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

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Summary

In this paper, we investigate source ghost generation using experimental data acquired using a dual-string air-gun array instrumented with two near-field hydrophone (NFH) channels per source element instead of the usual single NFH per source element. The extra NFHs enable us to solve directly for source ghosts, sidestepping the requirement for a ghost model. Experience has shown that the standard ghost model does not always represent well the physics of ghost generation for an air-gun array. In practice this model is typically parameterized via a frequency-dependent effective reflectivity, the magnitude of which often needs to be reduced more than expected for the effects of rough sea-surface scattering. The NFH recordings in this test are compared with synthetic data to highlight problems with the standard model of ghost generation and the results suggest that acoustically induced cavitation is responsible for the observed reduction in the amplitude of the ghost. We show examples of de-signature on seismic data using operators derived with and without a ghost model and discuss the merits and potential issues going forward.

Introduction

Far-field source signature estimation using NFH measurements has become an established technique that is key to accurate broadband de-signature of seismic data. The technique typically relies on the source array being instrumented, usually with one channel per source element which may be a single gun or a gun cluster. The NFH data are first used to solve for notional sources. These are defined as the signatures from a gun or gun cluster when the other guns in the array are firing and include interaction effects. A far field signature for the array can then be calculated as the superposition of the notional sources with appropriate phase shifts (Ziolkowski et al., 1982; Parkes et al., 1984). Notional signatures are found through least-squares inversion of the hydrophone data (Landrø and Sollie 1992; Hargreaves et al. 2015) using a simple model for propagation within the array and for the ghost arrivals, parameterized by a time delay and reflectivity at the sea-surface (Hargreaves et al., 2016). A problem with this simple model is that the source ghost can be smaller than expected, even when taking account of changes in reflectivity due to rough sea-surface scattering (Kragh and Combee, 2000; Ni et al., 2012; Telling et al., 2018a). An example taken from one of these studies is provided in Figure 1 where significant wave height (SWH) is used as a proxy to parameterize the reflectivity via the Rayleigh rough-sea model (Jovanovich et al., 1983). In the example shown, de-signature using the SWH=1m value observed during acquisition leads to visible artefacts in the data (yellow arrow), while using SWH=6m gives good results. Parkes and Hatton

Recent studies on signature estimation have been motivated to improve the representation of the source ghost by sidestepping the ghost model assumptions. Hampson (2017) and Kryvohuz and Campman (2017) describe approaches on how to exploit additional NFH measurements and eliminate the reflectivity parameter from NFH inversion. Landrø and co-authors (2011, 2016) and Khodabandeloo and Landrø (2018) have reported detailed insights into the physical mechanisms at work during air gun operation and specifically ghost generation. These studies have provided us with clues as to why the sea-surface interaction is not accurately described by the simple ghost model, and with strategies to deal with the problem.

The mis-match between observation and theory is specific to the source-side ghost, when the source is an array of air guns, because the pressure wavefield is very much larger at the source than at the receiver: this stretches the assumption of a linear acoustic response, as discussed in Hampson (2017). Non-linear behaviour includes the significant particle velocity at the free-surface in response to the reflection of the upgoing pressure wave which leads to the visible 'shot effect' (Parkes and Hatton, 1986), or 'spray dome' as it is known in the literature

⁽¹⁹⁸⁶⁾ propose an alternative scheme for signature estimation whereby the notional sources and their virtual image may each be solved for directly. The attraction of this approach is that it removes the need for a ghost model and for parameterization of the sea-surface reflectivity. However, for the inversion to be well-posed, this approach required double the number of NFH measurements.

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DOI: 10.3997/1365-2397.2019020



Figure 1 Figures reproduced from Telling et al. (2018a) showing evidence of a smaller than expected source-side ghost. The extracted wavelet from a flattened seabed (top left) has the receiver ghost removed to leave just the source ghost. A comparison is made between this de-ghosted, extracted wavelet and the optimized signature (bottom left), showing good agreement but a non-physical value of SWH=6m. The optimized and unoptimized signatures are compared (bottom right) with the latter assuming a reflectivity based on the 1 m SWH observed during acquisition. Top right is a comparison of the de-signature results on a shot gather with each of these signatures and shows ringing in the data (yellow arrow) for the unoptimized case.



Figure 2 Schematic layout of the source array in plan view with air gun volumes in cubic inches (left) and side view (right) showing the standard position of hydrophones 1m above guns (blue circles) and additional hydrophones at 3 m above guns (green circles), attached to ropes.

on underwater explosions (Cole, 1948). Furthermore, cavitation occurs when a high amplitude upgoing wave is reflected at the sea-surface, and the magnitude of the reflected wave – which is a wave of rarefaction – exceeds the local tensile strength of the sea-water. These non-linear phenomena are well-documented in association with shallow underwater explosions and we recognize again here that they may also be associated with arrays of air guns.

