Source ghost generation: observations from a dual near-field hydrophone test

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Summary

We evaluate experimental data acquired using a dual-string airgun array instrumented with two near-field hydrophone (NFH) channels per source element, and use these data to estimate far-field signatures without need for assumptions on the reflectivity of the sea-surface (Parkes and Hatton, 1986). The acquired NFH data are consistent with the presence of cavitation in the down-going wavefield and reveal details of the wavefield which are not predicted by a conventional ghost model. Directional de-signature operators are derived and applied to seismic data shot using the test configuration. Results are compared with a reference dataset processed using signatures estimated in the typical way i.e. from just one channel per element of NFH data, and using a frequency-dependent sea-surface reflection coefficient. We discuss the potential benefits of using additional NFH and outstanding issues going forward.

Introduction

Source signature estimation using NFH measurements is a well-established procedure and is typically based upon one channel of NFH data per source element (which may be a single gun or a gun cluster) and solving for notional sources, for example by iterative methods (Ziolkowski *et al.* 1982, Parkes *et al.* 1984) or least-squares inversion (Hargreaves *et al.* 2015). The notional sources are then used to derive directional far-field signatures. This problem is well-posed but it is necessary to assume a ghost model, parameterized by a time delay and reflectivity at the sea-surface (Hargreaves *et al.* 2016). Parkes and Hatton (1986) proposed that if two channels of NFH data are recorded per source element, notional sources and their virtual image may each be solved for directly, amounting to a separation of the up-going and down-going wave-fields. This approach, and more generally, exploiting additional NFH measurements, has recently received renewed interest (Hampson, 2017, Kryvohuz and Campman, 2017) as it can provide a better understanding of source ghost generation mechanisms and provide insight into why apparent sea-surface reflectivity is often lower than expected, even when taking into account sea-surface roughness (Kragh and Combee 2000, Ni *et al.* 2012, Telling *et al.* 2018).

Near-field data

The source array comprised two strings each with six source elements nominally at 7m depth, spaced at 3m in-line, with 8m cross-line between the strings, and total volume 2740in^3. NFHs were placed at depths of 6m and 4m. The shallower hydrophones were attached to the vertical suspension for the test, which led to some additional noise on the recordings; however for the main events the signal-to-noise was high. An example of the recordings, sampled at 0.5ms and taken from the starboard string, is given in Figure 1. A feature, especially obvious in the shallower recordings (which are closer to the sea-surface so that the ghost features more prominently) is that when the positive pulse is large, the negative amplitude is clipped. In other words, despite the calm sea-surface conditions during acquisition, the effective sea-surface reflectivity is not -1 and cannot be described by a single scalar. After this clipping, there follow some additional oscillations. Both clipping and oscillation are likely due to cavitation (Landro *et al.* 2016). Figure 1 also shows a comparison of the data with a synthetic trace constructed by forward modelling a simple Ormsby wavelet defined by four frequencies viz. 1-4-100-400Hz and assuming a ghost model with standard assumptions about the reflectivity arising from a 1m significant wave height rough sea-surface (see for example Jovanovich *et al.*, 1983), which is consistent with the sea state as described in the observer logs. There is broad agreement between the real data and synthetic on the timing, peak levels and shape of the positive arrivals but much poorer agreement on the ghost arrivals, notably due to clipped amplitudes and the appearance of subsequent lower-amplitude oscillations at about 10ms intervals.

