Signature estimation and drop-out implications for a triple source marine seismic survey

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SUMMARY

We demonstrate the compatibility of modern far-field signature estimation with triple source acquisition and the resilience of this estimation in the face of drop-outs. Our results are based on data acquired with a two-string, 2965 cubic inch source array, and with a de-tuned 2415 cubic inch variant of that array which exhibits reduced peak amplitude and lower primary-to-bubble ratio. Modelled signatures were compared with those derived by least-squares inversion of near-field hydrophone measurements, according to the method discussed in Hargreaves *et al.* (2015, 2016) and, after examining different choices of ghosting parameters, we derive de-signature operators and apply these to seismic shot records. We find that the de-tuned 2415 array gives comparable results to the full array after de-signature, which is encouraging for robustness of signature estimation in the face of drop-outs. We note improved de-signature results using a frequency-dependent sea-surface reflection coefficient which is smaller than predicted based on the sea state reported during acquisition. This suggests energy loss mechanisms are significant in the vicinity of the source array.

Introduction

Modern far-field source signature estimation and triple-source acquisition are two new tools in 3D marine acquisition. An example of modern far-field signature estimation is the least-squares technique of Hargreaves *et al.* (2015, 2016), which uses near-field hydrophone (NFH) data as inputs. This technique has proven to be quite robust with traditional three-string dual-source arrays, for example those with 18 source elements. Triple-source surveys often use two-string arrays as most seismic vessels are equipped with six strings for dual three-string array operations. While this reduces peak amplitude, and therefore environmental impact, it also means a two-string triple-source array is more sensitive to the drop-out of any individual source element. Additionally, the reduction in the number of source elements and NFHs increases sensitivity of the inversion to noise. In this paper we present results on far-field signature estimation and de-signature processing for a triple-source array and a de-tuned variant which represents a source drop-out condition worse than normally allowed in quality control specifications. Modelled signatures are compared to near-field hydrophone estimates. Ziolkowski (1987) investigated signature estimation and de-convolution for tuned and de-tuned airgun arrays in the band 10-100 Hz. We extend this to the range 2-200 Hz to assess de-bubble performance at low frequency and sensitivity to modelling of the source ghost at the high-frequency end. After examining different choices of ghosting parameters we derive de-signature operators and apply them to seismic shot records.

Method

Estimation of broadband source signatures (2-200 Hz) via inversion of NFH data relies on a relatively simple physical model of wave propagation and reflection occurring in the vicinity of the source array (see for example the original work of Ziolkowski *et al.* 1982, Parkes *et al.* 1984 and more recently Hargreaves *et al.*, 2015). Inclusion of bubble motion, use of measured rather than nominal x-y-z gun positions and use of a frequency-varying reflection coefficient to treat reflection from a rough-sea, refine the basic approach and generally allow us to de-signature data to a high standard. Nevertheless the model is still probably an over-simplification and for ghosting in particular we fit parameters that best explain the data (e.g. Hargreaves et al., 2016). We vary the reflection coefficient (**r**) via the significant wave-height parameter, *h*, see Figure 1, and also vary the array depth *z*, jointly with the aim of fine-tuning signatures. Parameter *h* modifies **r** as a function of frequency according to a Gaussian roughness model, (e.g. Jovanovich *et al.* 1983, Orji *et al.* 2013), and *h* is taken as four times the root-mean-square wave height. We assume **r** at 0 Hz is -1.0.

The triple-source 2965 in^3 array used for this test has twelve elements on two-strings. Modelled peak far-field output is 47 bar-m and primary-to-bubble ratio 22.8. The 2415 in^3 de-tuned variant is based on the 2965 but with two guns switched off, for an output 43 bar-m and primary-to-bubble ratio of 10.6. Both sources were deployed at 7 m and operated at 2000 psi. During the test data acquisition in the Barents Sea the crew noted a significant wave height of 1 m.

