A deblending strategy using alternating constant delay simultaneous source data
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Summary
This paper introduces a deblending strategy for simultaneous source data using alternating constant delays. The technique uses uncontaminated data to generate a cross-talk noise estimate for deblending. The effectiveness of the strategy is demonstrated on a broadband dual source marine dataset acquired offshore Indonesia.

Introduction
Simultaneous source (blended) acquisition in a land context has become an industry standard in some regions due to its ability to increase illumination and reduce acquisition costs (e.g. Howe et al., 2008). In the marine environment, the take-up of blended acquisition has been slower partly due to the lack of flexibility to modify the impulsive airgun source but also due to constraints on marine acquisition. Nevertheless, benefits for blended acquisition have been successfully demonstrated for towed streamer (Moore et al., 2012, Poole et al., 2013) and ocean bottom surveys (Davies et al., 2013). While higher fold datasets may be acquired in the same time, we are left with contamination noise from one source on the recording of the other, commonly known as cross-talk noise. One common strategy is to remove this noise before processing. Many techniques to remove the cross-talk noise rely on some level of randomisation to the timing of one source relative to the others. The randomised timing of the sources is used to avoid coherency of the cross-talk noise in one or more domains.

Over the years, several processing techniques to remove cross-talk noise have been proposed. Stefani et al. (2007) describe an approach based on impulsive denoise. In this strategy trace segments are initially flagged as being contaminated by noise following which they are reconstructed from surrounding data which are not significantly contaminated. While effective at removing strong noise contamination, the output often leaves weaker contamination noise. Another strategy focuses on the incremental removal of cross-talk energy through iterative signal extraction. The method begins with harsh signal enhancement of the time-aligned data. The result of the signal extraction is used to derive a cross-talk noise estimate which is subtracted from the input data. The process is repeated, each time relaxing the harshness of the signal extraction until the remaining cross-talk noise has been reduced to acceptable levels. Examples of this approach include Mahdad et al. (2010), Maraschini et al. (2012) and Peng et al. (2013). A final category of methods derive models of the data for each source simultaneously based on timing information, e.g. Akerberg et al. (2008) and Moore et al. (2008). Often the success of this approach relies on careful determination of model sparseness constraints.

This work focuses on a new approach where data are acquired using alternating constant time delays. Uncontaminated data are interpolated to calculate a cross-talk model which is repeatedly subtracted at increasingly later times.

Deblending strategy
The following description relates to marine dual source acquisition. The acquisition strategy consists of firing both sources every 25 m with an alternating constant time delay. The delay is long enough so that a segment of data is substantially unaffected by cross-talk noise. Figure 1 shows that on odd location S2 fires after S1 with a 1000 ms delay. On even locations the sequence is reversed with S2 firing first. This means that for odd locations the initial 1000 ms of data is unaffected by S2 and for even locations the initial 1000 ms of data is unaffected by S1. In this context we use the word location to mean a position in space where the leading source was fired.

Stage 1 of the deblending strategy consists of iterative interpolation and subtraction and is outlined in Figure 2. Red and blue trace segments relate to uncontaminated data from S1 and S2 respectively while black time windows contain energy from both S1 and S2. The approach begins by selecting odd locations from the input data. The odd locations (Figure 2a) contain 1000 ms of data from S1 without interference from S2. Interpolation is applied to estimate even location data with 1000 ms of S1 data uncontaminated by S2 (Figure 2b). The even locations output from this interpolation are delayed by 1000 ms so the timing is consistent with S2 interference noise for the even locations (Figure 2c). These delayed data are subtracted from the even location input data thus revealing an extra 1000 ms of S2 data unaffected by S1 (Figure 2d). The resulting even locations (Figure 2e) are next interpolated to produce odd locations free of contamination for the first 2000 ms (Figure 2f). These data are shifted down by 1000 ms (Figure 2g) and subtracted from the Figure 2d data to reveal odd locations free of contamination for 3000 ms. The process is repeated until the end of the record is reached, outputting the deblended shot gathers.
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The interpolation may be applied in any appropriate domain (e.g. common-receiver, common-channel, etc) with fx interpolation (Spitz, 1991), sinc interpolation or other suitable algorithms. Either a straight subtraction or adaptive subtraction may be used.