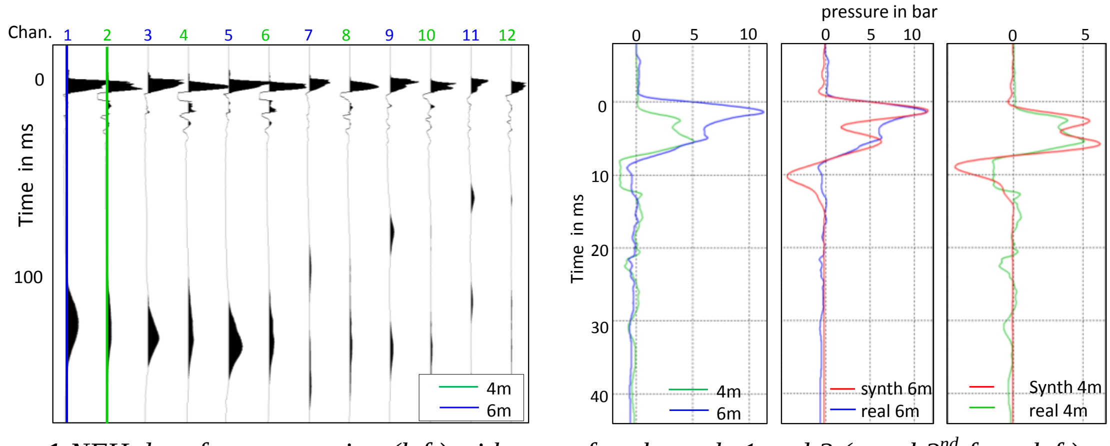

Figure 1 *NFH data from one string (left) with zoom for channels 1 and 2 (panel 2nd from left) which are co-located in x-y at depths of 4m and 6m respectively, followed by a comparison between real and synthetic recordings (3rd and 4th panels from left).*

Signature estimation

We estimated reference signatures using a least squares inversion method (Hargreaves *et al.* 2015, 2016) deriving 12 notional sources using recordings from the 12 hydrophones placed at 1m from the guns. We then estimated signatures using the dual configuration i.e. 24 hydrophones (Parkes and Hatton, 1986, Hampson, 2017) to derive 12 notional sources and 12 image sources. In the dual NFH method, the primary and ghost components of the far-field may be separately constructed from the corresponding set of derived notional signatures – see Figure 2 (left) or combined to give the total estimated far-field signature including the ghost – see Figure 2 (right). We used measured *x*, *y* and *z* coordinates of each source element derived from R-GPS positions and gun depth sensors respectively and assumed mirror positions for the virtual source element positions. A comparison between the total signature derived using dual NFHs without a free-surface assumption and the reference signature derived using single NFHs and a free-surface reflectivity defined by a significant wave height parameter, *h*¸are shown in Figure 3. The left-hand plot was derived using *h*=1m and the right-hand plot using *h*=4m. For reference, in the vicinity of the ghost notch frequency (nominally 107 Hz) for *h*=1m we have a reflection coefficient, *r* =-0.97 and for *h*=4m, we have *r* =-0.65. In both cases we have *r* =-1.0 at 0Hz. Directional signatures were derived from -30 to +70 degrees, and a de-signature operation was applied to the seismic data in τ-*p*, encapsulating source de-ghosting, de-bubble and matching to a zero-phase Ormsby wavelet. The results are shown in Figure 4 and indicate successful de-signature for all but the reference with nominal wave height parameter *h*=1m, which exhibits some residual ghosting artifacts. A further observation (not shown in these images, as it was only apparent at high angles e.g. far-offsets and on the direct arrival) is a slightly poorer performance for the test signature at de-convolving the later time bubble pulses. We noted higher noise level for the NFHs mounted at the 4m position: the relatively small bubble signal at later times means a lower signal-to-noise, which could explain this performance deficit. A dedicated rigid mounting position for these NFHs would help in this regard.

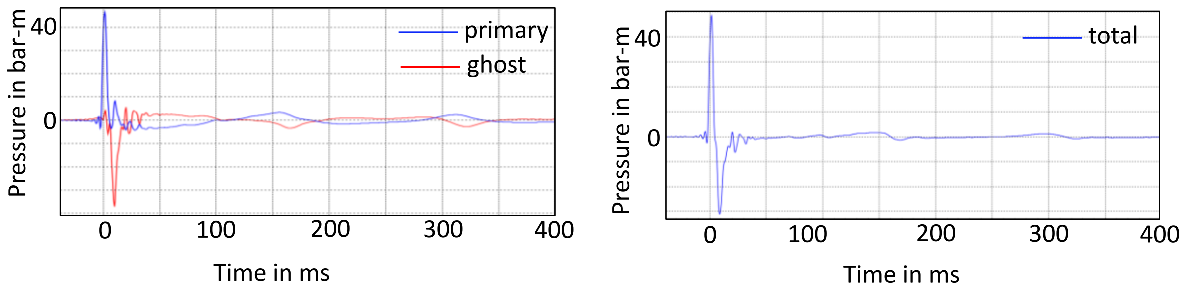

Figure 2 *Vertical far-field signatures estimated using dual NFH separated into components derived from source (primary) notionals and image source (ghost) notionals (left) and the total far-field signature (right).*

