De-signature of apparition blended seismic data

Lorenzo Casasanta, Rob Telling, Silvio Pierini and Sergio Grion

SUMMARY

State-of-the-art source de-signature technology uses near-field hydrophone recordings to achieve the ensemble of de-bubble, source de-ghosting and zero-phasing with one directional operator. This paper outlines average and shot-by-shot source de-signature strategies for apparition blended seismic data and their application to a triple-source apparition field data acquired in the Barents Sea We have observed that the periodically encoded firing of multiple source arrays results in blended near-field hydrophone recordings. The relatively large crossline distance between marine sources compared to the subarrays might imply that the contributions from neighbouring source arrays can be neglected because of geometrical energy spreading. We have found that ignoring source arrays interference results in sub-optimal directional de-signature operators. To address this interference, it is necessary to invert for the full set of notional sources for all the source arrays. The estimated far-field signatures at each shot location are then deblended prior to any average or shot-by-shot signature calculation. Furthermore, de-blending the far-field directional signatures requires correct handling of the bubble shot-by-shot variations which are not bandlimited to the signal apparition non-aliased regions.

Introduction

The rapid rise in the number of blended or simultaneous acquisitions with multiple sources has been driven by the need for lower costs, higher resolution and improved operational efficiency. However, it is customary to design seismic surveys where the blended overlap falls beneath the target zone of interest to avoid signal damage. In fact, conventional de-blending schemes rely on random firing dithers and enforce sparsity or coherency constraints in a delicate trade-off between blended noise attenuation and signal preservation. Conversely, in seismic data apparition (Pedersen et al.,2016) two, three or more sources are activated almost simultaneously with periodic shot-by-shot time delays of the order of milliseconds. The periodic encoding ensures a deterministic separation of the individual sources and an increased fold and sampling with respect to conventional blended surveys.

Casasanta et al., 2019 and Pedersen et al., 2019 have presented triple-source apparition blended field data tests acquired with towed streamers and ocean bottom acquisition systems. The subsequent broadband processing results highlighted comparable quality to data acquired conventionally without blending. Furthermore, both AVO and repeatability studies suggested that apparition may also be suitable for reservoir characterization and time-lapse monitoring.

The state-of-the-art source de-signature technology uses hydrophone recordings placed in the near field of the source array to obtain estimates of the notional signature of each gun for an individual shot (Ziolkowski et al.,1982). These are used to model the far-field signatures to achieve the ensemble of de-bubble, source de-ghosting and zero-phasing with one directional operator. Hargreaves et al., 2016 discuss how to retrieve local estimates of the array depth and sea-surface reflectivity to produce shot-by-shot estimates of the directional ghosted far-field which improves the low frequency treatment of the wavelet and the removal of the signature bubble pulse. Telling et al. 2017, further refine this method by introducing a frequency dependent reflectivity as a function of the significant wave height of the sea surface.

This paper discusses the application of the source de-signature processing step to apparition blended seismic acquisition. The periodically encoded firing of multiple source arrays results in blended near-field hydrophone recordings. We might expect that spherical energy spreading would cause the interference across source arrays to be relatively weak, because the crossline distance between sources is typically an order of magnitude larger than the separation of the airguns within a single or multiple string source array.

In the following we show that ignoring the contributions from neighbouring source arrays results in sub-optimal directional de-signature operators. Furthermore, de-blending the far-field directional signatures requires correct handling of the bubble shot-to-shot variations which are not bandlimited within the signal apparition non-aliased regions. Throughout the paper we use triple-source apparition blended field data acquired in the Barents Sea to test different average and shot-by-shot source de-signature strategies and to draw observations and conclusions.

