The determination of the far-field signature of an interacting array of marine seismic sources from near-field measurements—results from the Delft Air Gun Experiment

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Data from the Delft Air Gun Experiment demonstrate the success of a new method to determine the far-field signature of a marine seismic source array from near-field measurements. The method requires the wavefield of the array to be measured in the near field with hydrophones of known relative sensitivity and in a known geometrical configuration with respect to the monopole source elements within the array. If there are \( n \) such source elements, at least \( n \) near-field hydrophones are required to determine the wavefield.

The results from a North Sea line shot with a tuned airgun array show that the signature deconvolution for the wavelet calculated from these near-field measurements is at least as effective as the signature deconvolution for the measured far-field signature. The same line was shot again with the air guns out of synchronisation by as much as \( 100 \) ms; the data from the near-field hydrophones allow a deterministic signature deconvolution to be performed to yield a section very similar to that obtained with the tuned array. Without this signature deconvolution on the detuned data, the recovered section is unacceptable.

The full power of the method lies in its ability to specify the whole wavefield for each shot. Thus shot-to-shot variability and source directivity may be taken into account in processing. This power has not been exploited in the results presented here.

Introduction: The far-field measurement

A marine seismic source array of length \( D \) is directional at wavelengths \( \lambda \) that are not large compared with \( D \). For \( \lambda \approx D \) the array has a 'near field' within a range less than about \( D^2/\lambda \), and a 'far field' outside this range (see, for example, Stoffa & Ziolkowski 1983). In a particular direction the shape of the signal changes with distance in the near field. The 'far field' is defined as the region where the shape of the signal does not change with the distance. More precisely, in the far field both the amplitude and phase spectra of the retarded signature (with the traveltime removed) remain the same in a given direction. The signature does of course change with direction in the far field in a frequency-dependent way (see Fricke et al. 1985).

At seismic frequencies in the range 10–100 Hz, the wavelengths are 150–15 m in water with velocity 1500 m s\(^{-1}\). A typical air gun subarray is about 20 m long and is significantly directional at 100 Hz and not significantly directional at 10 Hz. The far field of a single 20 m subarray is at a range of about 35 m for a bandwidth up to 100 Hz, and at about 70 m for a bandwidth up to 200 Hz. A typical air gun array consists of a number of subarrays (see Fig. 3). The total array response is, of course, much more directional than the single subarray response.

A typical far-field measurement would be made as shown in Fig. 1, with the far-field hydrophone some 100 m below the subarray and the set-up almost stationary in the water. The measured signal, vertically below the array, would then be as shown as the upper trace of Fig. 2. This signal is about 200 ms long and is free of contamination from sea bottom echoes because there is sufficient depth of water beneath the far-field hydrophone. Every 75 m depth of water below the hydrophone delays the echo by 100 ms, since the sound has to travel through the water twice. To measure the 200 ms downgoing signal it is therefore necessary to have at least 150 m depth of water below the far-field hydrophone. Thus, to make this measurement at least 250 m depth of water is necessary. (The measurement of Fig. 2 was made in water of more than 400 m depth.)

Most marine seismic exploration is done on the shallow continental shelf at depths less than about 100 m. Production of oil from reservoirs in much deeper water is not of immediate concern. It follows that the far-field measurement of the source signature cannot be made during the seismic survey because the water is too shallow. It must be made in a separate experiment in deep water away from the survey area.

The source signature must vary with direction at

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The sound wave generated by an array of marine seismic sources is not simply the superposition of the sound waves which would be emitted by the individual source elements in the array acting independently. Each source is affected by the other nearby sources. The sources thus interact with one another, the interaction depending on the sizes of the sources and their geometrical configuration. This has been known for some years. Until what is hereafter called ‘the interaction invention’ (Ziolkowski et al. 1981, 1982, 1984), the only method to determine the far-field signature of the array was by measurement in the far field. The invention allowed the whole wavefield (not simply the far-field signature in one direction) to be determined from near-field measurements made in production.

