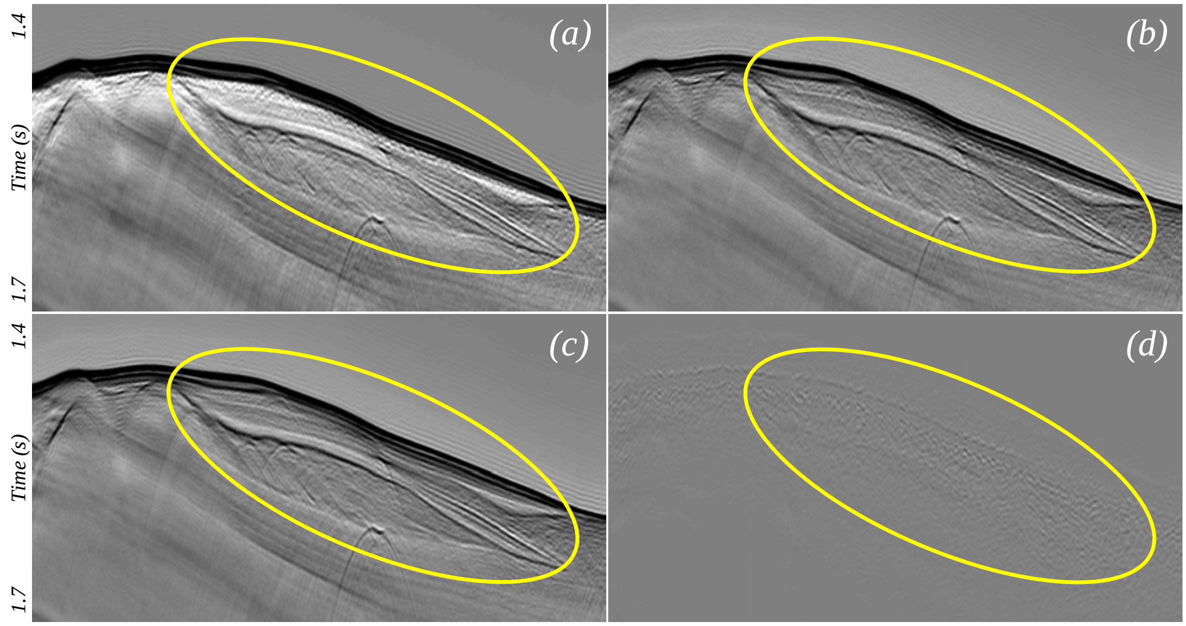

Figure 5: Zoomed stack section (a) before receiver deghosting, (b) after receiver deghosting using a flat sea surface datum, (c) after receiver deghosting using a variable sea surface datum, and (d) deghosting difference.

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EDITED REFERENCES

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