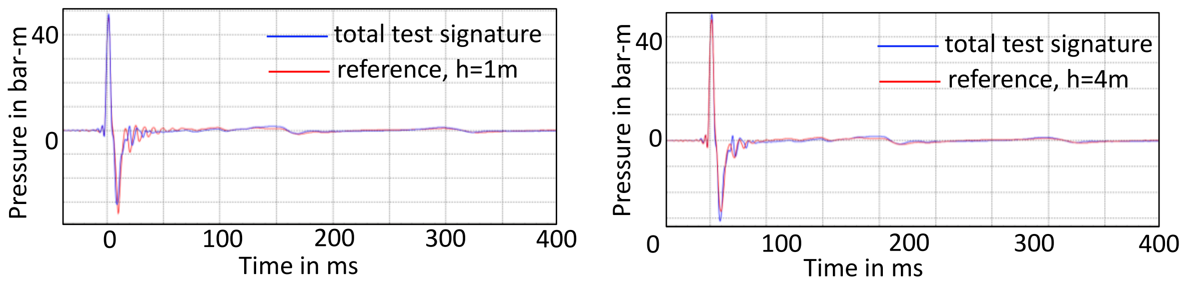

Figure 3 *Vertical far-field signature estimated using dual NFH (blue) compared against a signature estimated using a single NFH per source element (red) with the assumption of a wave height parameter, h=1m (left) and h=4m (right).*

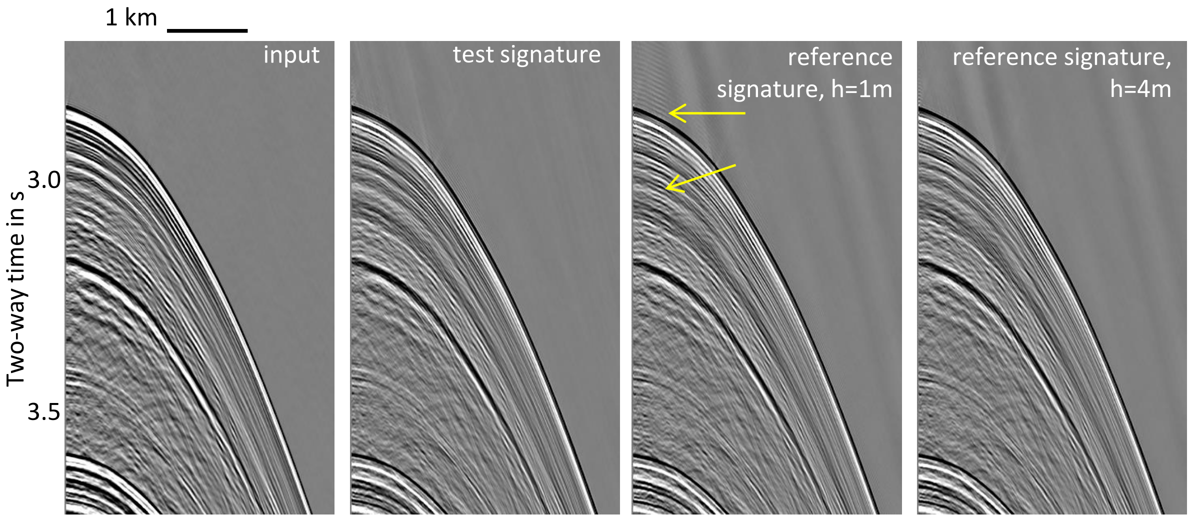

Figure 4 *Vertical far-field signature estimated using dual NFH (blue) compared against a signature estimated using a single NFH per source element (red) with the assumption of a wave height parameter, h=1m (left) and h=4m (right).*

Conclusions

The ghost amplitude is lower than expected for the given sea-state as observed here and in other studies and is consistent with the observation of clipping of the ghost in the near-field data. This is probably due to onset of cavitation in the water during ghost generation, e.g. as described in Landro *et al.* (2016) in addition to other non-linear effects (Hampson, 2017). Cavitation may arise since positive pressures of several bars of magnitude are emitted from the array and reflection at a free-surface will ultimately attempt to drop the pressure below zero putting the water into tension.

Using two NFH measurements per source element, we were able to derive a series of far-field signatures without making assumptions on the free-surface reflectivity and we used these to successfully de-signature the seismic data. The quality of the signatures appears to offer an improvement over those derived via the reference method with assumed nominal sea-surface reflectivity. This is due to the better representation of the ghost amplitude. When the magnitude of reflectivity is reduced at high frequencies (more so than expected for the given sea-state), results of the two methods are more comparable. This independent result validates the use of frequency dependent reflection coefficients. Signature estimation with dual NFH is a promising technique as it eliminates ghost parameterization and optimization and by incorporating finer details into the down-going wave-field also has potential to improve de-signature quality.

Acknowledgements

The crew of the *Polar Empress* and an undisclosed client are thanked for their cooperation in carrying out the test.

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