The invention followed directly from an understanding of the interaction mechanism. The sound wave generated by a single air gun is caused by the free oscillations of the bubble emitted by the gun. In an array of air guns each gun produces a separate oscillating bubble generating its own pressure wave. Thus each bubble oscillates in water in which the ambient pressure is fluctuating because of the pressure waves from the other bubbles. The pressure difference across each bubble in the array is thus not the same as it is when the bubble is oscillating on its own. Thus the oscillation of each bubble is modified by the other bubbles and the sound wave generated by these oscillations is also modified. Nevertheless, each bubble is producing a sound wave and, because the bubble is small compared with the wavelengths of this sound wave, the bubble has spherical symmetry.

If there are n sources (air guns, for example) in the array, there are n outward propagating spherical waves, each one centred on the oscillating bubble. Each of these waves has its own signature, known as ‘the notional source signature’ (Ziolkowski et al. 1982; Parkes et al. 1984). The sound wave at any point in the wavefield can be described as a superposition of the n notional source signatures in which there is a traveltime.
delay and a spherical divergence factor for each notional source signature. If the notional source signatures are known, the sound wave at any point in the wavefield can be calculated by this superposition. In particular, the far-field signature of the array can be determined. Thus the key to the determination of the wavefield is the determination of the \( n \) notional source signatures.

A single hydrophone anywhere in the wavefield will measure a sound wave that can be described as the superposition of these \( n \) notional source signatures. If we have \( n \) hydrophones in different places, each one measures something different, because the spherical divergence factors and time delays from any source to the different hydrophones are different. Since there are \( n \) notional source signatures to be found, we must make \( n \) independent measurements of the wavefield. This will yield \( n \) linear equations which can be solved for the \( n \) unknown notional source signatures. The time delays and spherical divergence factors can be calculated if the positions of these hydrophones are known relative to the geometry of the array. In order to relate the hydrophone responses to the pressure field, the relative sensitivities of the hydrophones must be known. Since this theory applies everywhere in the linear field, these measurements can be made very close to the guns, even as close as 1 m away. Because of the spherical divergence factor, the sea bottom echo can be neglected for water depths of about 20 m or greater. (The 20 m distance is of course arbitrary. In practice the noise level on the near-field hydrophones limits the effective dynamic range and 20 m may be a practical figure.) This allows the method to be used in production seismic surveys on the shallow continental shelf.

The invention thus consists of three parts. First, the measurement of the pressure field at \( n \) different known locations in the near field of the array. These measurements then define the wavefield. Secondly, the extraction of the notional source signatures from the measurements. Thirdly, the calculation of the wavefield, in particular the far-field signature in the vertical direction, by superposition of the notional source signatures.

Figure 1 shows an experiment to measure the vertically-travelling far-field signature, and also shows the \( n \) near-field hydrophones. Figure 2, taken from Parkes et al. (1984), shows a comparison of the measured far-field signature and the signal calculated from the near-field measurements made at the same time. It can be seen that the calculated far-field signature very closely resembles the far-field measurement.

The Delft Air Gun Experiment

Figure 2 was such a convincing demonstration of the power of this invention that it was not difficult to find sponsors willing to test the method in production. The test was carried out in May 1983 in the North Sea as part of the Delft Air Gun Experiment. The background to this project was described by Ziolkowski (1984).

For the interaction invention we made two tests. The first was to shoot a 20-km seismic line in the North Sea using a square air gun array of four identical subarrays, as shown in Fig. 3. Each subarray was as shown in Fig. 1. The seven near-field hydrophone responses for each subarray were digitally recorded on tape for each shot, the analogue filters being the same as for the receiver channels. The guns were fired simultaneously for each shot, using an LRS 100 gun controller to maintain synchronisation. The shot interval was 25 m, the receiver group interval was 25 m, and there were 100 receiver groups. The receiver cable depth was 7.5 m±1 m. The data were recorded with a 3.5 Hz low cut filter and a 128 Hz high cut filter, and sampled at 2 ms intervals.

