Shot by Shot Source Wave Field Estimation

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Summary

In this paper we discuss the behaviour of air gun source arrays in marine seismic acquisition. We comment the fact that the source configuration and depth are changing continually with the combined actions of surface waves, sea currents and general towing conditions. This has a direct effect on the emitted source pressure wave field and thus on the signature in the seismic data. We describe the method of backpropagation with relative motion that allows an efficient and robust estimation of notional and far-field signatures from near-field measurements at every shot point. The derived shot by shot signatures show very good correlation with sea-state and sea-currents, as we would expect. We show that the variation of the signature can affect the quality of seismic data. We demonstrate that the estimated far-field signatures describe the real variation of the signature in the data and we show how the estimated shot by shot signatures can be used to mitigate the effect of signature variations and thereby improve the quality of the seismic data.

Introduction

With the advent of the broadband seismic era, which has extended the useful frequency range to higher and lower frequencies, a better characterization of the probing source signature is necessary. Accurate knowledge of the emitted source wave field is key for successful processing and interpretation of seismic data. Whether it is used for imaging or for reservoir characterization, in 2D, 3D or 4D, the seismic output signature needs to be known precisely. Conventional marine surveying uses air-gun source arrays that are not compact or rigid structures; i.e. they are made of several independent source elements which can move relative to each other. In the most common arrangement, gun strings composing the source array are linked by depth ropes to surface floats and the flexible source array is towed by the vessel along the survey path (Figure 1). With the combined action of surface waves, underwater currents and towing conditions, the source configuration and depth changes continually from shot to shot throughout the survey. In addition, it is common that individual guns are de-activated due to failure, spare guns are activated at other positions for compensation, or gun pressure can fluctuate noticeably during the seismic acquisition. It is thus inevitable that the emitted source wave field will change from shot to shot throughout a survey. With the much improved quality of broadband seismic data, such shot to shot variations in the emitted source wave field can be important. Estimating shot by shot far-field signatures has thus recently gained much attention amongst the geophysical community. In this paper we describe a robust and efficient method to generate shot by shot signatures that takes into account continuous changes in the source array, and demonstrate the validity of these signatures on real seismic data.

From near-fields to far-fields: The method of back-propagation with relative motion

Modern air gun source arrays are equipped with various sensor units that allow real time monitoring and positioning of the source elements. In particular, the emitted pressure wave field at every shot point is recorded by near-field hydrophones located in the vicinity of each gun station (Figure 1). There are generally at least as many near-field hydrophones as there are source elements in the array. This allows the use of the notional source concept to derive a so-called notional signature for each gun (Ziolkowski et al. 1982). The notional signature for a given gun in the array is the net pressure output from that gun including the interaction effect from the other firing guns in the array together with the corresponding interaction effect from the ghost or mirror source. In the notional source method, the recorded signal $NF_i(t)$ at each near-field hydrophone is assumed to be a linear combination of the pressure wave field propagating directly from each individual gun in the array together with the corresponding pressure field reflected back from the nearby sea-surface:

$$NF_i(t) = \frac{1}{4\pi}\sum_{j=1}^{N} S_j(t) * \left[\frac{1}{r_{ij}}\delta\left(t-\frac{r_{ij}}{c}\right)+\frac{R_0}{rg_{ij}}\delta\left(t-\frac{rg_{ij}}{c}\right)\right],$$

where $S_j(t)$ is the notional time signature of gun j, N is the number of active guns in the array, r_{ij} and rg_{ij} are the distances from near-field hydrophone i to, respectively, the source element j and to its mirror, or sea-surface, ghost source, δ is the Dirac Delta function, R_0 is the sea-surface reflection coefficient, c is the acoustic velocity in water and * denotes the convolution sum. Reversing this process, the notional source signatures for each gun are calculated by propagating the recorded signals from all the near-field hydrophones back to their original source positions. This requires a good estimate of the sea-surface reflection coefficient and the acoustic velocity in water, but most importantly an accurate knowledge of the relative positions of the sources and the near-field hydrophones. In practice the near-field hydrophones are attached rigidly to the source framework, generally above the gun stations (Figure 1), and will therefore move through the water with the forward motion of the towing vessel. In contrast, the oscillating air bubbles, once released by the guns, are independent of the source forward motion. Instead, these will rise vertically towards the surface due to their buoyancy. In addition, the bubbles may also move laterally in the presence of sea-currents and/or from the coalescence effect with other nearby air bubbles. This relative motion between the pressure emitting bubbles and the near-field hydrophones has to be taken into account.