Following the above flow we have an estimate of data free of cross-talk noise. The odd locations are free of contamination from S2, and the even locations are free of contamination from S1. The second stage of the procedure begins by subtracting the output for stage 1 from the input data and is shown in Figure 3. The energy after subtraction reveals the cross-talk noise that was subtracted from the input. The cross-talk noise is then interpolated and shifted upwards before being subtracted from the input data to reveal data from the alternate source. Finally, the result is shifted upwards to be consistent with the firing time.

The final step in the flow consists of combining the data from stages 1 and 2. Odd location data from Stage 1 are combined with even location data from Stage 2 for the S1 output. Even location data from Stage 1 are combined with odd location data from Stage 2 for the S2 output.

While the success of this approach relies on adequate interpolation, it should be noted that the interpolated data is used only to suppress cross-talk noise and not for further processing. This ensures the amplitude preservation of the strategy. As the sources always fire with a significant delay, any residual cross-talk noise will have a different moveout compared to the remaining signal and hence will tend to stack out. This will not be the case with dithered acquisition strategies using smaller delays. The approach may be applied equally to single or dual vessel acquisition.

Data example

The field data example comes from a 3D narrow azimuth towed streamer acquisition acquired offshore Indonesia. A single marine vessel towing eight variable-depth streamers separated by 100 m with receiver depths from 7 m to 50 m was used. The receiver notch diversity relating to variable-depth streamer ensured the acquisition of high quality broadband data (Soubaras and Lafet, 2013). Two identical airgun sources (starboard and port) were towed at 6 m depth, with 50 m lateral separation. The leading source was fired every 25 m with a 1000 ms delay time as described above. The blended acquisition strategy was designed to increase the CMP fold with the aim of increasing the signal-to-noise ratio of the resulting stack.

Figure 4a shows raw data before deblending. The upper arrow highlights the direct arrival from the interfering source, and the lower arrow highlights the waterbottom reflection cross-talk noise. Data after deblending for S1 and S2 are shown in Figure 4b. The spectral comparison shows how the notches relating to the 1000 ms delay are corrected by the deblending process. The results show a high quality separation with little remaining cross-talk noise.

Figure 5 shows common channels at 285 m offset for S1 and S2 before and after deblending. The display highlights the alternating timing delay of the cross-talk noise from +1000 ms to -1000 ms with successive locations. The process has accurately removed the cross-talk noise even in the complex diffraction area at the left of the section.

Normal moveout corrected CMP gathers for S1 before and after deblending are shown in Figure 6. The upper and lower arrows highlight cross-talk noise relating to the -1000 ms and +1000 ms firing times of S2. The gatherers after deblending show how the cross-talk has been removed. Stack sections before and after deblending with difference and after receiver deghosting are shown in Figure 7. The results highlight the strength of this deblending strategy and its compatibility with broadband processing.
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Conclusions
This paper introduces a novel deblending approach based on an alternating constant source timing delay scheme. The strategy iteratively deblends data through interpolation and subtraction of time segments which have been designed to be unaffected by blended acquisition. The strategy has been validated on a broadband real data example.

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Figure 4; Shot gathers a) before deblending and b) after deblending. Inset spectral comparison. Spectrum: Red: Before deblending, Blue: S1, Green: S2.

Figure 5; Common channels a) before deblending and b) after deblending.
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Figure 6: NMO corrected CMP gathers a) before deblending and b) after deblending.

Figure 7: Stack section a) before deblending, b) after deblending, c) difference (cross-talk noise removed), and d) after receiver deghosting.
EDITED REFERENCES
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