Source signature estimation in shallow water surveys

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Summary

In this paper we analyze the impact of water bottom reflection on the near-field hydrophones in a shallow water survey and the consequent error on the reconstruction of the source signature. Then we present a deblending-based approach to attenuate this error.

Introduction

Airgun arrays are the most widely used source for marine seismic surveys, normally composed of three to six sub-arrays, each sub-array composed of six to 14 airguns. By releasing high pressure air, the airguns are actuated either simultaneously or with a time delay. Each airgun produces an impulsive quasi-spherical shockwave and, all together, generates a spiky signature with a spectrum close to white. In this paper, we call source signature the time evolution of the wavefield vertically below the source center.

Due to the interference between the shockwave and its reflection on the sea surface, the signature contains notches on the spectrum which are correlated to the airgun depths. The interference among individual airguns causes signature variation according to the observation azimuth, henceforth referred to as the directivity of the source signature.

In seismic processing, a typical procedure is to de-convolve the seismic trace with the source signature to reshape the reflectivity to spike. This requires good knowledge of the source signature in any direction.

Despite the stability of airguns, the response of the marine source array, as a complicated system, may vary from shot to shot. Various causes of source signature instability have been studied (Dragoset 2000; Laws and Kragh, 2002; Ni et al, 2012). In particular, such uncertainty is more visible on the high-frequency range or the directivity. So for wide-azimuth or broadband surveys, a good estimation of source signature and its directivity is very important.

One method to reconstruct the signature of an airgun array is based on the model that the whole pressure field can be seen as the contribution of the independent propagation of notional signatures of each individual airgun (Ziokowski 1982). By measuring the pressure shockwave from their near-field location (NF), we can invert for notional signatures and then propagate them to far-field to get the airgun array signature and its directivity.

The advantage in estimating source signature with near-field recording is that the signal is much stronger than environmental noise, as the hydrophones are located about one meter away from the nearest airgun. The main incertitude concerns the real geometry of guns and hydrophones, as well as the value to use for the reflection coefficient of the sea surface. When extra hydrophone data is introduced, these parameters can also be inverted to get a more precise result (Ni et al, 2014).

Water bottom residuals in shallow water survey

When the propagation time of the shockwave from the airgun to water bottom and back to the sea surface is shorter than the length of source signature, the reflections from the subsurface, hence called water bottom (WB) for simplicity, are also captured by the near-field hydrophone (NFH), as shown in figure 1. If WB reflections are not properly taken into account, those acoustic events would be considered by the inversion procedure as airgun outputs, and counted inside estimated notionals. The propagation to far-field of contaminated notionals would corrupt the source signature reconstruction.

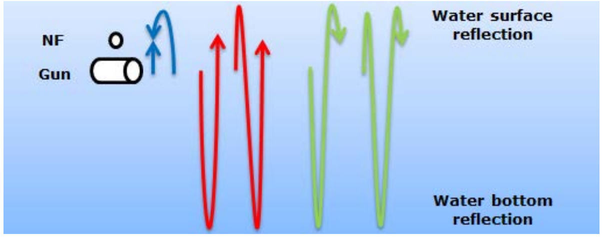

Figure 1 - Extra travel paths, received at near-field hydrophones, from water bottom reflection (red and green).

As the propagation follows the law of spherical divergence, the amplitude of this water bottom on the near-field recording is inversely proportional to the water depth. However, the water bottom reflection includes the entire contribution of the firing guns and will be captured by all the active hydrophones, so the impact on the estimated far-field signature is proportional to the full energy emission and the total number of near-field hydrophones.

Another important factor affecting the imprint of the sea floor on near-field recording is the reflection coefficient of the water bottom, which depends on the geological context: a rigid bottom of rock or a thick layer of soft sand results in very different reflectivity imprint. Normally the corresponding reflection coefficient varies from 0.3 to 0.6.

Suppose an experiment within a water column of 50 m, where the whole travel distance of WB reflection is twice

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as large (100 m), and its reflection coefficient is 0.6. For each actuated airgun, the NFH recording show amplitudes at the range of 3 bar for the primaries, and 0.02 bar for WB residuals. And for a typical source of 30 guns, the peak amplitude on each NFH is about 6 bars, and the WB residual is about 0.6 bar, which is so strong that it cannot be neglected.