The second test (test 5 in the experiment) was the same line, shot with the same parameters, except that the guns were not fired simultaneously.

Fig. 3. Plan of the configuration of air gun subarrays used in the experiment.

Test 1: line 1 (the tuned air gun source)
The first test was to determine whether the interaction method yielded results as good as the conventional
method, based on the far-field measurement. The data were processed to enable a comparison to be made between the conventional method and the new method using the interaction invention. The pre-stack processing was as follows: (1) signature deconvolution to minimum phase; (2) exponential gain correction \(e^{\omega t}\) to make the data more nearly stationary; (3) predictive deconvolution to remove sea-bottom multiples (using a 180-ms operator with a 60-ms gap); (4) removal of gain correction \(e^{-\omega t}\).

In this sequence the only process that depends on the signature is the signature deconvolution. In this process two far-field signatures could be used: the far-field signature as measured in the far field (the upper signature of Fig. 2), and the far-field signature calculated from the near-field measurements made in production. In order to make a comparison, the data were copied after demultiplex and the two sets processed in exactly the same way, except for the signature deconvolution. For a further comparison we made a third copy which was processed without any signature deconvolution.

The far-field signature of Fig. 2 was recorded with no low-cut filter and with a 128 Hz, 72 dB octave $^{-1}$ high-cut filter. The sampling interval was 2 ms. The elements of the signature deconvolution process are shown in Fig. 4. The signature is shown in 4(a), the desired minimum-phase output is shown in 4(b), the least-squares Wiener filter is shown in 4(c) and the convolution of 4(a) and 4(c) (the actual output) is shown in 4(d). Figure 5 shows the corresponding amplitude spectra. Since the far-field signature is not minimum phase, the desired minimum-phase output signal had to be delayed 100 ms to allow a causal shaping filter to be computed. The filter compresses the signal very well, with very little noise apparent in either the time domain or the frequency domain.

Every trace of every shot in the conventionally processed data was convolved with the filter shown in Fig. 4(c). Figure 9 shows a portion of the resulting stacked seismic section.

For the calculation of the far-field signature from near-field measurements, there were many possibilities. For every shot there was a different set of near-field measurements, so in principle a different signature could be calculated for every shot, to compensate for any shot-to-shot variations. Since the far-field signature could be calculated in any direction, it was in principle possible to use a signature other than the vertical one. It is even possible, with this data set, to take into account the variations of the signature with direction. For the Delft Air Gun Experiment we calculated only one vertical far-field signature and this was based on only one set of measurements from one air gun subarray.

Figure 6(a) shows the near-field hydrophone measurements recorded for one shot, and 6(b) shows the notional source signatures calculated from these measurements. The vertical far-field signature is then calculated from these notional source signatures by superposition and with the inclusion of the sea surface reflection. This signature is shown in Fig. 7(a). It differs slightly from the far-field signature calculation of Fig. 2 because a 3.5 Hz low cut filter was used for the production line.

Figure 7 shows the signature deconvolution using this calculated far-field signature: 7(a) shows the signature; 7(b) shows the minimum-phase 'desired output' signature, which is the same as 4(b); 7(c) shows the least-squares shaping filter; 7(d) shows the convolution of
Fig. 5. Amplitude spectra corresponding to the time signatures of Fig. 4 plotted on a linear scale: (a) the far-field signature spectrum; (b) the desired output spectrum; (c) the Wiener shaping filter spectrum; (d) the multiplication of spectra (a) and (c).