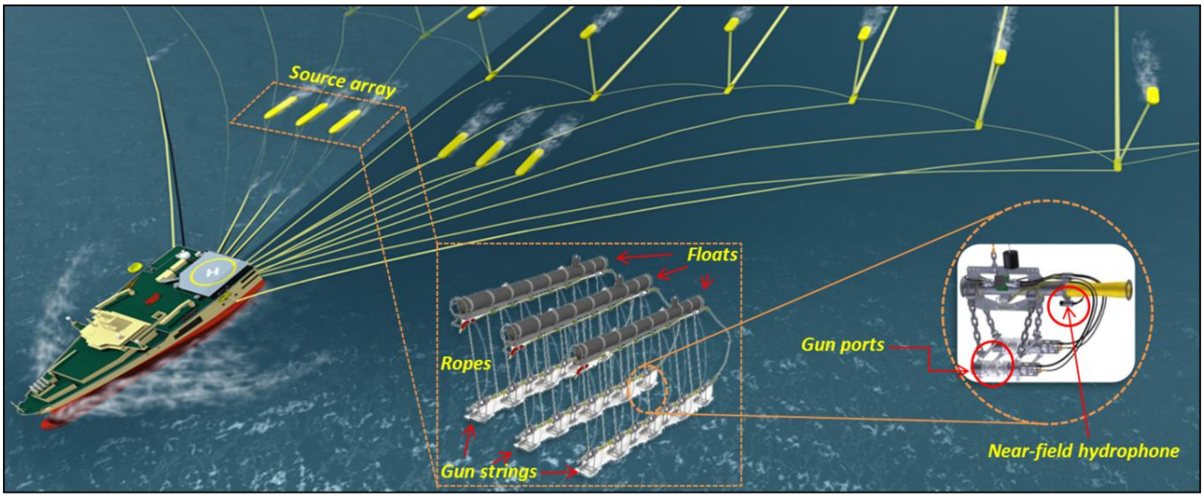

Figure 1 *Dual-source configuration. Each source is made of 3 gun strings suspended below floats.*

In the presented method, the near-field hydrophones are modelled as moving receivers and the oscillating air bubbles as independent moving sources. Note that this also applies to the mirror, or ghost, sources. Therefore, the relative motion is equally included for primaries and for ghosts and also both amplitude and phase effects are considered. For simplicity, the air bubbles are often considered to have a linear movement towards the surface and the same rise speed is used regardless of the gun volumes (e.g. Landrø et al. 1991). In reality the bubble rise speed is variable because of the acceleration due to gravity and because the bubble volume itself is changing continually due to the alternating expansion and collapse of the bubble. Furthermore, since bigger volumes of air are more buoyant than smaller volumes, the bubble rise is also dependent on the gun volume, provided the pressure is the same. In the presented method, we made use of an empirical, non-linear, volume-dependent bubble rise profile which has been derived from real measurements.

Validating the shot by shot signatures

The method described above has been used to generate shot by shot notional and far-field signatures for a number of surveys. We now demonstrate that the derived signatures contain the real shot to shot variation in the emitted source wave field.
We start by comparing the variation in the derived shot by shot far field signatures with acquisition conditions, as we would expect more source variability under more severe weather conditions. An example from the North Sea is shown on Figure 2 where shot by shot far field signatures from 3 different sequences of the same survey are displayed. The signatures are ghost free so we can clearly distinguish the bubble oscillations after the initial sharp peak. From inspection of the shot to shot variation in the bubble period, we can clearly see a very good correlation of the shot to shot signature variations with sea state. The sequence to the left, which was acquired in very calm weather, shows very little change from shot to shot in the bubble period and only later times are slightly affected. The sequence in the middle has been acquired at a different time under moderate sea-state. Shot to shot variations in the bubble period are now more pronounced at later times and some variation at earlier times can be distinguished. Finally, the sequence to the right was acquired at yet another time in very rough weather. Shot to shot variation in the later bubble oscillation are now very pronounced and the earlier bubble pulse is now clearly affected. A similar exercise was done on a different survey acquired in an area with strong underwater currents and a similarly good correlation between sea current direction and signature variation was observed.

Since any variation in the emitted source wave field will directly impact the seismic data recorded by the streamers, we now show that the shot to shot variations in the derived far-field signatures correspond to real shot to shot signature variation in the seismic data.

