Deblending by Using Ghost

S. Wu* (Delft University of Technology), G.J.A. van Groenestijn (PGS) & G. Blacquière (TU Delft)

SUMMARY

The source ghost introduced by the sea surface reflection is usually considered noise which needs to be removed before imaging. We propose to utilize the source ghost in deblending as a natural blending code such that the end result is both deblended and deghosted. This method is easy to combine with other temporal source codes and provides an interesting alternative to deal with the current depth distributed source for a broadband solution. In this abstract, we discuss how to use the source ghosts in the case of lateral blending and vertical blending to deblend and deghost with illustrations of simple synthetic models. We applied the method to field data where two sources are blended in the same lateral position but at different depths. The results obtained show that it is possible to deblend and deghost in one step in the variable depth source setting.

Introduction

In a blended acquisition source encoding is needed for the separation of the blended sources. In marine seismic surveys, many approaches of temporal source encoding have been utilized (Abma et al., 2015; Mueller et al., 2015; Wu et al., 2015; Vaage, 2002). In this work, we consider the natural blended source, i.e. source ghosts, as part of the blending code (Berkhout and Blacquière, 2014). With the help of this natural blending code in depth, it is possible to deblend and deghost in one step. Additionally, it is easy to combine with other temporal source codes and provides an interesting alternative to deal with the current depth distributed broadband source.

In this abstract, we present three cases where source ghosts are treated as signal and then separated from the source response. In the first case, two sources are activated near simultaneously at different lateral locations. They are towed at different depths, and therefore these two sources also have different source ghosts correspondingly. In the second case, the blended source geometry is the same as in the first case. However this time each physical source is activated in a shot-repetition fashion, i.e. activated twice with certain time delays (Wu et al., 2015). The third case contains two sources situated at the same lateral position but at different depths. All three cases will be illustrated and discussed in the following sections and we will refer to these three cases as lateral blending with ghost, lateral blending with ghost and shot repetition, and vertical blending, respectively.

The forward model

To write down the forward model of blending with the natural blended source, i.e. the source ghost, we use the detail-hiding matrix notation described in Berkhout (1982). The monochromatic blended data, $\mathbf{P}'$, can be formulated as:

$$\mathbf{P}' = \mathbf{P}(z_0; z_0)\mathbf{G\Gamma} \,, \tag{1}$$

where $\mathbf{P}(z_0; z_0)$ represents the unblended data acquired with both source and receiver arrays at the sea surface z_0. $\mathbf{G}$ is the source ghost operator that generate the source responses with ghost for all the sources presented in $\mathbf{P}(z_0; z_0)$:

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & & & \\ & \mathbf{G}_2 & & \\ & & \ddots & \\ & & & \mathbf{G}_m \end{bmatrix}, \; with \; \mathbf{G}_m = \mathbf{W}^+(z_s) + \mathbf{RW}^-(z_s) \;\; . \tag{2}$$

The number of sources in the unblended and ghost free data $\mathbf{P}$ determines the size of $\mathbf{G}$. In the source ghost operator $\mathbf{G}$, $\mathbf{W}^+(\mathrm{z_s})$ forward extrapolates the wavefield to the actual source depth z_s, while $\mathbf{RW}^-(\mathrm{z_s})$ backward extrapolates the wavefield to the ghost depth $-z_s$ and applies the sea surface reflectivity $\mathbf{R}$, which generates the source ghost. After applying $\mathbf{G}$, all the sources are extrapolated from the sea surface to their designated depths below and above the sea surface.
In equation 1, $\mathbf{\Gamma}$ is the blending matrix that contains the temporal source encoding. Each column of $\mathbf{\Gamma}$ corresponds to one blended seismic experiment, and each row corresponds to a source location. Each nonzero element of $\mathbf{\Gamma}$ is formulated as a sum of phase shifts, based on the firing time delay $\Delta t_{kl,n}$:

$$\mathbf{\Gamma}_{kl} = \sum_{n=1}^{N} e^{-j\omega\Delta t_{kl,n}} \;. \tag{3}$$

Note that, this formulation is also suitable in cases where the sources are fired without a code. In that case each nonzero element of $\mathbf{\Gamma}$ equals one. Figure 1a shows an example where no time shift has been applied. In the case where only one shot is fired at each source position ($n = 1$ in equation 3), the blending matrix $\mathbf{\Gamma}$ represents the dithering blending code. In the case of shot repetition ($n \geq 2$ in equation 3), $\mathbf{\Gamma}$ becomes a sum of time shifts which adds the benefit of deblending within a single common shot gather (Wu et al., 2015). In Figure 1d, an example of lateral blending with ghost and shot repetition is shown.