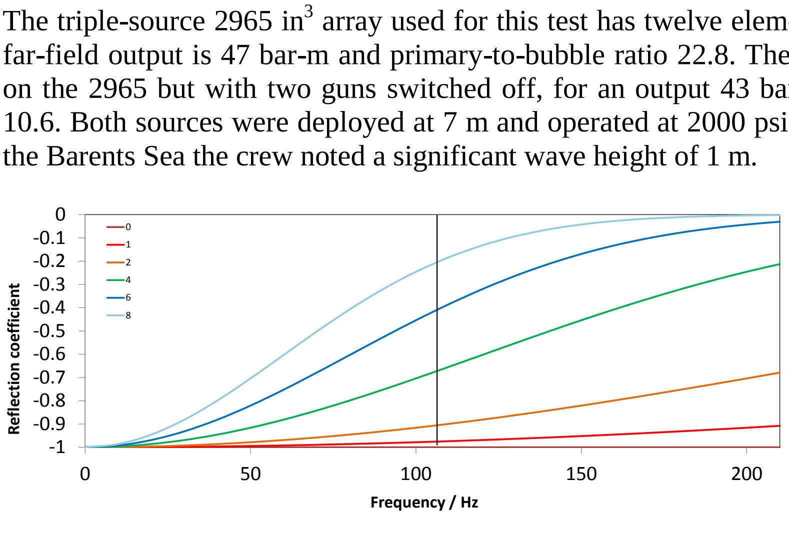

Figure 1 **r** *as a function of frequency for variation of the parameter h, which physically represents significant wave height in meters. The vertical line marks the ghost notch frequency for an array at 7 m depth.*

Results

Figure 2 shows the far-field signature at vertical take-off for the 2965 array obtained with and without optimisation. The optimised wavelet with *z*=7 and *h*=6 is free from spurious oscillations close to the main pulse. Figure 2 also shows a comparison of the optimised far-field signatures for the 2965 and 2415 arrays, to demonstrate that differences in peak amplitude and peak-to-bubble ratio are well captured by NFH inversion. Figures 3-4 show modelled spectra at vertical take-off for the 2965 array compared with those estimated from the NFH data for different parameter values: a high value of *h* (top) and a *z* value in the range 6.5 to 7m (bottom) for the NFH inversion best match the character of the modelled signature. Figure 5 shows a comparison of our estimates for each array with the wavelets extracted from the sea-bed, after flattening and stacking the sea-bottom wavelet on common offset sections. Directional signatures were estimated from the NFH data for take-off angles from -30^0 to $+70^0$ and operators were derived to de-convolve the seismic data, matching to a zero-phased Ormsby wavelet. The results of de-signature are shown in Figure 6 and discussed in the next section.

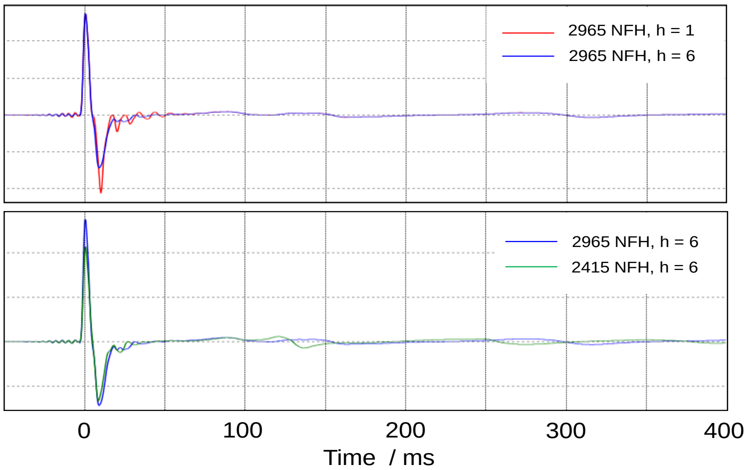

***Figure 2** Top: Ghosted far-field signatures estimated for h=1 (red) and h=6 (blue). h=6 is the optimised result, reducing ringing at the source ghost notch frequency. Bottom: Optimised wavelets for the 2965 (blue) and de-tuned 2415 array (green).*