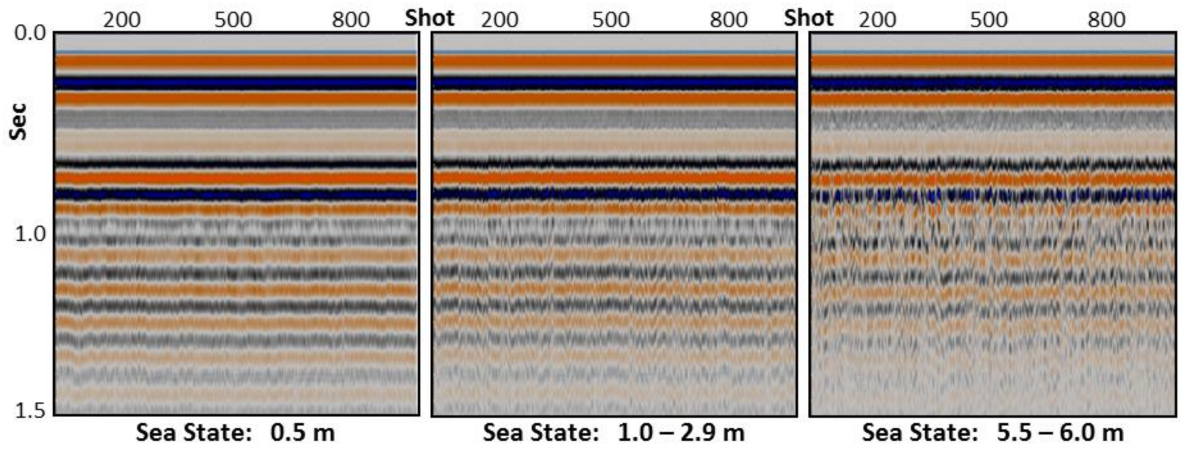

Figure 2 *North Sea data. Shot by shot signature variation with sea state: calm (left), moderate (middle) and rough (right)*

To demonstrate this, we derive correction filters from the estimated shot by shot far field signatures and use these to remove the shot to shot signature variation in the corresponding seismic data. The seismic data is also ghost-free such that the signature, with its bubble oscillations, can be clearly distinguished. Figure 3 shows an example near offset trace from a survey in the North Sea taken from a sequence acquired in marginal weather conditions. The upper display is the original ghost-free near offset trace data without shot to shot variation correction. The lower display is the same near offset trace data after the application of shot to shot correction. The jittery pattern in the bubble period in the upper display, which resulted from significant variations in the source output due to high sea state, has been significantly reduced after the application of the shot to shot signature variation correction. The seismic horizons, which have a blurred appearance on the raw data, are now much more continuous and smooth.

