EAGE ANNUAL 2018
80TH CONFERENCE + EXHIBITION
COPENHAGEN | DENMARK

We A10 08

Multi-Sensor Receiver Deghosting Using Data Domain Sparseness Weights

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

Summary

While the benefits of vertical particle velocity measurements are well known for towed streamer receiver deghosting, in many cases high noise levels can cause practical issues. We describe an inversion-driven receiver deghosting approach which is jointly constrained by hydrophone data and prior wavefield separated data. Prior wavefield separated data can relate to an up-going or down-going wavefield, obtained by combining hydrophone and particle velocity data. Use of prior wavefield separation data provides the joint inversion with signal at hydrophone notch frequencies, as well as making it less sensitive to variations in the free surface datum than hydrophone-only inversion methods. The use of data domain sparseness constraints makes the approach practical as it may be applied to data without explicit prior denoise. The proposed method is validated on synthetic and real data examples.

Introduction

The advent of broadband towed streamer data has extended usable bandwidth at both low and high frequencies. As well as enriching the overall seismic image, improved low frequencies have enabled more reliable full waveform inversion results (Ratcliffe et al., 2013), while improved high frequencies better inform interpretation of thin-layered structures. Strategies to deliver marine towed streamer broadband data range from processing-only approaches using horizontal tow hydrophone-only streamers, to combined acquisition and processing schemes which may consist of multi-level streamers (Sønneland et al., 1986), variable depth streamers (Soubaras, 2010) or dual sensor streamers (Carlson et al., 2007). While the benefits of vertical particle motion data in separating up-going and down-going wavefields are well known (Carlson et al., 2007), in practice, the recordings often contain noise at lower frequencies and may also be contaminated by equipment mounted on the streamers. Consequently, the particle motion data may require noise attenuation before use (Peng et al., 2014), and at low frequencies may in many cases be unusable. Aggressive noise attenuation of the accelerometer data may lead to signal damage.

We introduce an inversion-driven receiver deghosting approach combining multi-measurement data and data domain sparseness weights. The approach may work with raw particle velocity data without explicit prior noise attenuation, making it flexible and easy to use. The approach may be used on towed streamer or ocean bottom datasets.

Method

The inversion-based approach derives a surface-datum model of the up-going wavefield, m, that is constrained by the time-space hydrophone, h, and prior wavefield separated data, s, computed using vertical particle velocity and hydrophone data. The prior wavefield separation may relate to up-going data (for example, from PZ summation) or down-going data (for example, from PZ subtraction). While at some offsets and frequencies the prior wavefield separation provides the inversion with wavefield separated data having a high signal-to-noise ratio, at other offsets and frequencies it may be contaminated with noise. To mitigate this, the inversion can be conditioned with data domain sparseness weights, W_d, which may be a function of time, space, and frequency (Poole, 2015). Weights may be obtained via a comparison of measured particle velocity data and simulated particle velocity data, in a way similar to that described by Peng et al. (2014). Such a methodology enables the inversion to rely less on the prior wavefield separated data in regions where it is contaminated by noise. Model domain sparseness weights, W_m, may also be used to constrain the inversion further, for example following Trad et al. (2003). The inversion problem is described by the following equation:

$$W_d \begin{pmatrix} h \\ s \end{pmatrix} = W_d \begin{pmatrix} L_U + L_D \\ L_S \end{pmatrix} W_m m. \tag{1}$$

L_U and L_D are linear operators transforming the surface-datum model respectively to up-going and down-going time-space data at the recorded datum. In the case that the model domain is the $\tau - p$ domain, and using frequency domain notation for brevity, the operators may be given by:

$$L_U = \quad e^{-2\pi i f (p_x x + p_y y - p_z z)} \; ; \quad L_D = R e^{-2\pi i f (p_x x + p_y y + p_z z)}, \tag{2}$$

where R is the free surface reflectivity, (x, y, z) is a receiver offset relative to a source, and (p_x, p_y, p_z) are the associated receiver-side slownesses, (p_x, p_y) defining the model domain and p_z relating to a redatum from surface to the recorded receiver depth. The linear operator L_S may equal either L_U or L_D, depending on whether the prior wavefield separated data relates to up-going or down-going data respectively. This approach has similarities to the multi-measurement formulations of Poole (2014) and Wang et al. (2014) but it is less reliant on a ghost model due to the additional constraint of the prior wavefield separated data, and less sensitive to recording noise due to the data domain sparseness weights. The reghosting operator may also be modified to incorporate wave-height variations if required (for example, following King and Poole, 2015).