Fig. 6. (a) Traces 15–21: a set of near-field measurements from the air gun subarray shown in Fig. 1, for the tuned array, test 1, line 1; (b) traces 8–14: the notional source signatures derived from the measurements (a).
7(a) and 7(c) (the actual output). Figure 8 shows the amplitude spectra of the four wavelets of Fig. 7. Again the signature is not minimum phase and a time delay of about 250 ms had to be introduced into the desired output to allow the filter to be causal. The main difference between the filter 7(c) and that shown in 4(c) is caused by the introduction of a low-cut filter for the near-field measurements. This filter is not necessary for these measurements, of course, but was used to attenuate low-frequency noise in the seismic reflection data.

The result of using the signature deconvolution of Fig. 7(c) on the data is shown in Fig. 10. A comparison of Figs 9 and 10 shows very little difference. The full power of the interaction invention has yet to be exploited on these data: it is still possible to take into account source directivity and shot-to-shot signature variations. From this simple comparison it is clear that the invention allows the data to be processed with a resolution at least as good as with a careful far-field measurement.

For comparison, Fig. 11 shows the result of omitting the signature deconvolution step. The source signature is so good that, even without signature deconvolution, this is an acceptable section. However, the signature deconvolution does increase the resolution especially at depth, as expected.

There is nothing surprising about the comparison between Figs 9 and 10. Once the test of the invention shown in Fig. 2 is accepted, the comparison between Figs 9 and 10 is to be expected. We therefore decided to put the invention to a more severe test.

**Test 5: Line 1R (the detuned air gun source)**
A sharp source signature is obtained by ensuring that the air guns are fired together, and a gun controller is used to ensure synchronisation to within about 1 ms. Marine data acquisition specifications usually require gun synchronisation to better than ±2 ms. At the suggestion of John Broom of Britoil, we decided to shoot the line again with the guns wildly out of synchronisation with random time delays between guns (the line was in the same place, but shot in the reverse direction). To make the processing easier, we used the LRS 100 gun controller to maintain poor synchronisation, and we made all the subarrays fire their guns in the same sequence. The firing order was as follows: 4, 2, 5, 1, 6, 7. All guns no. 4 fired together, all guns no. 2 fired together about 30 ms later, then all guns no. 5, etc. The time delay between the firing of the guns no. 4 and the guns no. 7 was 99 ms.

Figure 12(a) shows the near-field hydrophone measurements from one of the subarrays for one shot. Figure 12(b) shows the notional source signatures calculated from these measurements, and Fig. 13(a) shows the vertical far-field signature calculated from these notional sources.

In processing this line we wanted to show that the near-field measurements were essential to determine the far-field signature for deconvolution. That is, we
copied the data after multiplexing and processed one set without signature deconvolution, and the other set with signature deconvolution. The processing was otherwise identical with that for test 1. The section without signature deconvolution is shown in Fig. 15, the section with signature deconvolution is shown in Fig. 16.

Details of the signature deconvolution process are shown in Figs 13 and 14, and we see that the spectrum of the signature of 13(a) has many deep notches, as shown in Fig. 14(a). The filter 13(c) has a very difficult job to compress the signal of 13(a) to the wavelet (13b), and manages to do so only with the introduction of significant noise, as shown in 13(d). The noise is inevitable because of the huge difference in amplitude spectra of the signature and the desired minimum-phase output wavelet. For signature deconvolution of the data, every trace of every shot of the line was convolved with the filter 13(c). The resulting stacked seismic section of Fig. 16 is recognisably the same as that shown in Figs 9 or 10. Without signature deconvolution (Fig. 15), the result is clearly unsatisfactory.

Obviously the signature shown in Fig. 13(a) is far from ideal, and no one would knowingly shoot seismic data with such a poor signal. The processing of the data, using the far-field signature calculated from the near-field recordings, clearly shows that it is possible to retrieve something from this apparently hopeless situation, and produce an acceptable result. In practice, of course, one would not expect production parameters to be as wildly out of specification as in this second test.