Deblending method

By minimizing the objective function $\|\mathrm{P}' - \mathrm{P}\Gamma\Gamma\|_2^2$, a least-square solution is obtained for P, and used as the start of the iteration. This solution, P_{ps}, is often referred to as the pseudo-deblended data:

$$\mathbf{P}_{ps} = \mathbf{P}'\left(\boldsymbol{\Gamma}^{\mathrm{H}}\boldsymbol{\Gamma}\right)^{-\mathbf{1}}\boldsymbol{\Gamma}^{\mathrm{H}}\left(\mathbf{G}^{\mathrm{H}}\mathbf{G}\right)^{-\mathbf{1}}\mathbf{G}^{\mathrm{H}} . \quad (4)$$

In the pseudo-deblending process described by the above equation, the blended data is correlated with the source code in time *and* depth.

Lateral blending with ghost

In the case of lateral blending with ghost, two sources at different depths are blended (Figure 1a). No firing time delays have been applied. It can be clearly observed that the ghost of the blended sources have different phase shifts. Figure 1b shows a pseudo-deblended shot gather where the left source has been focused and the right source is dispersed. The amplitude of the focused signal is twice as strong compared with both its side lobes (ghosts) and the dispersed right source. Note that the pseudo-deblended data has a lower amplitude as a result of the amplitude shaping terms $\left(\boldsymbol{\Gamma}^{\mathrm{H}}\boldsymbol{\Gamma}\right)^{-\mathbf{1}}$ and $\left(\mathbf{G}^{\mathrm{H}}\mathbf{G}\right)^{-\mathbf{1}}$ in equation 4. By using the fact the desired signal has the strongest amplitude in the shot gather, an iterative scheme which is similar to the one by Mahdad et al. (2011) is applied to obtain the deblended and deghosted left shot (Figure 1c). The notches in the f-k spectrum of the pseudo-deblended data are recovered by the algorithm (Berkhout and Blacquière, 2014), though one can still observe a small imprint of blending in the f-k spectrum of the deblended shot. For the right source (which is not displayed), the pseudo-deblended data and the deblending result have the same behaviour. This example shows that it is possible to deblend by using only the natural blending code