Once the up-going wavefield model has been found by inversion, deghosted data, d, may be obtained by subtracting the corresponding ghost model from the input hydrophone data, for example

$$d = h - \; L_D W_m m. \tag{3}$$

The particle velocity data may have been corrected for obliquity prior to separation; alternatively, the hydrophone data may have had an inverse obliquity correction applied to make it consistent with particle velocity amplitudes. In the latter case, the deghosted data, d, may subsequently have an obliquity correction applied. It should be noted that particle velocity data may have been calculated by integrating particle acceleration data.

Following the observations of Robertsson et al. (2008), the approach may be modified to make use of the dealiasing properties of particle velocity data, v, in the y-direction, as follows:

$$W_d \begin{pmatrix} h \\ s \\ v \end{pmatrix} = W_d \begin{pmatrix} L_U + L_D \\ L_S \\ cos(\gamma_p)(L_U + L_D) \end{pmatrix} W_m m, \tag{4}$$

where γ_p is the angle between the sensor orientation (the y-direction) and the ray-path direction corresponding to a model slowness, p.

Synthetic example

Shot gather synthetic data relating to a 1D reflector at 2 km depth in a constant velocity medium of 1500 m.s^{-1} is given in Figures 1a and 1b, for hydrophone and vertical particle velocity data respectively. Figure 1c shows the up-going data obtained by averaging the data in Figures 1a and 1b. Figure 1d shows the data of Figure 1c after addition of impulsive random noise. An application of the proposed scheme *without* data domain sparseness weights is shown in Figure 1e, using hydrophone data (Figure 1a) and noise-free up-going data (Figure 1c) as input. The result shows an accurate deghosting, comparable to the ideal result of Figure 1c. Additional results from the proposed scheme *without* data domain sparseness weights are shown in Figure 1f, here using hydrophone data (Figure 1a) and noisy up-going data (Figure 1d) as input. We observe that the noisy input data has contaminated the output by smearing the noise. Figure 1g shows results from the proposed scheme with data domain sparseness weights, using hydrophone data (Figure 1a) and noisy up-going data (Figure 1d) as input. This illustrates how the use of data domain sparseness weights has reduced the noise contamination on the output data; the results are now consistent with the ideal case of Figure 1c.

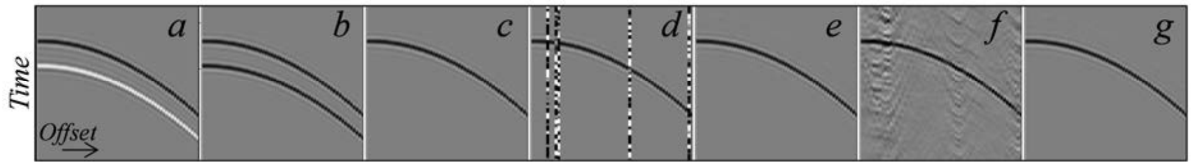

Figure 1 *Synthetic shot gather data: (a) input hydrophone data, (b) ideal vertical particle velocity data, (c) ½(a + b), (d) c + impulsive noise, (e) proposed method using a and c with no data domain sparseness, (f) proposed method using a and d with no data domain sparseness, (g) proposed method using a and d with data domain sparseness.*

Real data examples

The first data example is from the Norwegian North Sea, an acquisition consisting of 12 streamers, each separated by 75 m. Figure 2 shows the data in 10 Hz frequency panels for (a) hydrophone input, (b) vertical particle velocity input, (c) receiver deghosting using hydrophone-only data, and (d) receiver deghosting with the proposed approach using hydrophone and up-going data.