De-signature using an average directional signature estimate

In September 2017 an apparition triple-source line was acquired in the Barents Sea using a modulation code where only one of the sources is delayed by 8ms at each 18.75m separated shot point to ensure optimally low de-blending noise for 4ms processing at 80% of Nyquist (Casasanta et al., 2019). Three identical 2965in^3 source arrays are separated 25m in the crossline direction and they comprise two sub-arrays of six airguns each. The 15m long sub-arrays are 7.5m apart crossline and each airgun is 3m apart along the inline direction. The array volume and configuration results in a more symmetrical and less directional pressure radiation pattern when compared to three string source arrays. Each airgun is paired with a hydrophone whose recordings are used to estimate the notional sources (Ziolkowski et al.,1982) and to model the optimized far-field ghosted directional signatures as presented in Telling et al. 2017.

The source signature of the ensemble of the three source arrays firing simultaneously has a strong directivity pattern especially in the crossline direction. In principle, this might warrant full 3D de-signature before apparition de-blending which is not the preferred approach with streamer data for reasons of coarse data sampling and computational cost. Alternatively, one can observe that the near-field hydrophone recordings and consequently the estimate of the directional far-field signatures are periodically encoded in the same way as the seismic recording. The isolation of each source would remove the apparition-induced azimuthal directivity therefore justifying the use of a 2D de-signature approach. Casasanta et al. 2019 have proposed a 2D de-signature flow for the apparition test-line based on an average directional signature. They initially conjectured that three source arrays were independent by assuming that the near-field hydrophones in a given source array would mostly record the energy emitted by its nearest neighbor airguns. This equates to separate far-field signature computations for each of the three source arrays using 12 hydrophone recordings to estimate 12 notional sources per array. After compensating for the 8ms periodic time-delay (Figure 1a), a median stack of the directional signatures over shot locations and source arrays produces a unique source signature that can be deconvolved from the seismic before apparition de-blending. A more in-depth analysis of the results shows a systematic difference of the signature estimates with respect to the shot location as illustrated

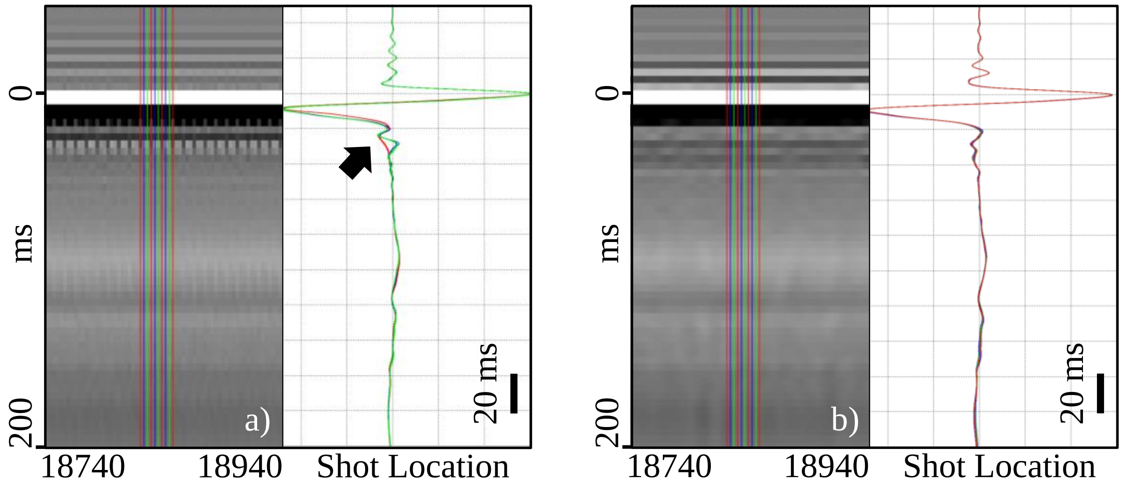

Figure 1 *Shot-by-shot estimates of the vertical far-field signatures for the central source array neglecting (a) and de-blending (b) the contribution from the port and starboard source arrays.*