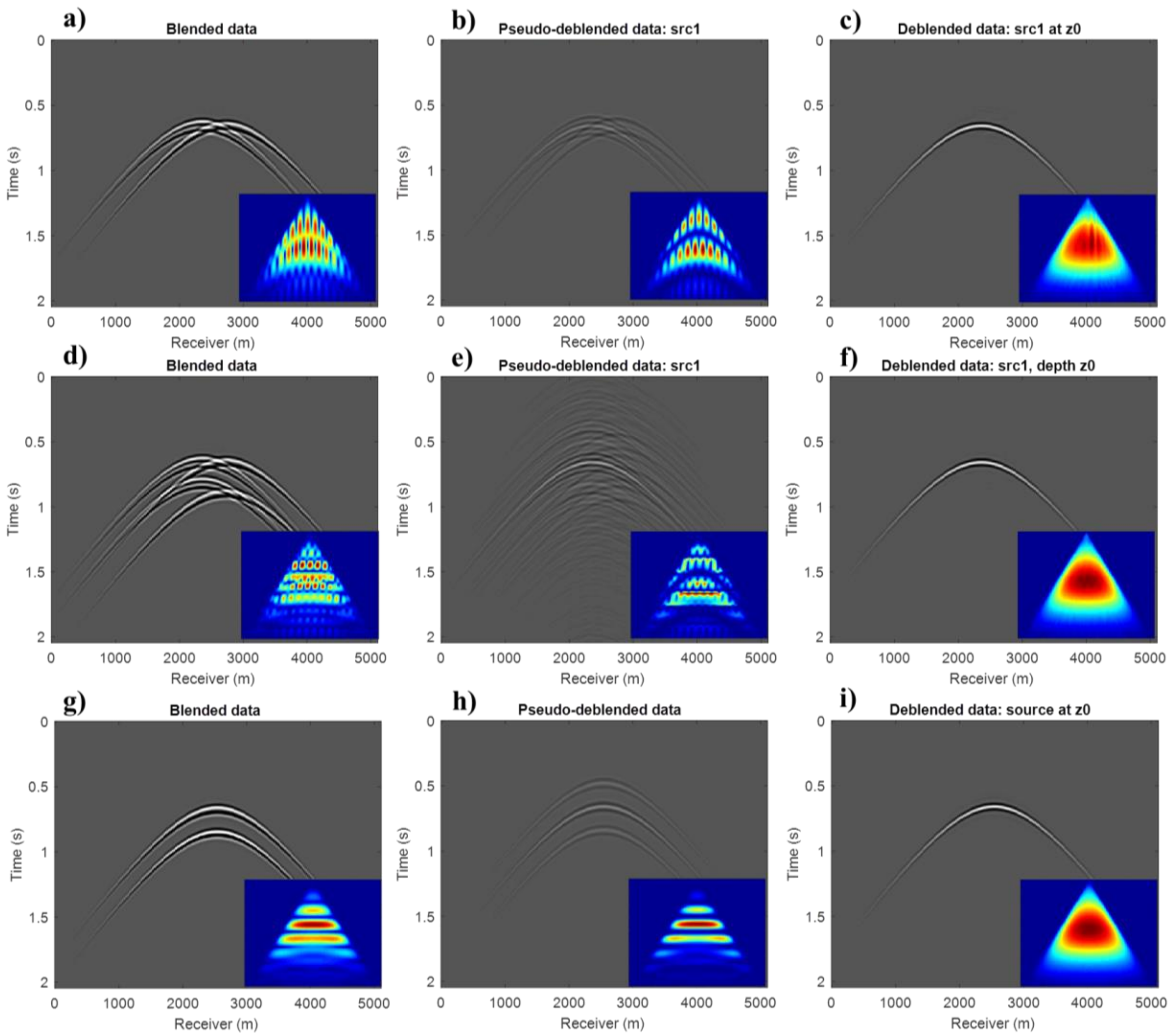

Figure 1 *Lateral blending with ghost: a) blended data, b) pseudo-deblended for the left source, c) deblended and deghosted left source; lateral blending with ghost and shot repetition: d) blended data, e) pseudo-deblended left source, f) deblended and deghosted left source; vertical blending: g) blended data, h) pseudo-deblended data, i) deblended and deghosted source.*

in depth (ghost), without involving the temporal source code.

Lateral blending with ghost and shot repetition
In the case of lateral blending with ghost and shot repetition, two blended sources are both activated twice with certain time delays. The shot gather in Figure 1d simply adds two shots compared with the shot gather in Figure 1a. After pseudo-deblending, again the left source is focused and has a higher amplitude compared to the dispersed right source (Figure 1e), and the side lobes of the signal are dispersed due to the shot-repetition code. Compared with the previous case, the signal to blending noise ratio in the pseudo-deblended data is higher and also the result in Figure 1f shows a better recovered f-k spectrum. This example shows that with a more sophisticated temporal source code, it is possible to improve the deblending and deghosting result. Note that the inclusion of the temporal source code can be easily implemented by changing the blending matrix in the forward model.

Vertical blending
An example of vertical blending with two sources is provided in Figure 1g. Instead of shooting twice, an extra physical source is added and allocated at a different depth. In Figure 1h, the focused signal in the pseudo-deblended data contains the contribution of four responses, i.e. two sources and their corresponding ghosts. The deblended and deghosted shot is shown in Figure 1i. The f-k spectrum of the result is again ghost free. This example shows an alternative method to deal with the current depth distributed sources. A field data example in this case will be discussed in the following section.

Example on field data

We tested the method on field data acquired in the Møre margin high, Norwegian sea. Two identical sub-sources are deployed with random time delays and located at the same lateral position and different depth at 10 m and 14 m. The streamers are located at a depth of 25 m with the receiver spacing being 12.5 m. The data is interpolated to have denser spatial sampling, and roughly receiver deghosted. Additionally a time window which mutes both direct waves is applied. Figure 2a illustrates the blended shot gather with two overlapping shots that both contain sources ghosts, and Figure 2c shows its f-k spectrum with frequencies up to 60 Hz. Note that the receiver deghosting has not been perfect. With a source at depth 14 m we normally expect the first source ghost notch at around 53 Hz. The reason that we don’t observe this source ghost notch is that this notch is filled up by the overlapping shot at a depth of 10m. The horizontal notches are a result of vertical blending.

Figure 2b illustrates the deblended and deghosted data. From receiver 0 to 6000 m, the shot is separated quite well, including the later weak events around 10 s. From receiver 6000 m to 10000 m, some parts of the interfering shot are not completely removed, see e.g. the erroneous events that appear to be faster than the water bottom reflection. It is likely because of the small phase difference between the 10 m and the 14 m source and both their ghosts for high-angle events. After deblending, the source ghost has been removed which results in a higher resolution, see Figure 2b. The f-k spectrum of deblended shot has no ghost notch at around 53Hz (Figure 2d). The horizontal notches have been mostly recovered, though it shows again the difficulty of recovering the events at high angles.

