Source designature of ocean bottom node data using deterministic airgun modeling

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SUMMARY

Seismic airguns are not an impulsive source and hence marine seismic data must be designatured before interpretation. We demonstrate how deterministic modeling of the airgun signature can be used to designature field data. A heuristic approach is used to generalize the single airgun model to a small array of closely spaced guns where the bubbles from the different guns coalesce. The simulated signatures are used to designature data from a near-surface survey around a production rig. The results illustrate the importance of deconvolving with the correct source signature and compare favorably to prediction-error filtering.

INTRODUCTION

The data recorded in a seismic survey is the convolution of the source signature, wave propagation and the reflectivity. The reflectivity, or equivalently the velocity and density structure of the subsurface, is the important quantity for geological interpretation. In this abstract, we discuss how marine seismic data can be designatured using deterministic modeling of the airgun signature.

Seismic airguns are the main source used in marine seismic surveys. An airgun functions by discharging highly pressurized air into the water, forming a bubble that expands and contracts. This produces a source signature with an initial peak due to the rapid expansion of the bubble when the airgun discharges and subsequent oscillations associated with the dynamics of the bubble expansion and collapse (Figure 1). Tuned airgun arrays have been used to minimize the bubble oscillations and make signature more impulsive (e.g., Dragoset, 2000), thereby simplifying the problem of source deconvolution. However, the signature of the airgun array can often still be seen in the data, especially for smaller surveys with fewer guns where the array cannot be tuned as well.

There are several methods for source designaturing. Statistical methods such as prediction-error filtering (PEF) are commonly used in the industry (Yilmaz, 2011). PEF attempts to solve the blind-deconvolution in which the spectrum of the signature and the deconvolution of the source signature are performed at the same time. Alternatively, the signature can be measured directly from near-field hydrophones and deconvolved from the data (Ziolkowski et al., 1981, 1984; Ziolkowski, 1991; Landrø et al., 1991; Landrø and Sollie, 1992; Laws et al., 1998; Kryvohuz and Campman, 2016) although there are some issues with the reliability of the near-field hydrophones as well as artificially propagating high frequency noise measured in the near-field to the far-field. Finally, physics-based modeling of the airgun-bubble dynamics can be used to estimate the source signature (Ziolkowski, 1970; Li et al., 2010; de Graaf et al., 2014; Watson et al., 2016). Commercial software packages like *Nucleus* and *Gundalf* use a combination of numerical modeling and measured signatures of individual airguns to determine the signature of an array of airguns.

Here, we examine how physics-based modeling of the airgun dynamics can be used to estimate the source signature. We briefly discuss the numerical model and show that the simulated signature is comparable to that predicted by *Nucleus* before demonstrating how the simulated source signature can be deconvolved from the observed data in order to improve the quality of the observations.

MODEL

We model the airgun dynamics with a similar method to that outlined in the seminal paper by Ziolkowski (1970). We solve the compressible Euler equations in the water and evaluate the solution on the bubble wall to obtain the modified Herring equation (Herring, 1941; Cole, 1948; Vokurka, 1986),

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{p - p_\infty}{\rho_\infty} + \frac{R}{\rho_\infty c_\infty}\dot{p} - \alpha\dot{R}, \qquad (1)$$

where R and $\dot{R} = dR/dt$ are the radius and velocity of the bubble wall, respectively, p is the pressure inside the bubble, and p_∞, ρ_∞ and c_∞ are the pressure, density, and speed of sound, respectively, in the water infinitely far from the bubble. Numerical models of airgun signatures typically under predict the damping observed in the data. Hence, α is included as a damping constant (Langhammer and Landrø, 1996) to obtain a better fit between simulation and observations.

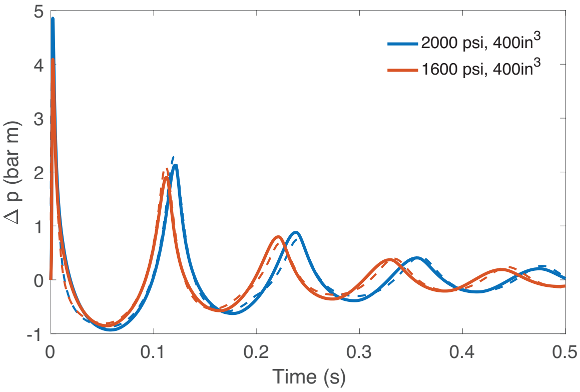

Figure 1: The simulated signatures (solid) are in good agreement with the *Nucleus* signatures (dashed).