in Figure 1a for the central source array. This bias has the same periodicity of the apparition modulation code and it is most evident right after the ghost trough around the time of arrival of the primary and ghost pulse from the port and starboard source arrays. Figure 2a displays the NRMS map of the directional signatures estimated assuming independent source arrays and their median stack trace. This result indicates that neighbouring array interference cannot be ignored. It is most apparent in the central array signatures where the contributions from the port and starboard sums constructively around the same time of arrival, but weaker distortions are also measured for the port and starboard signatures. To properly handle the interfering arrays , we carry out the inversion of the ensemble of the 36 notional sources for the three source arrays. Then, we calculate an average directional signature per source array after apparition de-blending the computed shot-by-shot far-field signatures at each shot location. Average directional de-signature operators for the three sources are then applied to the seismic after apparition de-blending. Figure 1b displays the deblended vertical signatures for the central array which do not show any residual distortion as the interferences between arrays have been properly considered and deblended. The same observation holds for Figure 2b for which the NRMS between apparition de-blended far-field signatures and their median stack trace is significantly lower. The remaining variations are related to the local changes of the array depth, sea-surface reflectivity and bubble pulse which we address in the next section. Figure 3a and 3b measures the impact onto the seismic of the described average de-signature operators. If the water-bottom reflection coefficient varies slowly over shot locations, we expect almost identical reflected wavelets

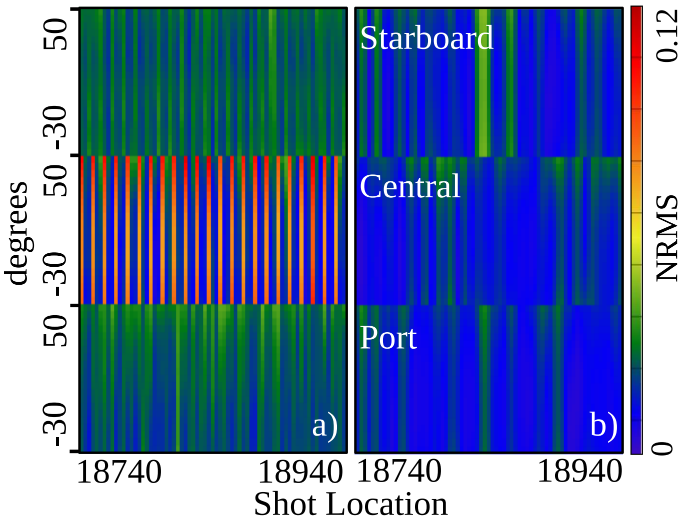

Figure 2 *(a) NRMS map of the 8ms time-delay aligned far-field directional signatures and their median stack trace assuming array interactions are negligible. (b) NRMS map of the apparition de-blended far-field signatures and their median stack trace. Vertical axis is the take-off angle for the port, central, and starboard source.*

per common channel and therefore small trace-to-trace NRMS, acting as a gauge of de-signature quality. What we find is that the full-band trace-to-trace NRMS extracted from the water bottom after apparition de-blending and flattening is lower when we include the arrays interference in the signature modelling.

De-signature using shot-by-shot directional signature estimates

We achieve a shot-by-shot directional de-signature by using the deblended far-field signature estimates at each shot location without any averaging. This should improve the removal of the signature bubble pulse whose variations strongly depend on the local changes of the source array and sea-surface reflectivity. Unfortunately Figure 3c tells differently with the NRMS worsening at the low frequency bands (2-4Hz and 4-8Hz) where the bubble energy is concentrated. It turns out that the main bubble pulse and its harmonic variations are not bandlimited within the signal apparition non-aliased regions as highlighted by the white arrow in Figure 4a. Furthermore, those variations are spatially uncorrelated and cannot be de-aliased as in Casasanta et al. 2019, therefore introducing strong aliasing artefacts to the deblended signatures (Figure 4b, white arrow) and seismic (Figure 3c).