For the hydrophone-only example, although overall there is a high signal-to-noise ratio before and after deghosting, the signal is noticeably weaker at the ghost notch of ~40 Hz, a frequency where we see the strong signal from the vertical particle velocity data amplified due to the ghost peak. While some noise is present in the particle velocity data, mainly relating to the birds and other equipment attached to the streamer, the data domain sparseness weights used in the proposed method prevent this noise from contaminating the result. We also observe that the proposed method results in stronger signal around the hydrophone notch than the hydrophone-only deghosting solution.

The second data example is from the Porcupine Basin region of the Irish Sea. This acquisition comprised 14 streamers towed at 12 m depth, each separated by 100 m. Figure 3 shows full bandwidth displays for (a) input hydrophone data, (b) hydrophone-only deghosted data, and (c) deghosted data with the proposed approach. Corresponding displays band-limited around the hydrophone notch are given in (d), (e) and (f) respectively. The proposed approach provides improved data resolution and less residual ghost than the hydrophone-only solution. This is particularly evident in the band-limited displays where the contribution of the vertical particle velocity data highlights increased signal strength at frequencies corresponding to the hydrophone notch.

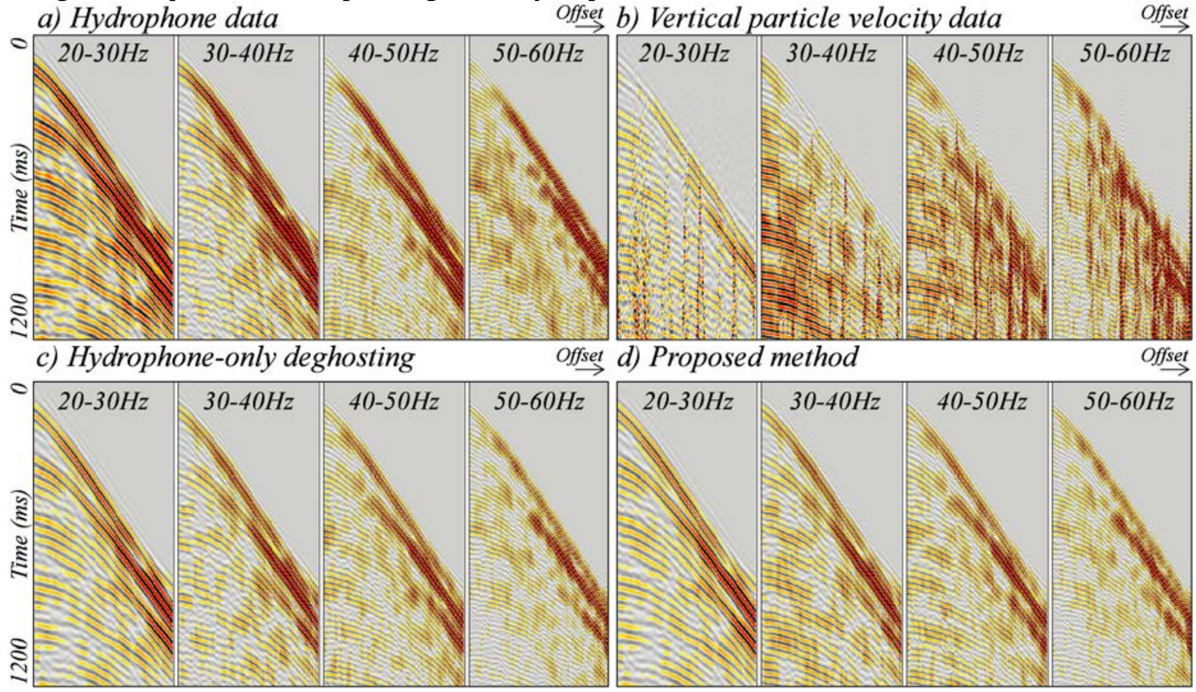

Figure 2 *Shot gather data in frequency panels: (a) raw hydrophone data, (b) vertical particle velocity data, (c) hydrophone-only receiver deghosting, (d) receiver deghosting constrained by hydrophone and up-going data ½(a+ b).*