The pressure perturbation in the water is related to the bubble dynamics by (Keller and Kolodner, 1956)

$$\Delta p(r,t) = \rho_\infty \left[\frac{\ddot{V}(t - r/c_\infty)}{4\pi r} - \frac{\dot{V}(t - r/c_\infty)^2}{32\pi^2 r^4} \right], \qquad (2)$$

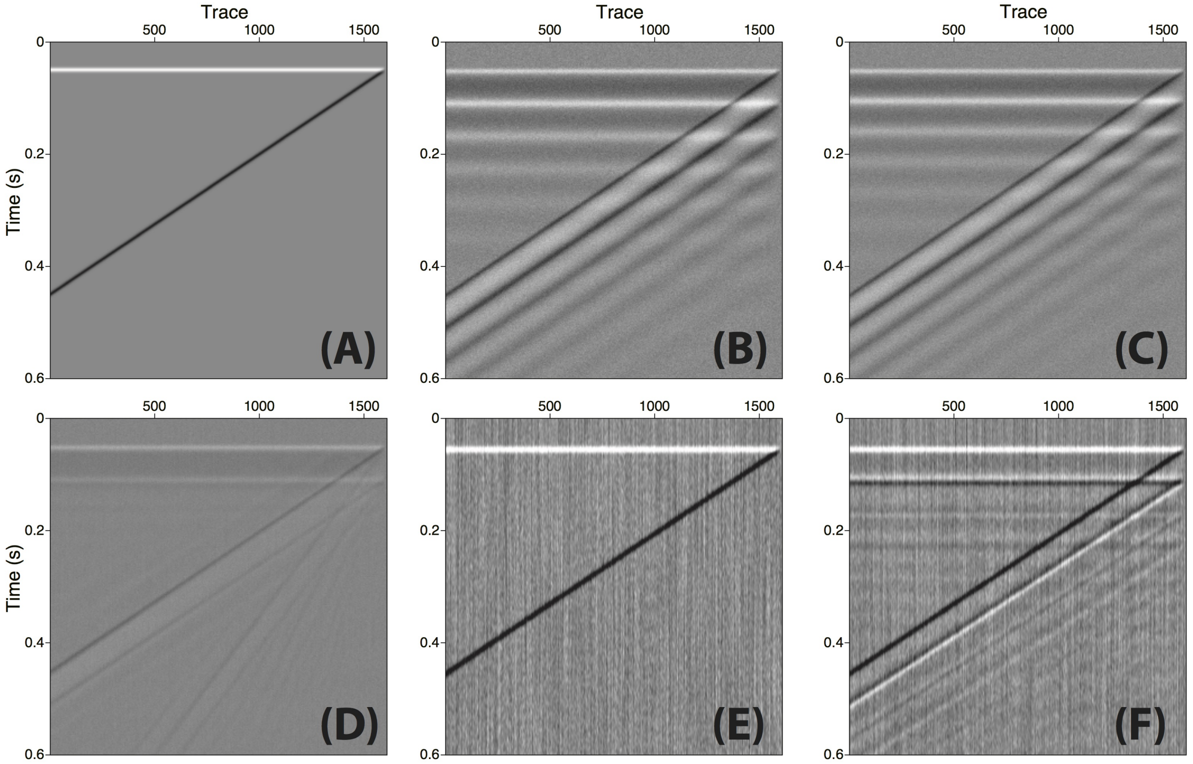

Figure 2: (A) Reflectivity model. (B) Synthetic data generated by convolving the reflectivity model with the simulated signature of the 2000 psi airgun shown in Figure 1. (C) Synthetic data generated by convolving the reflectivity model with the simulated signature of the 1600 psi airgun shown in Figure 1. (D) Prediction-error filter applied to the synthetic data shown in (B). (E) Synthetic data shown in (B) deconvolved with the correct signature (2000 psi airgun). (F) Synthetic data shown in (C) deconvolved with the wrong signature (2000 psi airgun).

where Δp is the pressure perturbation in the water, r is the distance from the center of the bubble to the receiver and $V = 4/3\pi R^3$ is the volume of the bubble. For further details on the numerical model the reader is referred to Watson et al. (2016) and the references therein.