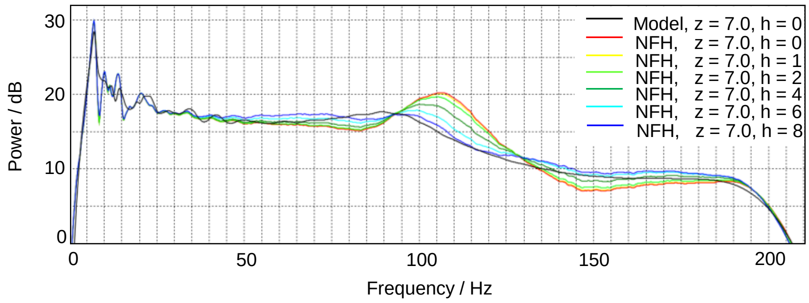

***Figure 3** 2965 far-field signatures without ghost: comparison of modelled signature (z=7 m) to NFH estimated signatures with depth fixed at 7 m and varying h.*

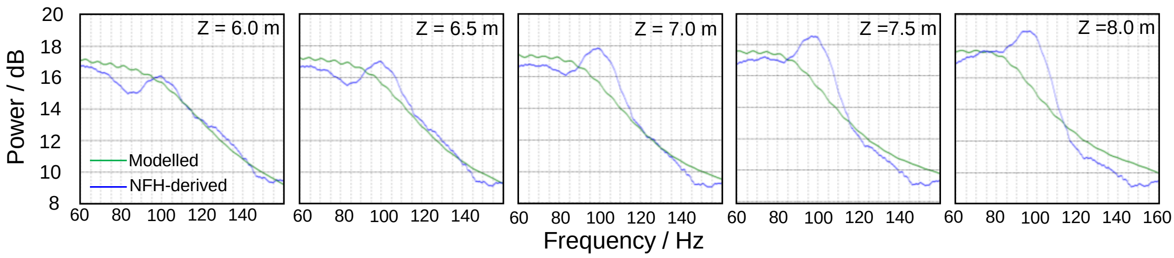

***Figure 4** 2965 far-field signatures without ghost: comparison of NFH-derived signatures (h=6) to modelled signatures as a function of depth z, varying in range ± 1 m.*

Discussion

In Figure 6, the de-signature results for the reference (2965) and de-tuned (2415) array are comparable in appearance and the effect of optimization on the signature is to substantially reduce residual ghost energy in the form of ringing. Best results were obtained by reducing the magnitude of the sea-surface reflection coefficient **r** as a function of frequency, but more so than suggested by using the rough-sea model with *h*=1 m, the observed significant wave height during acquisition. Some confidence in our derivation is provided by comparison with the wavelets extracted from the sea-bed (Figure 5). Others too have noted low **r** values on the source-side e.g. Ni *et al.* (2012) inferred **r** as low as -0.5 at vertical incidence. Their suggestion that this may have been due to attenuation by the source floats is unlikely given that their area above the array is estimated to be less than 5% of the Fresnel zone at 100 Hz that contributes to the reflection.

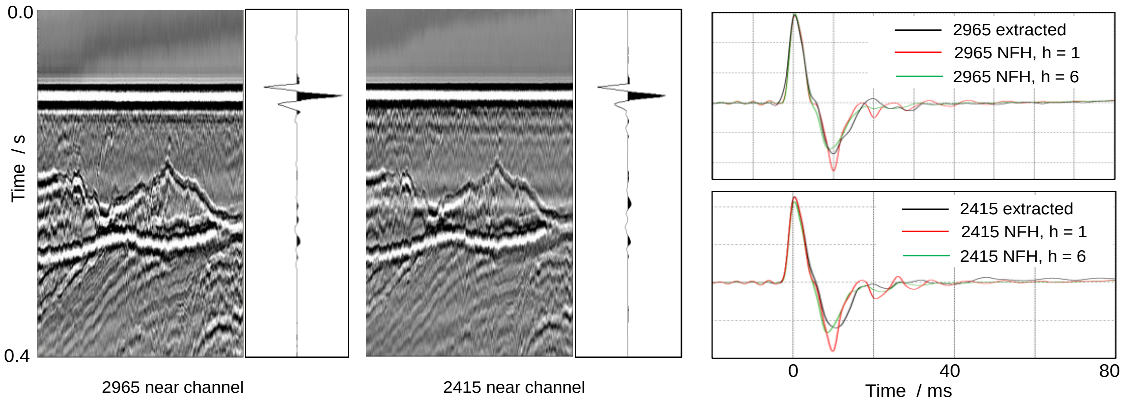

Figure 5 *Sea-bed extracted wavelet for each array (left). These are receiver de-ghosted and compared (right) with NFH-derived wavelets for h=1 (red) and h=6 (green).*