If no change is made on far-field reconstruction algorithms, this residual energy will be preserved and propagated to the final signature. An example with synthetic data is shown in Figure 2 in which WB residuals could be clearly followed through the section of shot to shot far-field signatures.

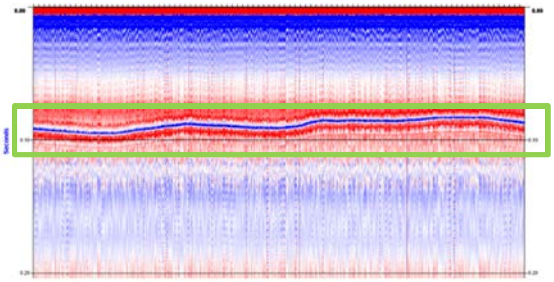

Figure 2 - Synthetic data shows the imprint of water bottom reflection on estimated source signature from NFH

One of the attempts to remove this sea floor reflection error was proposed by Hopperstad et al, 2006, and consists of including the reflection at the sea floor in propagation model, so that the inversion can still correctly estimate notionals of each airgun.

However, such a shot-to-shot based method depends on the parameters of the model, including the bathymetry, the complexity of the near surface, and the reflection coefficient. In addition, if the water column is really shallow, even the water bottom multiple should be taken into account.

Method and results

We base our method on the continuity of the sea floor, using a deblending method to attenuate the impact of the water bottom reflection on the source signature estimation.

Deblending-based water bottom attenuation

The signature for each shot i, estimated through near-field inversion method could be expressed as the following:

$$\mathrm{sig_i} = \mathrm{FF} + \delta\mathrm{FF_i} + \mathrm{WB(d_i)} \qquad (1)$$

where FF is the perfect signature of the source, $\delta\mathrm{FF_i}$ is the instability from shot-to-shot of this signature, and $\mathrm{WB(d_i)}$ is the reflection of water bottom at depth $\mathrm{d_i}$. In terms of energy: $\mathrm{FF} > \mathrm{WB(d_i)} > \delta\mathrm{FF_i}$.

The average signature $\mathrm{FF} = \mathrm{mean(sig_i)}$ could already be considered as a good estimation of the source signature, thanks to desynchronized aspect of WB reflections due to depth variation of sea floor. Subtracting the average signature from (1), a perturbation term accounting for WB reflection and source instability could be estimated:

$$\widehat{sig_i} = sig_i - FF = \delta FF_i + WB(d_i) \qquad (2)$$

A good estimation of $WB(d_i)$ could be realized by:

- filtering out $\delta\mathrm{FF_i}$ through high pass filters, as $\delta\mathrm{FF_i}$ is mostly low frequency
- stacking all signatures together after the alignment of water bottom reflections

Finally by removing the contribution of $\mathrm{WB(d_i)}$ from (1) and combining with (2) a good estimation of source signature preserving the shot-to-shot variation is achieved:

$$\widetilde{\mathrm{sig_i}} = FF + \delta FF_i = FF + \widehat{sig_i} - WB(d_i) \qquad (3)$$

Preservation of shot-to-shot variation

Figure 3 shows the results obtained by the application of deblending approach on synthetic data, without prior knowledge of the water bottom. Almost all WB residuals are removed, while keeping the shot-to-shot source signature variation. This variation is crucial for the quantification of the stability of the source, and could be used to make decision on the need for shot-to-shot designature of seismic data (Ni et al, 2012).

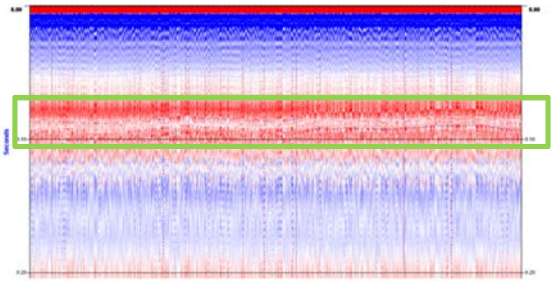

Figure 3 – Source signatures with WB removed by deblending method, preserving the shot-to-shot variation.

Compatibility with directional signature estimation

Once the water bottom is deblended from the raw estimated far-field signature, then its contribution is removed from

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every NFH channel, with the assumption that the WB reflection is equally received on every hydrophone.

This procedure allows near-field input without water bottom residuals, and then a normal estimation of directivity could be applied (Niang et al, 2013).