SYNTHETICS

The importance of using the correct signature in the designature process is illustrated using a synthetic example. A model of the subsurface consisting of a wedge of high acoustic impedance within a background medium with a lower acoustic impedance is generated. There is a flat negative reflector at the top of the wedge and a dipping positive reflector at the base (Figure 2A).

Synthetic data is generated by convolving the reflectivity model with the two simulated signatures shown in Figure 1; a 400 in^3 airgun pressurized to 2000 psi (Figure 2B) and a 400 in^3 airgun that has developed an air leak and is pressurized to 1600 psi (Figure 2C). Random noise is added to give a signal-to-noise ratio of 2.

Figure 2E shows the reflectivity model produced when the synthetic data is deconvolved with the correct source signature. The result, as expected, is, the same as the initial reflectivity model, apart from the addition of random noise. Figure 2F shows the reflectivity model produced when the synthetic data is deconvolved with the wrong source signature. The synthetic data was generated with the 1600 psi airgun signature but the deconvolution was performed with the 2000 psi airgun signature. The reflectivity model still contains significant ringing. This illustrates the challenges faced in designaturing field data where the source signature may be unknown or may differ from the expected value.

Prediction-error filters (PFEs) are used to remove predictable information from a dataset. Figure 2D shows the application of a PEF to the synthetic data shown in Figure 2B. The PEF removes some of the ringing but introduces additional artificial noise. This is because the synthetic data involves two reflectors with different dips which introduces non-stationarity. As we estimate a single prediction-error filter for each trace, we cannot properly account for this non-stationarity which prevents the prediction-error filter from fully predicting all of the ringing and leads to additional artifacts.

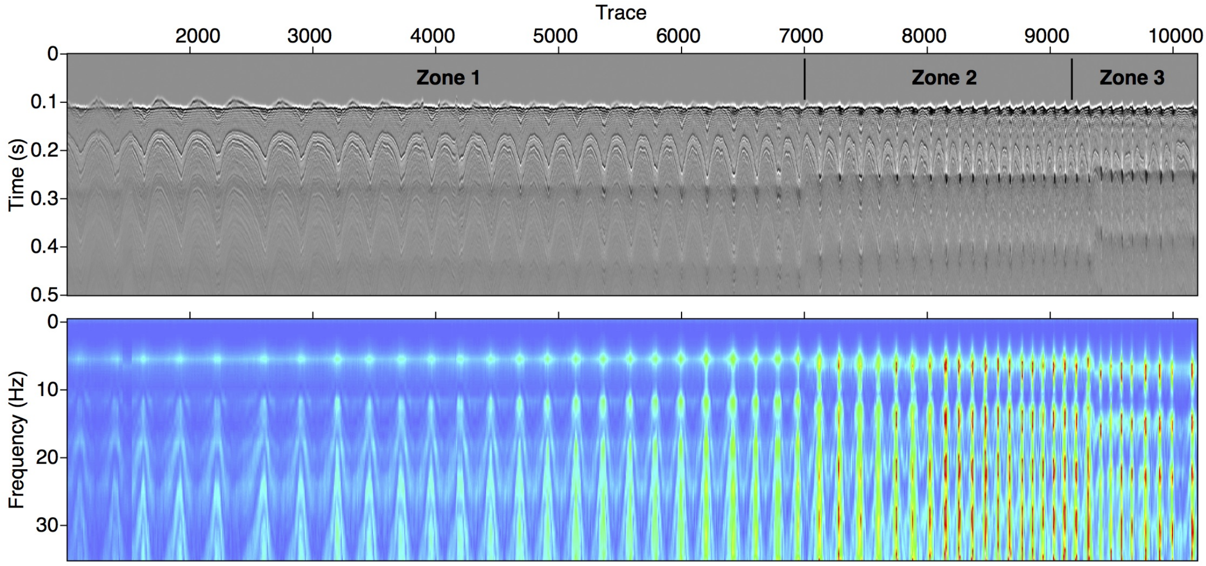

Figure 3: Data in the time domain after HMO (top) and frequency domain (bottom). Note the discontinuities around trace 7000 and trace 9300 due to the airgun failure.