1 TECHNICAL ARTICLE

In this work, we aim to further describe and understand the ghost response and to evaluate the parameter-free modelling approach using data acquired in a field test. The test data comprise a sequence of 25 shots of dual near-field hydrophone data and the associated seismic data (Telling et al., 2018b). We estimate far-field signatures, assess the results of a de-signature processing sequence and compare these against the reference case with a standard parameterized inversion.

Test configuration

The test source array is composed of two strings with six source elements each i.e. 12 elements in total (a single element can be a single air gun or cluster of air guns). Nominally, the sources are at 7 m depth, spaced at 3 m in-line and with 8 m cross-line between the strings, with actual coordinates for each source element recorded on a shot-by-shot basis, with *x* and *y* positions derived from the two R-GPS receivers on each float, and the *z* position provided by the gun depth sensors. The total volume for the two-string array is 2740in³ using guns of type Teledyne Bolt Model 1500LL or 1900 LLXT with capacities in the range 40-300in³, see Figure 2. The NFH are co-located with the source elements in *x* and *y*. The first set of 12 NFH are positioned 1m vertically above the guns, as is standard, while the second set of 12 hydrophones are attached to the vertical suspension ropes 3 m above each source element. Data for the hydrophones were

acquired at 2kHz sample frequency. The conditions during acquisition were reported in the Observer's log as relatively calm with a maximum SWH of 1m.

Near-field data

Example recordings for the NFHs in the standard position and for the experimental position are shown in Figures 3 and Figure 4 respectively. The direct arrivals on the NFHs at 6 m depth (1 m from the guns) are greater in amplitude than those for the NFHs at 4 m depth (3 m from the guns) and the ghost arrivals slightly less prominent. We note that the ghost arrivals appear less sharp than the direct arrivals and that they are followed by some additional oscillations, the first of which we label as a secondary event. There appears to be some lateral move-out and amplitude variation to this event, suggesting its origin is at a central position within the array. This additional feature is not explained by a simple model of direct and ghost arrivals as it lies outside of arrival times for both. For example, the longest expected delay time (for a ghost path length over the long diagonal between sub-arrays) corresponds to 13 ms and the secondary event occurs after 20 ms. Arrivals from the water-bottom (2200 m) and stern of vessel (280 m) also lie well outside the range of interest.

Figure 5 shows a more detailed view of each trace for the starboard sub-array, this time with both shallow and deep hydrophones alternating in the display. These plots show that some of the ghosts have what can be described as a clipped appearance. This is especially clear on the shallower hydrophone records. As an exercise to understand the event timing and amplitudes in the recorded traces better, we show a comparison to synthetic traces generated by forward modelling, from each source position to each hydrophone and taking into account geometrical spreading that varies inversely with the distance of propagation. A simple scaled Ormsby wavelet was used, defined by four frequencies viz. 1-4-100-400 Hz and we used a ghost model with standard assumptions about the reflectivity arising from a rough sea-surface with 1 m significant wave height (see for example Jovanovich et al., 1983), consistent with the observed sea state during the experiment.

The real and synthetic traces are compared for a position on the starboard string (Figure 5, bottom left) and a position near the centre, (Figure 5, bottom right). We note that there is broad agreement between the real data and the synthetic on the timing, peak levels and shape of the positive arrivals but much poorer agreement on the ghost arrivals, notably due to the clipped amplitudes noted above and also the appearance of subsequent







Figure 4 Example NFH records at the experimental position 3 m above the guns, which is a depth of 4 m. The annotated image to the right is a slice view at the position of the blue line. The lower part of the figure shows the variation of the selected channel over 25 shots. The shot point interval is 30 m.



Figure 5 Example data for the starboard string (top) showing both deep (odd channels, blue) and shallow (even channels, green) hydrophones (alternating in the gather) with a time zoom indicated by the dotted grey arrows for channels 1,2 (bottom left) and 7, 8 (bottom right). Alongside each of these zoom displays is a comparison of each channel with a simple synthetic (red). Positions within the array are shown in plan view by red circles (top right).

○ ○ ○ ○ ○ ○ ○ Virtual SRCs at -7m

Sea-surface

NFH1 at 6 m

Sea-surface

NFH2 at 4 m

NFH1 at 6 m

Real SRCs at 7m

SRCs at 7 m

Standard approach

- · Single NFH per source element
- Inversion for real notional sources using ghost model: the virtual sources are simply assumed to be a filtered copy of the real sources
- 6 measurements, 6 unknowns per sub-array
- Parameter-free approach

0 9 O O O Virtual SRCs at -7m 10 11 12 8

06

4 5

02 0-3 0 0

- Dual NFHs per source element

 - Inversion for real and virtual notional sources
 - 12 measurements, 12 unknowns per sub-array

Figure 6 The two approaches used in this study for signature estimation, showing just one sub-array for clarity. For the full array, there are double the number of source elements and hydrophones.

lower-amplitude oscillations at about 10 ms intervals e.g. Figure 5 bottom, 3rd panel from left. The ghost appears weaker than expected at both observation depths, which indicates to us that the standard ghost model does not provide an accurate picture of the physics of ghost generation within the vicinity of the array.