Case study

In order to verify the validity of the method, several field tests were carried out.

Comparisons of signatures in shallow and deep waters

In the first sea trial, we tested the deblending method in an area with 50-250 m of water, using a 3366 cubic inch source array of 36 airguns and 21 NFH. In order to build a reference signature we acquired 200 shots with the same source but in deep water (>1000 m).

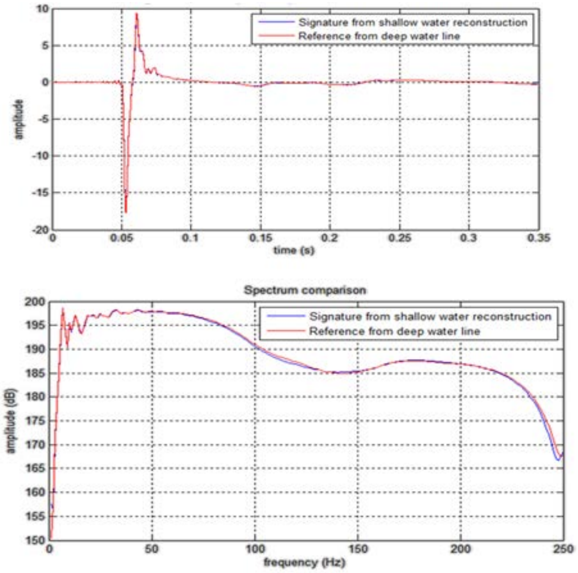

Figure 4 – Field data: in blue the estimated source signature on 50-250 m of water column, while in red the reference signature estimated in deep water. Perfect match.

The arrival time diversity of WB reflections is used to achieve the deblending, by selecting 1,000 random shots in the whole survey area, and by stacking the reconstructed far-field signature aligned on the primary peaks. This process attenuates WB residuals very efficiently. Figure 4 demonstrates the accuracy of the reconstructed signature in the shallow water area in comparison with the reference signature estimated in deep water field test. Both signatures match perfectly.

Using the same stacking method, another sail line with a smooth bathymetry variation (60-65 m) has been processed. Figure 5 shows that the lack of water depth diversity introduces up to 2 dB of error in the bandwidth of 20 Hz to 150 Hz of the spectrum of estimated far-field signature.

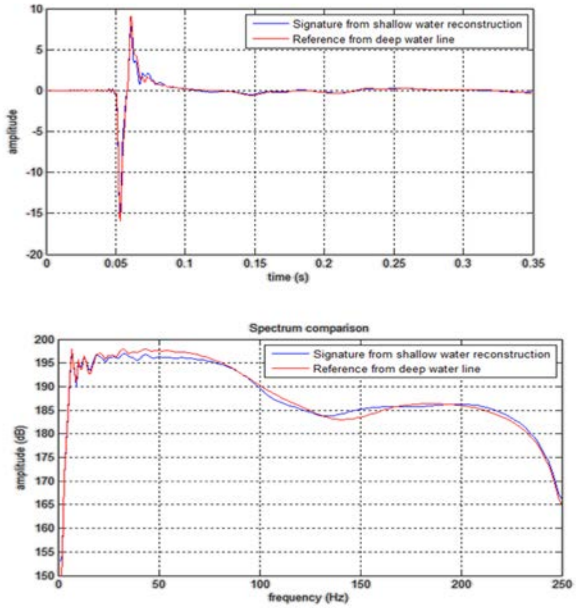

Figure 5 – Field data: in blue the estimated source signature on 60-65 m of water column, while in red the reference signature estimated in deep water. 2 dB of error.

Deblending of shallow water bottom residuals

A second field test was carried out on a more complex sea floor: shallow in one side (~100m), and very steep on the other side (100m to 1000m). The goal is to extract the WB residuals from every source signature in the shooting line.

Figure 6 shows extremely clearly the water bottom residual, occurring in the bubble period of estimated far-field signatures. If these residuals are not correctly removed, those far-fields cannot be used for de-bubbling or designature purposes.

The extracted residuals of water bottom after deblending are presented in the Figure 7. It is interesting to notice that this technique is able to remove not only the water bottom refection, but also some imprint of the geology of near surface. In addition, in the deeper part, some clear water bottom multiples are also visible. This demonstrates the advantage of the proposed deblending method that does not require prior knowledge of the structure for modeling. Figure 8 illustrates how difficult it could be to model WB

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reflections given the complexity of the subsurface in the area.