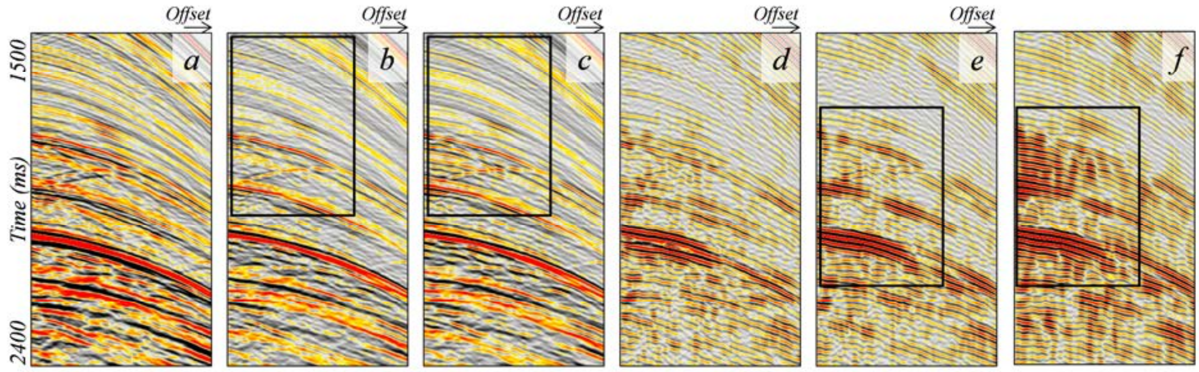

Figure 3 *Shot gather data: (a) raw hydrophone data, (b) hydrophone-only receiver deghosting, (c) the proposed method. Corresponding band-limited displays around the hydrophone notch (56-64Hz) are shown in (d), (e) and (f) respectively.*

Figure 4 shows migrated stack comparisons of (a) input hydrophone data, (b) hydrophone-only deghosting, and (c) the proposed approach, with corresponding band-limited displays around the hydrophone ghost notch shown in (d), (e) and (f) respectively. The band-limited displays show a significant improvement in the level of signal in the hydrophone notch using the proposed approach. On the full bandwidth displays, the results of the proposed approach provide an improvement in the clarity of the fine layering.

Conclusions

A towed streamer receiver deghosting approach, constrained by prior wavefield separated data and data domain sparseness weights, has been introduced. The use of sparseness weights makes the approach resilient to noise contamination in the input data, so that it is practical and easy to use. Two real data examples have demonstrated the benefits of using multi-sensor data in this way to provide enhanced receiver deghosting relative to hydrophone-only solutions.