Reflection of a positive pressure at a free-surface is expected to form a ghost of comparable amplitude and opposite sign i.e. a rarefaction. However, when the positive upgoing wave pressure is sufficiently large (e.g. of several bars), the reflected total pressure can drop below zero. For example, at 5 m depth, the water would begin to be placed under tension at an amplitude of -1.5 bar. Water will not sustain significant tension and hence a large ghost pulse will tend to cause transient cavitation. The oscillation we observe in the NFH recording may be related to the subsequent collapse of the cavitation 'cloud'. Although not observed here due to the sample rate, cavity collapse is known to be associated with the emission of high-frequency noise (Landrø et al., 2011, 2016). In summary, despite the calm sea-surface conditions during acquisition, the effective sea-surface reflectivity is not -1.0 and features in the down-going wave suggest deviation from the simple ghost model.

Signature estimation

We estimate signatures using a least squares inversion method as described in Hargreaves et al. (2015), which is a hybrid frequency-time domain algorithm that incorporates relative motion of the sources and hydrophones due to forward motion of the array through the water and the rise of the buoyant bubbles. In the new approach we use the full set of 24 NFH, solving for 12 real sources and 12 image notional sources, assuming mirror positions for the virtual source elements (Parkes and Hatton, 1986; Hampson, 2017), and we refer to this as the parameter-free approach. For reference we also estimate signatures in the standard way, whereby 12 notional sources are derived using recordings from 12 hydrophones placed at 1 m from the guns and a parameterized ghost model is used (Hargreaves et al., 2016; Telling et al., 2018a). We refer to this as the standard approach. See Figure 6 for an outline sketch of the two approaches to signature estimation. Mounting the shallower hydrophones on the array suspension ropes led to some additional random noise on the recordings which was attenuated before processing.

The parameter-free approach allows the primary and ghost components of the far-field to be separately constructed from the corresponding set of derived notional signatures, or to be combined to give the total estimated far-field signature including the ghost. Figure 7 shows the separate primary and ghost contributions to the far-field signature (left) and the combined total signature (right). A comparison between the total vertical signature derived using the parameter-free approach and the reference signature we derive using the standard approach (reflectivity defined by the proxy SWH parameter) is shown in Figure 8. Note that RMS roughness is defined as one quarter of SWH. The left-hand plot shows the signature derived using a SWH=1m as per the observed sea-state which looks very ringy after the ghost peak. The right-hand plot shows the vertical signature we derive using a SWH= 4m and optimized by minimizing a residual around the ghost notch frequency (Hargreaves et al. 2016; Telling et al. 2018a). The latter looks more comparable with the signature from the parameter-free approach but the SWH parameter does not represent the observed sea-state. For reference, in the vicinity of the ghost notch frequency (nominally 107 Hz) for SWH=1m, the reflection coefficient r=-0.97 and for SWH=4m, r=-0.65. In both cases we have r=-1.0 at 0Hz.

A direct check on the veracity of these estimated vertical signatures would ideally be made using a hydrophone positioned in the far-field. This was not part of our test but comparing the recordings from a neighbouring non-firing array with a forward modelling of the estimated notionals at horizontal take-off, we find the ratio of energy in the error for the parameter-free approach is approximately half that of the standard approach with SWH=4m. To understand if the lower error translates into improved data quality, we now look at de-signature applied to the seismic data.



Figure 7 Vertical far-field signatures estimated using the dual NFH parameter-free approach, separated into components derived from real notionals (primary) and virtual notionals (ghost) (left) and the total far-field signature (right).



Figure 8 Vertical far-field signatures estimated using the parameter-free approach (blue) compared against a signature estimated using the standard method and a single NFH per source element (red) with the assumption of a wave height parameter, SWH=1m (left) and SWH=4m (right).

De-signature processing

1 km

We apply de-signature to the seismic data in *t-p*, using directional filters derived from each set of far-field wavelets for take-off angles in the range -30 to +70 degrees. This process encapsulates source de-ghosting, de-bubble and matching to a zero-phase Ormsby wavelet. The results are shown in Figure 9 and Figure 10.