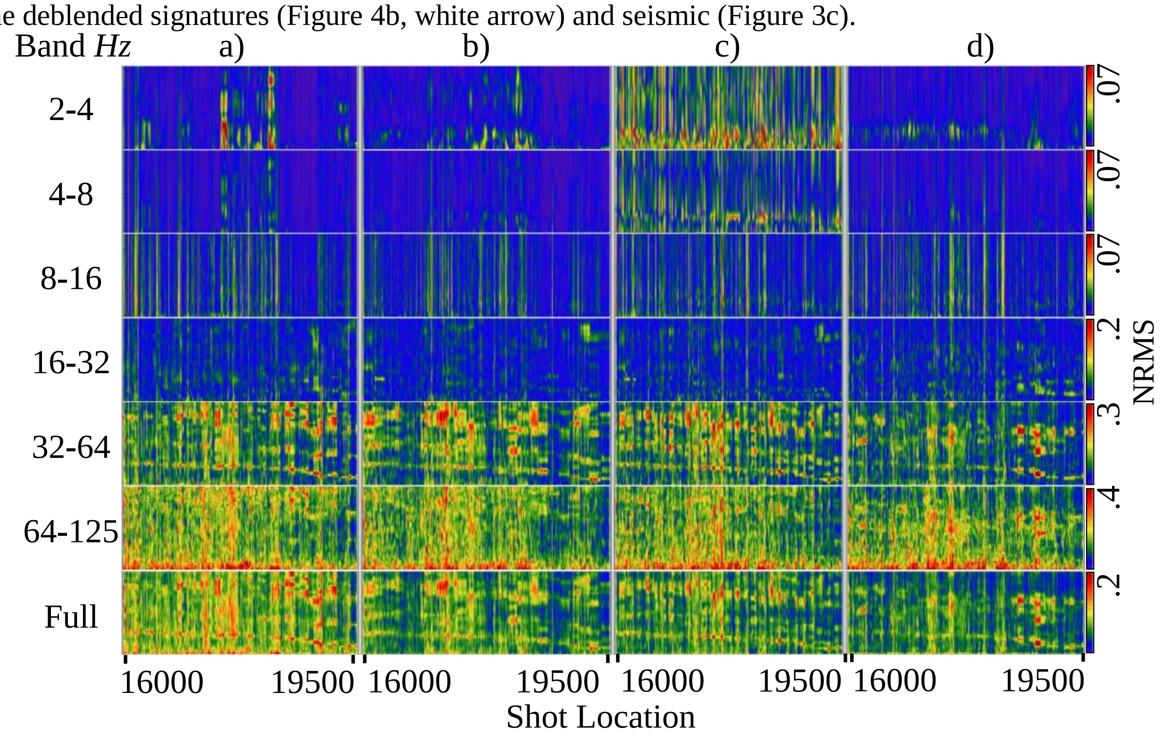

Figure 3 *Trace-to-trace NRMS of apparition deblended data, extracted from the flattened water bottom reflection after de-signature for different frequency bands. For each band, in the vertical axis are the first 50 channels for the central source-cable 6 pair. The directional de-signature is applied either before blending (a) or after de-blending (b-c-d) of the seismic records. The results (a-b) use median average directional signatures of either the blended (a) or de-blended far-field signatures (b) at each shot location. In (a) there is also an average over the three source-arrays. The results (c) use de-blended shot-by-shot estimates of the directional ghost far-field and bubble pulse. (d) is like (c) but a 1D shot-by-shot de-bubble operator is applied before de-blending to the far-field signatures and the seismic records. The full band NRMS average over 36 source-cable pairs is: (a) 8.35±5.64 10^{-2} , (b) 6.41±4.56 10^{-2} , (c) 6.55±5.11 10^{-2}, (d) 5.92±5.25 10^{-2}*

To circumvent this problem, we assume that at the low frequencies' characteristic of the bubble oscillation the response of the ensemble three source arrays is omni-directional, and this permits to derive a shot-by-shot 1D de-bubble operator from the un-ghosted signatures before de-blending. The 1D de-bubble operator is then applied to both signatures and to seismic prior to apparition de-blending. Figure 4c shows nicely separated signal cones for the vertical far-field signatures with the bubble shot-by-shot variations effectively removed. Apparition de-blending is applied to both the de-bubble directional shot-by-shot signatures (Figure 4d) and the seismic records. With the deblended and de-bubbled directional far-field signatures we then design a shot-by-shot source de-ghosting and zero-phase operator to apply to the seismic. By using this shot-by-shot de-signature flow we have improved the seismic de-signature and achieved a lower full band NRMS (Figure 3d) with the uplift most apparent in the 2-4 and 4-8 Hz bands.