Conclusions
The determination of the far-field signature of a marine seismic source array by measurement in the far field vertically below the array suffers from a number of difficulties. First, it cannot be made in water shallower than about 250 m, and therefore cannot be made during the vast majority of marine seismic surveys carried out for the oil industry. Secondly, the far-field measurement must normally be made with the hydrophone and the source array almost stationary in the water. In normal surveying the ship’s speed is about 5 knots, and the guns are lifted up somewhat relative to their positions when the ship is not moving. Thus the normal far-field measurement cannot give the signature used in the survey. Thirdly, the signature shape varies with direction, but the normal far-field measurement cannot measure this variation. Finally, shot-to-shot variations in the signature during the survey cannot be measured by the separate far-field measurement in deep water.

The interaction invention overcomes all of these difficulties, but requires that the pressure field of an n gun source array be measured in at least n known positions in the near field. These measurements define the wavefield of the source array and, from these measurements, the far-field signature of the array can be calculated in any direction.

In two tests of this invention carried out in the North Sea as part of the Delft Air Gun Experiment, the near-field hydrophone measurements were used to calculate
Fig. 9. A piece of the processed data from line 1, test 1, in which the signature deconvolution operator was calculated from the far-field measurement as described in Figs 4 and 5. The displayed section is 8.75 km long.
Fig. 10. The same data as Fig. 9, except that the signature deconvolution operator was calculated from the near-field measurements as described in Figs 6, 7 and 8.
Fig. 11. The same data as Figs 9 and 10, without signature deconvolution.
Fig. 12. (a) traces 8–14: a set of near-field measurements from the air gun subarray shown in Fig. 1, for the detuned firing test of test 5, line 1R; (b) traces 1–7: the notional source signatures derived from the measurements (a).

Fig. 13. Signature deconvolution using the far-field signature calculated from near-field measurements, test 5, line 1R: (a) the far-field signature; (b) the minimum-phase desired output signal, same as 4(b) and 8(b); (c) the Wiener shaping filter for a 500-msec delay in the desired output (0.5% white noise was added to stabilise the calculation); (d) the convolution of (a) and (c) (not on the same timescale).
Fig. 14. Amplitude spectra corresponding to the time signatures of Fig. 13 plotted on a linear scale: (a) the spectrum of the far-field signature; (b) the desired output spectrum; (c) the Wiener shaping filter system; (d) the multiplication of spectra (a) and (c).

the vertical far-field signature for use in the design of a signature deconvolution operator. In the first test a 20-km line was shot with a tuned air gun array for which a vertical far-field measurement was available. The result of signature deconvolution based on the near-field measurements was at least as good as that based on the far-field measurement. In the second test the line was shot again with a detuned air gun array in which the guns were out of synchronisation by up to 100 ms. Signature deconvolution based on the near-field measurements was able to recover an acceptable seismic section that can be compared with that shot with the tuned array. The section recovered without this signature deconvolution of the detuned data is unacceptable.

It has now been clearly demonstrated that near-field measurements can be used to define the wavefield of the source array and can be used for signature deconvolution. The far-field measurement is now obsolete for this purpose. In the tests described above the near-field measurements allow both shot-to-shot variations in the wavefield and the source directivity to be taken into account. In the results shown these variations have been ignored. However, there are possibilities for further improvements in the resolution of the data by considering these factors.

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Alek Gorski of Merlin Geophysical processed all the data and made valuable contributions at every step of the processing, especially in the signature deconvolution. My former students computed the notional source
Fig. 15. A piece of the processed data from line IR. test 5, shot with the detuned air gun array, in which no signature deconvolution was performed.
Fig. 16. The same data as in Fig. 15. Signature deconvolution was applied using the filter shown in Fig. 13(c), calculated from near-field measurements as described in Figs 12, 13, and 14. Compare this figure with Figs 9 and 10 shot with the tuned air gun array.
signatures from the near-field measurements and calculated the far-field signatures (Cees van der Schans of Shell) and designed the minimum-phase desired output signature (Wietze Eckhardt of Jason Geosystems).

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