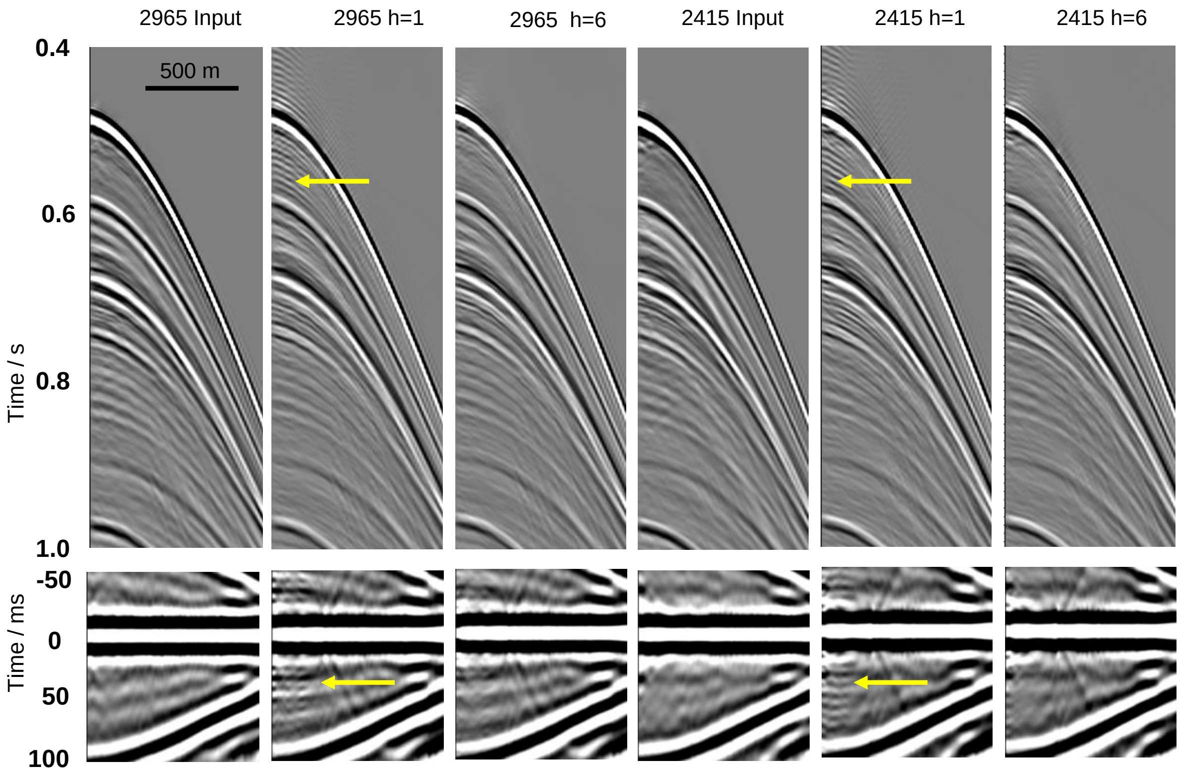

Figure 6 *De-signature processing on an example shot gather(top) and corresponding autocorrelation (bottom), for the 2965 and 2415 arrays showing the sequence of input, result with h=1, and with h=6.*