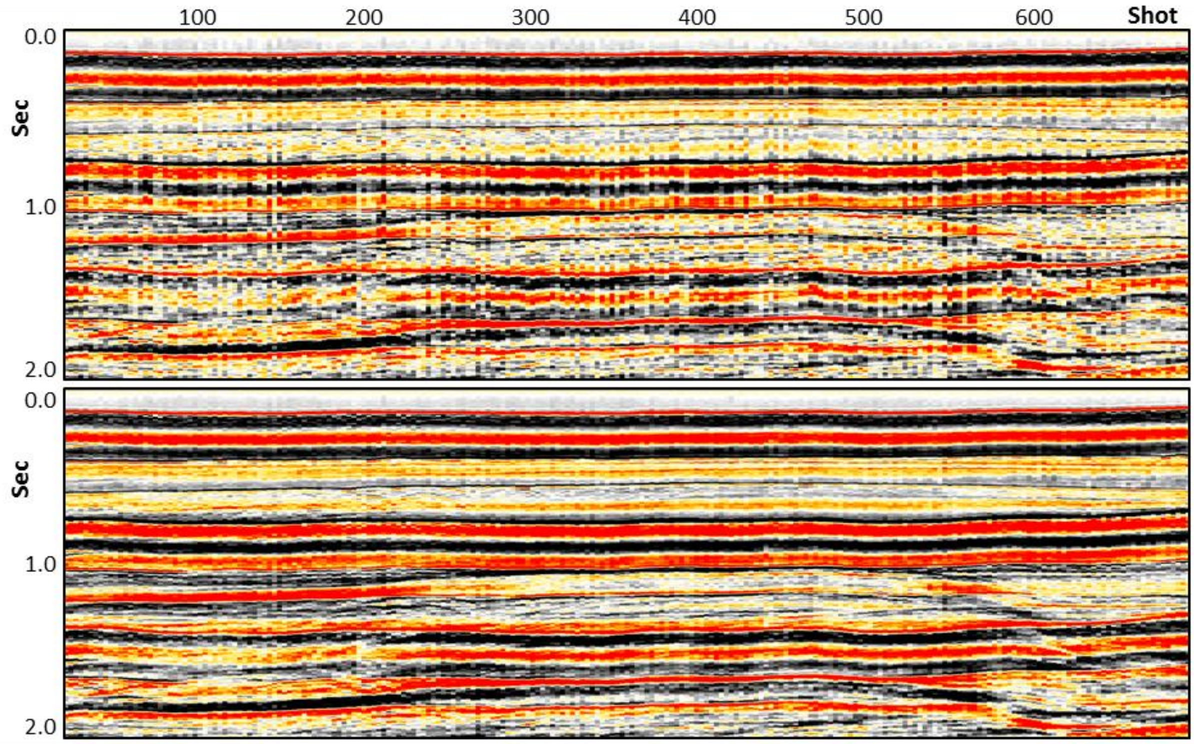

Figure 3 *Ghost-free near offset trace before (upper) and after (lower) signature variation correction.*

Another example from another survey is shown in Figure 4. Due to the very complex geology in the survey area, which makes it difficult to distinguish the signature in the data, we focus the display on the direct arrival where the signature with its bubble oscillations is clearly distinguishable. The display on the left shows the raw ghost-free near offset trace while the display to the right shows the same near offset trace after shot to shot correction is applied. The sequence was acquired in relatively calm weather but there was a gun dropout approximately midway between the start of line and end of line. A gun that started to show signs of misbehavior was deactivated and a spare gun with same volume was activated to preserve the source energy output. While the initial peak energy is indeed preserved, we can clearly see that the bubble oscillation trend has changed significantly after the gun dropout and substitution. This difference in the signature before and after the gun dropout has been significantly reduced after the application of the shot to shot correction (Figure 4, right).
The two examples above clearly demonstrate that the shot by shot source signatures, that have been derived from near-field measurements using the method of back-propagation with relative motion described previously, contain the real shot to shot variation - and any other systematic changes - in the signature in the seismic data.

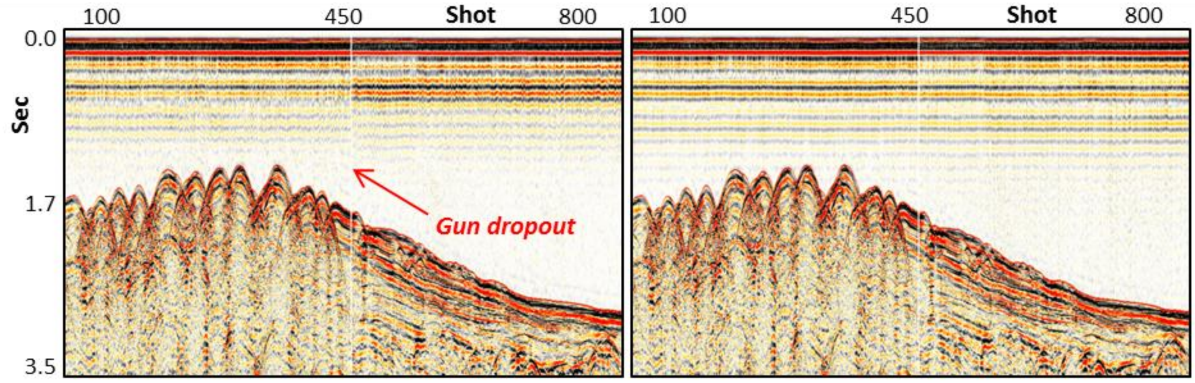

Figure 4 *Ghost-free near offset trace before (left) and after (right) signature variation correction.*

Conclusion

Towing a seismic air-gun source array in highly dynamic sea conditions can result in significant variations in the source geometry and depth throughout a survey. The emitted source wave field is therefore changing continually and so does the signature in the seismic data. Using the method of back-propagation with relative motion, we have been able to estimate the emitted source wave field at every shot point from near-field measurements recorded at the source location. We have confirmed the close relationship between shot to shot signature variation and changes in sea conditions. We have also demonstrated how these and other systematic changes directly affect the seismic data. Finally, we have demonstrated that the derived shot by shot signatures reflect real changes of the signature in the data and we have been able to correct for these variations.

Acknowledgements

We thank PGS for the permission to publish the data. We would also like to thank the dedicated crew members of the PGS vessels that have collected the data and generated on-board the shot by shot signatures used in this work. Special thanks to Wietze Eckhardt for supervising the work on-board.

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