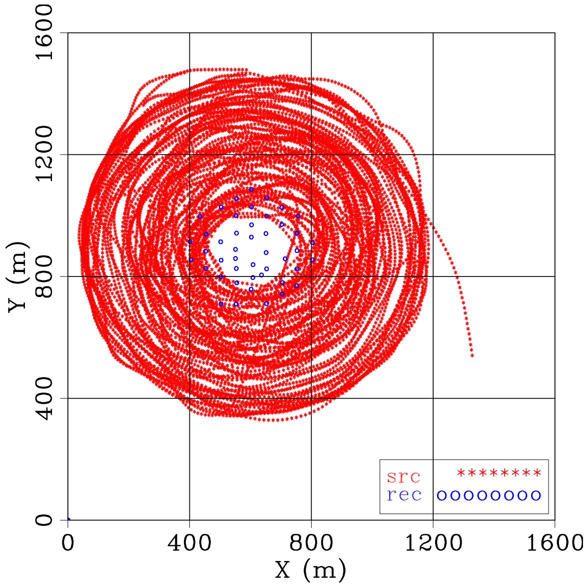

Figure 4: Shot-receiver geometry for the Apache Forties survey around the Delta platform.

DATA

The Apache Forties oil field data were acquired as part of an ocean-bottom node survey around three production rigs in the North Sea. The goal of the survey was to image gas clouds and other shallow drilling hazards near the rigs (Alves, 2015; Jennings and Ronen, 2016). We focus on the data collected around the Delta platform. The Delta survey consisted of 14485 shots and 48 nodes. The source vessel circled the platform and spiraled inwards. Receivers were arranged in a roughly hexagonal pattern around the platform with a 50 m node spacing (Alves, 2015). The parabolic reflectors seen in the data in the time domain and the clear vertical bands of increased energy in the frequency domain are a result of the spiral acquisition geometry. The horizontal banding is a result of the non-impulsive source signature.

The seismic source was a cluster of three 250 in^3 airguns. There were issues with the airgun array during acquisition. A leak developed around trace 7000 and the array operated with reduced pressure to at least one of the guns. Eventually, one gun failed approximately at trace 9300 reducing the array to two 250 in^3 airguns. The changing source signature is clearly visible in the data (Figure 3). Once the air leak develops the dominant frequency of the source shifts to higher frequencies because less mass is ejected from the array into the water. This means that the bubble generated is smaller and hence oscillates faster. For analysis, we divide the data into three zones as shown in Figure 3.

The source signature is simulated in each of the three zones. A heuristic approach is taken to estimate the source signature for the array of airguns from the single airgun model described above. Initially the airguns do not interact. Therefore, the first instances of the signal are the summation of the pressure perturbations from the multiple airguns. Based on the detailed calculations of Barker and Landrø (2014), we introduce a scaling factor were the amplitude of the summation is reduced by 10%. By the time of the first bubble peak the bubbles from the multiple airguns have coalesced (the distance between the airguns is 1 m) and subsequently behave as a single large bubble. This can be simulated as a single airgun with a volume equal to the total volume of the array. The signal is tapered in between