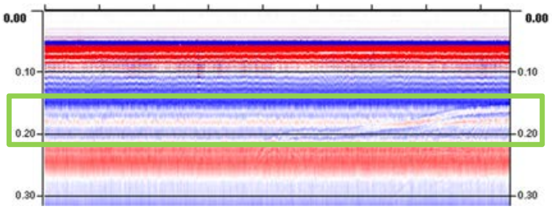

Figure 6 – Reconstructed signature, where the residual of water bottom is visible around 0.2s.

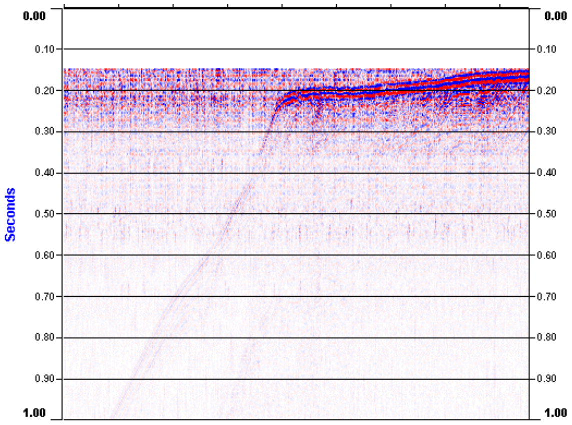

Figure 7 – Deblending output: residuals from WB, near surface and their multiples. The visible energy from far-field could be considered as noise (42 dB below Figure 6).

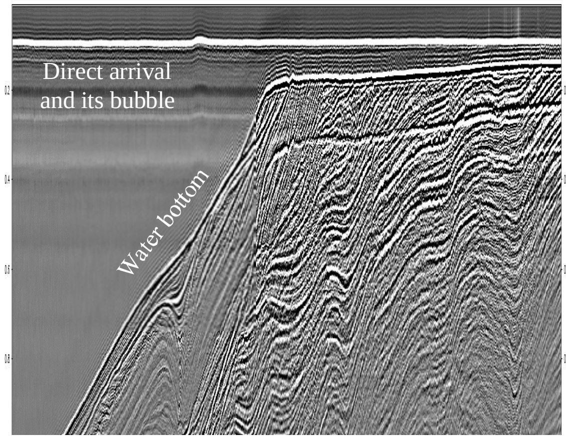

Figure 8 – Near offset streamer seismic stack..

By comparing the deblending outputs to the seismic data of Figure 8, we can see that the water bottom matches the geology very well. The quality of water bottom estimation allows a successful removal of water bottom residuals as shown in Figure 9.

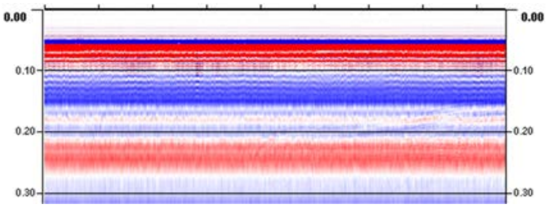

Figure 9 –Reconstruction signature, with WB removed.

Conclusions

With synthetic data and two sets of real data, we found that the deblending-based water bottom attenuation for signature estimation works very well. The method is robust and allows us to get the signature without water bottom residuals. It does not require knowledge of the bathymetry or geology; and it preserves the shot-to-shot source variation, providing full signature directivity with the sea floor attenuated.

However, this method has its drawbacks as well. If the sea floor for the whole survey area is very flat, any blind deblending will make it difficult to distinguish the water bottom residuals from the bubble of source signature. This problem could be resolved by guided deblending with the help of seismic data or by windowed Fourier transforms to separate the low-frequency bubble event from the high-frequency water bottom residuals.

For the case of extremely shallow water, i.e., water depth less than 15 m, the assumption that water bottom has the same imprint on all near-field hydrophones is no longer valid. The directivity (offsets, azimuths) of the water bottom reflection should be taken into account.

An added value of this method is the extra zero-offset seismic data of water bottom obtained by the near-field recording, which could be useful for SRME or other de-multiple techniques, where any additional zero-offset information is valuable.

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EDITED REFERENCES

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