Kryvohuz *et al.* (2016) and Kryvohuz and Campman (2017) estimated frequency-dependent **r** via NFH measurements, finding values of around -1.0 at 0 Hz and -0.5 at 100 Hz. Hatton (2007) reported **r** in the range -1.0 to -0.3, depending on incident pressure, citing non-linear effects that accompany the high intensity acoustic field close to the source, similarly in Hampson (2017), although without comment on frequency dependence in **r**. The phenomena that may explain observed energy loss include the formation of a transient cavitation cloud in the proximity of the array, e.g. Landro *et al.* (2016) and also formation of a spray dome arising from the high particle velocity at the free-surface. Cavitation can occur when the magnitude of the ghost exceeds the tensile strength of sea-water (note the modelled ghost for 2965 array and **r**=-1.0 is -47 bar-m, suggesting this criterion is met), and lasts of the order of 10 ms (Landro *et al.* 2016). A consequence is that we expect a reduced maximum amplitude for the source ghost i.e. reduced magnitude of **r**, and generally a loss of coherent energy in the ghost wave-field that increases with frequency: equating 10 ms duration to a quarter-cycle, leads us to expect the effect to be significant above 25 Hz**.**

Conclusions

We have demonstrated that the use of low environmental impact two-string arrays in triple source acquisition is compatible with modern far-field signature estimation, and that a de-tuned source with reduced peak amplitude and primary-to-bubble ratio can offer comparable data quality after de-signature using optimised far-field signature estimates. The results indicate that the signature estimation method is robust with respect to array changes that may occur due to drop-outs. It was necessary to assume a frequency-dependent **r** with greater reduction in magnitude than predicted for coherent interference effects for the observed sea-surface roughness. This suggests acoustic energy loss mechanisms are at play in the proximity of the source array that reduce amplitude of the source ghost. Further understanding of this may be gained by making extra measurements in the near field, as suggested by Parkes and Hatton (1986) and investigated recently by Kryvohuz (2016), Kryvohuz and Campman (2017) and Hampson (2017).

Acknowledgements

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References

Hampson, G. [2017]. Notional ghosts. *86th Annual SEG Meeting* Expanded Abstracts

Hargreaves, N., Grion, S. and Telling, R. [2015]. Estimation of air-gun array signatures from near-gun measurements - least-squares inversion, bubble motion and error analysis. *85th SEG Meeting* Expanded Abstracts, 149-153.

Hargreaves, N., Telling, R., Grion, S. [2016]. Source deghosting and directional designature using near-field derived airgun signatures. *78th EAGE Conference and Exhibition*, Extended Abstracts

Hatton, L. [2007]. An empirical relationship between surface reflection coefficient and source array amplitude. www.leshatton.org

Jovanovich, D. B, Sumner, R. D. and Atkins-Easterlin, S. L. [1983]. Ghosting and marine signature deconvolution. *Geophysics*, **48** (11) 1468-1485.

Kryvohuz, M. and Campman, X. [2017]. Source-side up-down wavefield separation using dual NFHs, *79th EAGE Conference and Exhibition*, Extended Abstracts

Kryvohuz, M [2016]. Optimization of sea-surface reflection coefficient and source geometry in conventional dual source flip/flop marine seismic acquisition. *86th Annual SEG Meeting*, Expanded Abstracts, 188-192

Landro, M., Ni, Y. and Amundsen, L. [2016]. Reducing high-frequency ghost cavitation signals from marine air-gun arrays, *Geophysics*, **81**, P33-P46

Ni, Y., Niang, C., Siliqi, R. [2012]. Monitoring the stability of airgun source array signature. *82nd Annual SEG Meeting*, Expanded Abstracts, 1-5

Orji, O., Sollner, W. and Gelius, L. J. [2013]. Sea surface reflection coefficient estimation. *83rd Annual SEG Meeting*, Expanded Abstracts, 51-55.

Parkes, G. E., Ziolkowski, A., Hatton, L. and Haugland, T. [1984]. The signature of an airgun array: computation from near-field measurements including interactions — Practical considerations. *Geophysics*, **49**, 105–111

Parkes, G. and Hatton, L. [1986] *The Marine Seismic Souce*. D. Reidel, Dordrecht

Ziolkowski, A., Parkes, G., Hatton, L. and Haugland T. [1982]. The signature of an air gun array: Computation from near-field measurements including interactions. *Geophysics*, **47** (10), 1413-1421.

Ziolkowski, A. [1987].The determination of the far-field signature of an interacting array of marine seismic sources from near-field measurement – results from the Delft air gun experiment. *First Break*, **5** (1), 15-29