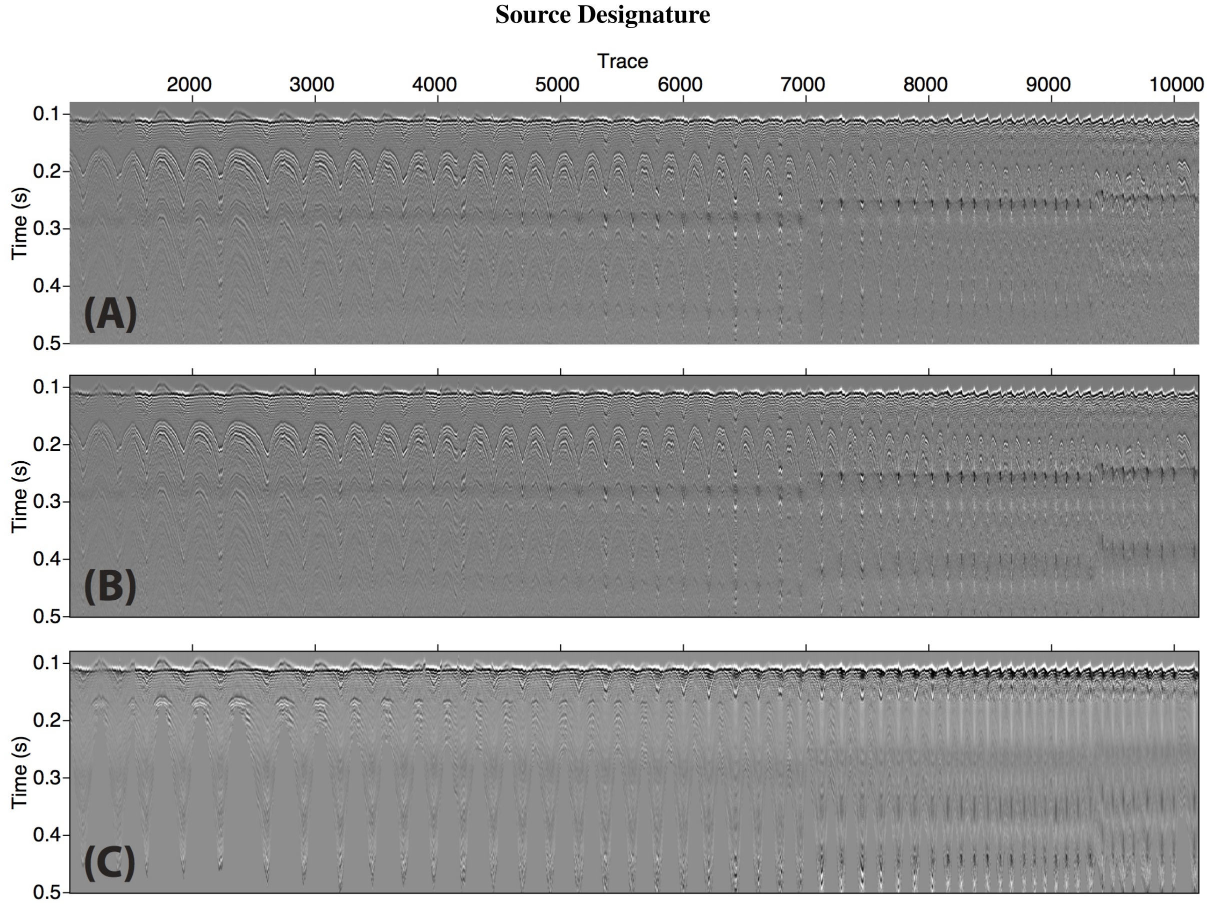

Figure 5: (A) Data deconvolved using the simulated source signature. The source signature is simulated for each of the three zones. (B) Data deconvolved using the simulated source signature from zone 1 to deconvolve from all three zones. (C) Data deconvolved using a prediction-error filter. The prediction error filter is applied zone by zone.

these two limits to give a smooth source signature. Note that this approximation can be justified for a small array of closely spaced airguns but is not valid for larger arrays where directivity effects become important and bubble coalescence is more complicated.

Figure 5 shows the deconvolution of the data using the simulated signatures (5A and 5B) and using a prediction-error filter (5C). Figure 5A is designatured using a different simulated signature for each of the three zones. Figure 5B is designatured using the simulated signature from zone 1. The results are the same for zone 1. For zones 2 and 3 bubble energy remains in Figure 5B that is not present in Figure 5A. As with the synthetics, this demonstrates the importance of deconvolving with the correct source signature.

Note that for both Figure 5A and Figure 5B a dark band of energy around 0.25 s remains after designaturing. The energy increasing to the right in each zone. This may be due to the source signature changing within each zone or may be an artifact of the spiral acquisition geometry.

CONCLUSION

We show how deterministic modeling of the airgun signature can be used to designature ocean bottom node data. We show that using an incorrect signature, such as not accounting for a pressure drop due to an air leak, may do more harm than good. We also show that using indeterministic prediction error filter may create spurious events.

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2017 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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