The results demonstrate high-quality de-signature for all but the standard signature with the nominal SWH=1m, which exhibits some residual ghosting artefacts visible in *x*-*t* and *f*-*k*. However, inspection of Figures 8 and 10 shows that there are small differences between both the signatures and the de-signature results for the parameter-free approach and optimized standard approach (SWH=4m). These indicate that the standard ghost model does not fully describe source ghost generation even with an artificial effective sea surface reflectivity. Further work is planned to better understand the observed spectral differences and stability of the inversion in the presence of noise.

Discussion

In our experience, the source ghost appears to be smaller than expected in most seismic exploration surveys. Detailed inspection of the experimental NFH data discussed in this article shows evidence of ghost clipping. We note that this may be modelled by an effective sea-surface reflectivity parameter or, when dual NFH data are available, by directly solving for the ghost using the parameter-free approach.

The reduction in amplitude is probably due to the onset of cavitation in the water during formation of the ghost, in addition to other non-linear effects such as formation of a spray dome at



Figure 9 Input shot record (first left) and after de-signature using the signature from the parameter-free approach (2^{nd} from left) and two variants of signatures from the standard approach with SWH=1m (3^{nd} from left) with visible ringing in the shallow data indicated by the yellow arrows and with the optimized SWH=4m (4^{th} from left) which is comparable with the result from the parameter-free signature. The receiver ghost is still present.



Figure 10 f-k spectra (wavenumber normalized by 1/sample interval) corresponding to the shot records in Figure 9. The yellow arrow highlights artefacts from poor de-ghosting. The red arrows highlight a small difference between the parameter-free and standard SWH=4m results arising from spectral differences in the signatures in the band 100-150 Hz. Note that there is a ~50 Hz notch with higher orders also present, due to the receiver ghost.



Figure 11 2D finite difference modelling of the pressure field arising from a six-element source array firing at 7 m below an ideal free-surface at times T=0 ms, 5 ms and 10 ms going from left to right. The top sequence is the modelled relative acoustic pressure and the bottom sequence has the depth-varying ambient hydrostatic and atmospheric pressure components superimposed.

the sea-surface. Positive pressures of several bars in magnitude are emitted from the array and, when reflected at the free-surface, can generate bulk cavitation in the region where the total pressure falls below zero and the water is placed under tension. The sea-water layer close to the surface will not typically sustain large tensions since it contains large numbers of pre-existing bubbles at the micron scale (Medwin and Clay, 1998). Cavitation is the formation of a transient 'cloud' of vapour bubbles. Coherent down-going energy, particularly at high frequencies, will be lost as work done during the initial rapid expansion of this 'cloud' and the effect is to clip the ghost wavelet, as observed in the NFH recordings.

The results from de-signature suggest that the parameter-free approach leads to an improvement in de-ghosting compared to the baseline standard approach. However, the parameter-free results are largely in agreement with the optimized standard result, suggesting that energy-loss mechanisms conform at least approximately to the frequency-varying model used for parameterization of reflectivity from a rough surface. Nevertheless, the parameter-free approach has the advantage of removing the need for an optimization step.

To test the cavitation hypothesis further i.e. how large negative pressures may develop in time and space in the vicinity of a typical source array, we performed 2D finite difference modelling. For simplicity we considered a six-element source array with identical elements, each outputting 2 bar peak pressure at 1 m (this is a modest typical value; large source elements may produce peak pressures in excess of 4bar at 1 m). In Figure 11 we plot the relative acoustic pressure such as might be recorded on a hydrophone and the net pressure which includes the components due to hydrostatic water pressure and atmospheric air pressure. These components are important to consider in this context since they give us a reference to zero absolute pressure. In both cases, non-linear effects are absent from the modelling and perfect reflection occurs at the sea surface. The results in Figure 11 demonstrate the potential for generation of large net tension in the water, of the order of a bar, in a central position between the guns and the sea-surface.

Conclusions

The source ghost from air-gun arrays of conventional design can be lower in magnitude than predicted by the standard ghost model. The ghost is understood to be modified by the effects of transient cavitation in the water. Standard signature estimation, using a single NFH channel per source element, treats these effects through parameterization of a frequency-dependent effective sea-surface reflectivity. Here, using two NFH measurements per source element, we are able to derive a series of far-field signatures without making assumptions on the free-surface reflectivity and use these to successfully de-signature the seismic data. The quality of the signatures offers an improvement over those derived via the deterministic standard approach but if the reflectivity used for the standard method is optimized, the results of the two methods are more comparable although not identical. While the dual NFH approach requires additional instrumentation, it is an attractive proposition since it reduces the need for optimization and does not require development of a more detailed ghost model incorporating non-linear effects. Since the estimated ghost is derived from additional measurements rather than from a ghost model, the parameter-free method has potential for improved accuracy that could be important for 4D applications. Further investigation is required to understand the noise sensitivity of this approach.

Acknowledgements

We wish to thank the crew of the *Polar Empress* and an anonymous client for their cooperation in carrying out the dual NFH experiment.

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