Introduction

Blended marine acquisition designs - i.e. with temporal and spatial overlap between shot records - appear as the next goal of the oil and gas exploration industry. The separation process (‘deblending’) has been addressed as a blind signal separation problem by Ikelle (2007), using Independent Component Analysis as the tool to distinguish between the different blended sources. Another fastly evolving field, that of Compressive Sensing or Compressive Sampling, has contributed to the separation of blended data through the work of Lin and Herrmann (2009). It is worth mentioning that both these approaches use source encoding (e.g. sweeps or random phase or/and amplitude encoding), hence they are inappropriate for direct application to the marine case.

By reforming the deblending problem into a denoising one, treating the interference from the secondary blended sources as noise, one can use all kinds of signal processing tools available. It has been reported by various authors - e.g. Moore et al. (2008), Ackerberg et al. (2008) - that by sorting the acquired blended data into a different domain than that of the common source gathers, the interference noise appears as random spikes, thus, the separation turns into a typical random noise removal procedure.

Methods that make use of this property of blended data have already been published. Huo et al. (2009) use a vector median filter after resorting the data into common mid-point gathers. This two-dimensional filter acts locally and effectively reduces the amplitude of the interference that has now turned into randomly distributed spikes, therefore leading to separation when the data is resorted into common source gathers. Moore et al. (2008) use filters designed in the Radon domain to perform the removal of the random noise.

Spitz et al. (2008) have introduced the idea of building a noise model based on the earth’s velocity model and the wave equation. The modeled responses are then used to adaptively subtract the interference noise from the data. This method requires an accurate velocity model and it is, in general, computationally intensive. Moving a step further, Kim et al. (2009) build a noise model from the data itself and then adaptively subtract it from the acquired data. This algorithm acts in the common offset domain and is applied on OBC data.

In the present work, an iterative estimation-subtraction process has been developed to deblend marine data. Resorting the data in common detector, common offset or common mid-point gathers and applying a simple F-K filter offers the necessary signal to noise ratio for the iterative method to start. The method is applied on a real marine dataset, where the blending process has been simulated numerically.

Method

In a blended marine survey, multiple sources fire with time delays (allowing overlapping records) while their response is being recorded by the same detectors, see Berkhout et al. (2009). The signal acquired contains all the reflectivity information - as long as the sources fire in an incoherent manner, e.g. with random time delays. In the case of blending the number of shot records is \( n \) times smaller than the corresponding number in the case of a regular survey if \( n \) is the number of sources involved in the blending. The first step towards separation is to estimate the \textit{unblended} shot records by copying the blended shot records and shifting them in time to compensate for the time delays introduced in the field. This process is called \textit{pseudo-deblending}. In this way, the estimated signal recorded by detector \( k \) due to source \( l \) is given by:

\[
\langle P_{kl} \rangle = P_{k1} e^{-j\omega(\tau_1 - \tau_1)} + P_{k2} e^{-j\omega(\tau_2 - \tau_1)} + \ldots + P_{kl} + \ldots + P_{kn} e^{-j\omega(\tau_n - \tau_1)}
\]  

(1)