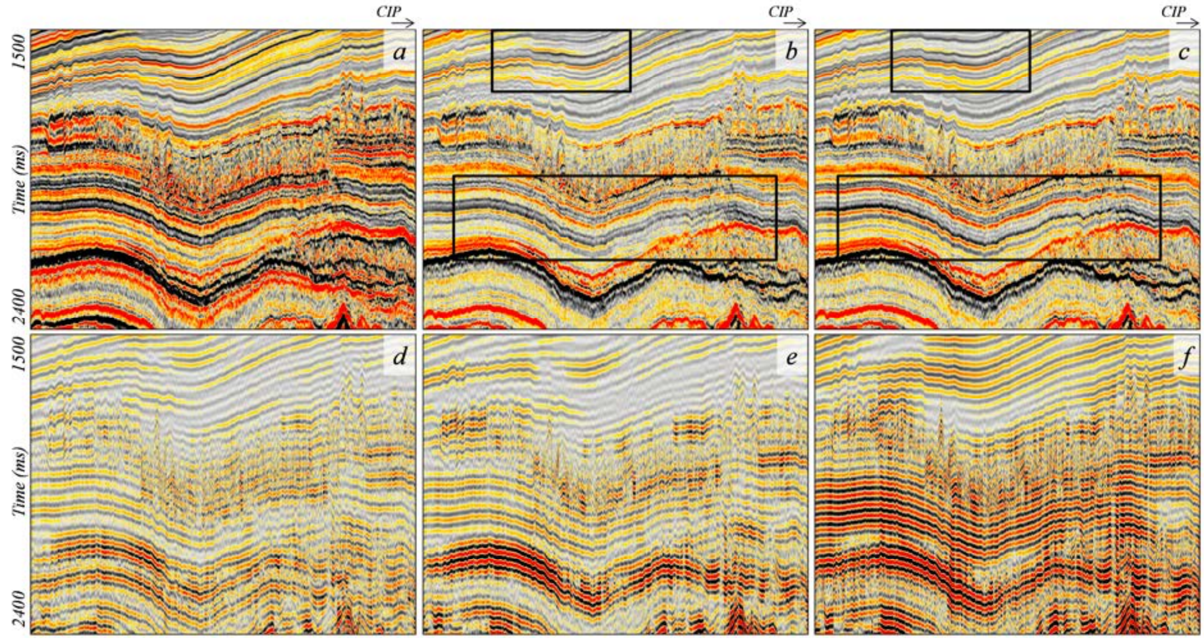

Figure 4 *Migrated stack data: (a) input hydrophone, (b) hydrophone-only receiver deghosting, (c) the proposed method. Corresponding displays band-limited around the hydrophone notch (56-64Hz) are shown in (d), (e) and (f) respectively.*

Acknowledgements

We thank CGG Multi-Client New Ventures for the data examples, CGG Subsurface Imaging for assistance with the processing, and Simon King for help preparing data examples.

References

Carlson, D.H., Long, A., Söllner, W., Tabti, H., Tenghamn, R. and Lunde, N. [2007] Increased resolution and penetration from a towed dual-sensor streamer. *First Break*, **25**(12), 71–77.

King, S. and Poole, G. [2015] Hydrophone-only receiver deghosting using a variable sea surface datum. *85th Annual International Meeting*, *SEG*, Expanded Abstracts, 4610-4614.

Peng, C., Jin, H. and Wang, P. [2014] Noise attenuation for multi-sensor streamer data via cooperative de-noising. *84th Annual International Meeting*, *SEG*, Expanded Abstracts, 1878-1882.

Poole, G. [2014] Wavefield separation using hydrophone and particle velocity components with arbitrary orientation. *84th Annual International Meeting*, *SEG*, Expanded Abstracts, 1858-1862.

Poole, G. [2015] Radon modelling with time-frequency sparseness weights. *85th Annual International Meeting*, *SEG*, Expanded Abstracts, 4510-4514.

Ratcliffe, A., Jupp, R., Wombell, R., Body, G., Durussel, V., Fernandes, A., Gosling, B. and Lombardi, M. [2013] Full-waveform inversion of variable-depth streamer data: An application to shallow channel modeling in the North Sea. *The Leading Edge*, **32**(9), 1110-1115.

Robertsson, J.O.A., Moore, I., Vassallo, M., Özdemir, K., van Manen, D.J. and Özbek, A. [2008] On the use of multicomponent streamer recordings for reconstruction of pressure wavefields in the crossline direction. *Geophysics*, **73**(5), A45-A49.

Sønneland, L., Berg, L.E., Eidsvig, P., Haugen, A., Fotland, B. and Vestby, J. [1986] 2-D deghosting using vertical receiver arrays. *56th Annual International Meeting*, *SEG*, Expanded Abstracts. 516-519.

Soubaras, R. [2010] Deghosting by joint deconvolution of a migration and a mirror migration. *80th Annual International Meeting*, *SEG*, Expanded Abstracts, 3406-3410.

Trad, D., Ulrych, T. and Sacchi, M. [2003] Latest views of the sparse Radon transform. *Geophysics*, **68**(1), 386-399.

Wang, P., Jin, H., Peng, C. and Ray, S. [2014] Joint hydrophone and accelerometer receiver deghosting using sparse Tau-P inversion. *84th Annual International Meeting*, *SEG*, Expanded Abstracts, 1894-1898.