Conclusions

This paper discussed different approaches to estimate and apply directional source de-signature operators to apparition blended seismic data and addressed two main challenges: 1) the contributions from neighboring source arrays are not negligible, in particular for the central array where the contributions from the port and starboard arrays reinforce constructively; 2) shot-by-shot bubble variations are aliased and create artefacts in signature deblending. To properly handle the interfering arrays, we inverted for the ensemble of the 36 notional sources for the three source arrays. The calculation of average signatures of apparition blended seismic data requires de-blending of the computed far-field signatures priory to any averaging. Shot-by-shot de-signature of apparition data requires first the removal of the bubble variations from the signatures and seismic data prior to de-blending, and then application of shot-by-shot de-ghosting and zero-phasing after deblending. The test we performed on field data acquired in the Barents Sea proves the validity of the approaches discussed. Incremental improvements have been observed with shot-by-shot de-signature with the uplift most apparent in the 2-4 and 4-8 Hz band where the bubble energy is concentrated. Finally, we speculate these conclusions will still hold for wider source separations where neighbouring array contributions have comparable magnitude to shallow sea-bottom reflections which, if not properly handled, distort the estimated signatures.

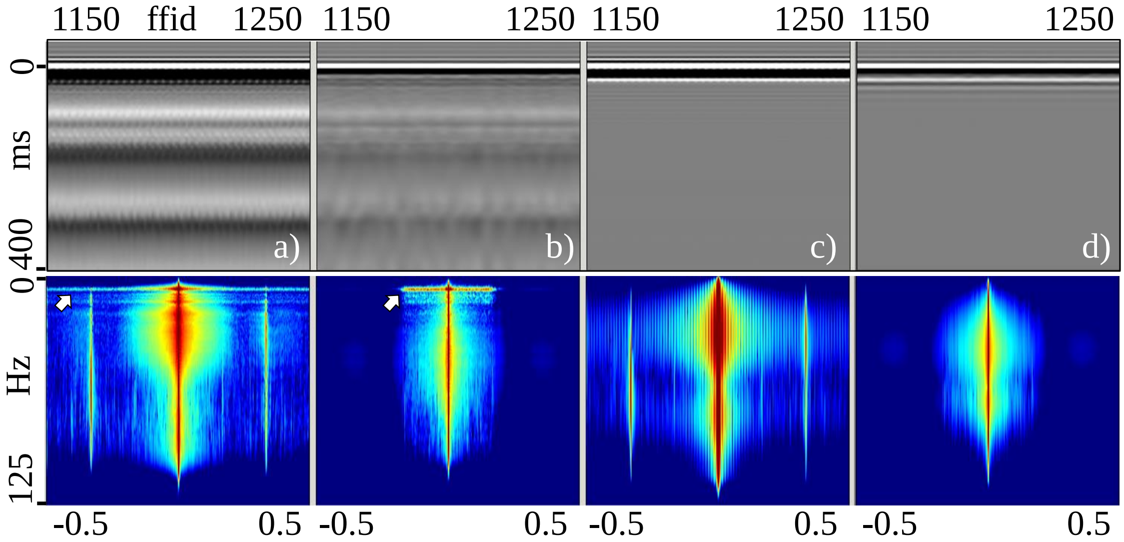

Figure 4 *Estimated far-field signatures at vertical take-off angle (top) and their f-k spectra (bottom) for consecutive shot locations before (a), (c) and after (b), (d) apparition de-blending for the central source. In (a) the shot-by-shot bubble variations are aliased and create artefacts in the signature de-blending (b). In (c) the shot-by-shot bubble pulse variations have been removed prior de-blending resulting in cleaner shot-by-shot estimates of the far-field ghosted signatures (d). The horizontal wavenumber axis is normalized with respect to the 18.75m shot interval.*

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