where \( P_{kl} \) is the element of data matrix \( P \). It represents a frequency component of the desired \textit{unblended} trace. The other terms are traces due to other sources, shifted in time, introducing blending interference. From equation 1 it becomes clear that if an unblended trace \( P_{kl} \) is known, the interference it causes to the other traces can be removed by applying the appropriate time shifts and then subtracting it from the blended data. However, the initial unblended data \( P_{kl} \) is not available and if it were, there would be no need of such a deblending method. Suppose, though, that \textit{part} of \( P_{kl} \) could be extracted from the blended data \( \langle P_{kl} \rangle \). Then, an iterative estimation - subtraction process could start where more of the
interference noise is removed at each iteration. Such a method will now be discussed. As a start the blended data is resorted in a domain perpendicular to the common source domain, such as the common offset, common mid-point or common detector domain. In such a perpendicular domain, the signal is arranged in coherent events but the blending interference appears as ‘randomly’ distributed spikes. So, a method that can distinguish between coherent and incoherent events -to some degree- shall be able to -partly- suppress the blending interference. A simple example of such a method is F-K filtering, making sure that the pseudo-deblended data reside in the signal frequency-wavenumber band. The spikes are functions that have a white spectrum in the spatial wavenumber direction, extending out of the signal cone. Thus, by passing only the signal bandwidth, the spikes are somewhat suppressed and we may assume that the highest amplitudes of the pseudo-deblended data now most likely belong to the desired signal $P_{kl}$ only. Obviously more advanced filter types may be used. Next, a threshold is applied, leaving these highest amplitudes. This results in an estimate of $P_{kl}$ in which all energy present -most likely- belongs to $P_{kl}$ and which does not contain any blending noise. By estimating the interference noise caused by this signal, see equation 1, and adaptively subtracting it from the pseudo-deblended data, a better estimate of the unblended data is obtained. Using this as the new input to the filter, the threshold can be lowered and an even better estimate is obtained. Repeating this process leads to the gradual removal of interference noise from the pseudo-deblended data, until no further improvement is achieved.

A stopping criterion has been implemented to monitor and terminate the process when the energy of the output is minimum. After processing all the gathers in the perpendicular domain, the deblended data can be re-arranged in common shot gathers. The procedure is depicted in Figure 1 for processing in the common detector domain.

**Results**

A 2-D blended marine acquisition has been simulated from a real, unblended marine dataset acquired at the Haltenbanken field in Norway. The dataset was acquired with spatial and temporal sampling inter-
Figure 2 (a) Unblended shot record from the marine dataset, (b) initial estimate (pseudo-deblended result), (c) estimate after 3 iterations, (d) estimate after 42 iterations, (e) estimate after 84 iterations and (f) final deblended result after 126 iterations.
vals of 25 m and 4 ms respectively. Figure 2(a) shows a shot record from this dataset. The deblending procedure is carried out in the common offset domain. The near-offsets are processed first until no further improvement can be achieved; the middle and far-offsets follow.

The simulated blended acquisition design consists of a 2-D line on which three sources fire with small random time delays. All detectors of the simulated survey record all three sources, resulting in blended shot records that contain negative offsets as well. The additional traces required for the simulation of this survey were computed from the existing data using reciprocity. A shot record of the simulated survey, after pseudo-deblending, can be seen in figure 2(b). Notice the three different shot records that have been blended into one. The signal-to-noise ratio of this shot record (as far as interference noise is concerned) is around -6 dB (i.e., more noise than signal).

Figures 2(c)-(e) show intermediate results of the algorithm after 3, 42 and 84 iterations while the algorithm processes the near, the middle and the far offsets respectively. The interference noise is gradually removed until the algorithm reaches a point where no further improvement can be achieved. The final deblended output of the algorithm is shown in figure 2(f). Although some residual energy is left, the result is close to the desired output, with the signal-to-noise ratio being approximately 10 dB. Hence, the enhancement, in terms of signal-to-noise ratio, achieved by this simple implementation of the algorithm is around 16 dB in this example.

Summary and Conclusions

An iterative method for the separation of blended marine data (i.e., with impulsive sources) has been presented in this paper. The blending noise is estimated using a model based on signal energy extracted from the blended data. This noise estimate is then subtracted from the blended data. The result, which now contains less blending noise, is input to the next iteration. The key to signal extraction from blended data containing interference noise, is the incoherency of the blending noise (as opposed to the coherency of the signal) accomplished by resorting the data into a different domain than the common source domain (common detector, common offset or common mid-point). The method is based on existing denoising techniques, but their results are considered to be intermediate only and are used at each iteration for a better estimate of the interference. Promising results have been obtained from applying the method to real data where the blending process was simulated numerically.

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References