Conclusions and discussion

In a blended acquisition, source encoding is needed. The ghost, as a result of the strong sea reflectivity, has a phase difference from the source response with respect to the tow-depth. Therefore it can be considered a source code and benefit the deblending process. With this natural blending code in depth (ghost), it is possible to deblend and deghost in one step. In addition, the combination of a more sophisticated temporal source code and the source code in depth can be easily implemented and can improve the results.
For vertical blending, we view our method as an interesting alternative to deal with the current depth distributed source to give a broadband solution. The test on field data shows promising results. Under

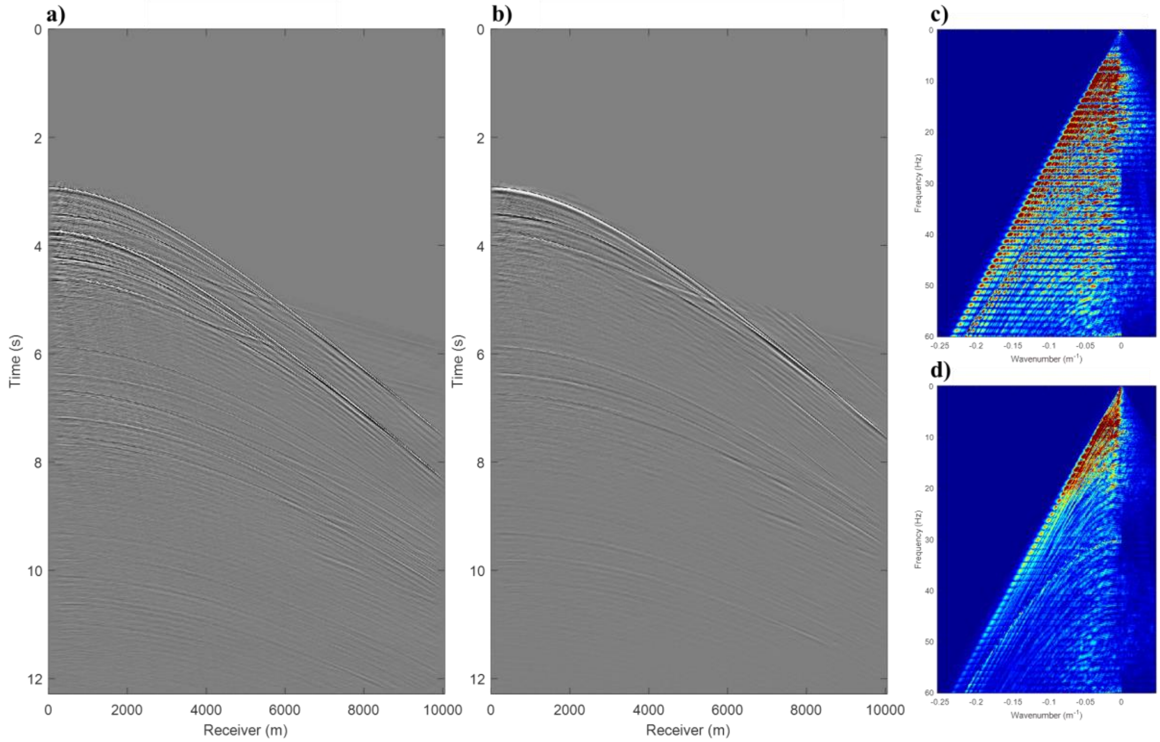

***Figure 2** a) Vertically blended field data and d) its f-k spectrum; b) deblended data and e) its f-k spectrum.*

the same source geometry, it should also be possible to focus the two sources which have not reflected at the free surface, and the two ghosts which have reflected at the free surface separately. In this way, the deblending and deghosting scheme will not require an assumption about the free sea surface.

Acknowledgements

The authors would like to acknowledge the members of the DELPHI consortium at TU Delft for their support, and PGS for permission to publish the field data.

References

Abma, R., Howe, D., Foster, M., Ahmed, I., Tanis, M., Zhang, Q., Arogunmati, A. and Alexander, G. [2015] Independent simultaneous source acquisition and processing. *Geophysics*, **80**(6), WD37-WD44.

Berkhout, A.J. [1982] *Seismic migration, imaging of acoustic energy by wave field extrapolation, A: theoretical aspects.* Elsevier.

Berkhout, A.J. and Blacquière, G. [2014] Combining deblending with source deghosting. *76th EAGE Meeting*, Extended Abstracts.

Mahdad, A., Doulgeris, P. and Blacquière, G. [2011] Separation of blended data by iterative estimation and subtraction of blending interference noise. *Geophysics*, **76**(3), Q9-Q17.

Mueller, M.B., Halliday, D.F., van Manen, D.J., and Robertsson J.O.A. [2015] The benefit of encoded source sequences for simultaneous source separation. *Geophysics*, **80**(5), V133-V143.

Vaage, S.T. [2002] *Method and system for acquiring marine seismic data by using multiple sources.* US patent 6,906,981.

Wu, S., Blacquière, G. and van Groenestijn, G.J.A. [2015] Shot repetition: an alternative approach to blending in marine seismic. *SEG Technical Program Expanded Abstracts 2015.*