The Impact of Wave-Induced Source Variations On 4D Repeatability

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Summary

Small waveform and directivity variations of marine airgun signatures due to waves interacting with the source float are a source of 4D noise. We are assessing the magnitude of this noise by first measuring the amount of variability from near-source auxiliary data and then modeling synthetic time-lapse ocean bottom seismic data with realistic source variations based on the measured statistics and standard ocean wave models. We quantify the contribution of source variations to 4D noise as a function of sea state by calculating the NRMSD attribute in the image domain. We find that up to 4% NRMSD can be attributed to source variations under realistic scenarios, with two main contributing effects: variations of individual gun signatures due to pressure changes, and array directivity variations due to the wave-induced pitch and roll of the source floats. The latter effect has a larger impact on the 4D noise in our simulations and depends more on the wave steepness rather than the wave height. While waveform variations can be addressed by a nearfield-based shot-by-shot designature, directivity variations are difficult to correct without knowledge of the sea surface shape.

Introduction

Advances in 4D acquisition and processing technology have continually led to an increase in survey-to-survey repeatability and reduction of 4D noise. This is particularly apparent for permanent reservoir monitoring (PRM) solutions with ocean bottom cables. Such systems offer the best results in terms of repeatability, mainly because receivers are fixed in place and uncoupled from the source. The quality of a 4D image is typically quantified through the normalized RMS of the difference (NRMSD), a measure of 4D noise in the image (Kragh & Christie, 2002). Some recent PRM case studies report NRMSD values in the 3-5% range (e.g., Thedy et al., 2015; Buizard et al., 2013), which is considered excellent and allows for quantitative interpretation and faster survey repeat cycles, even in complex reservoirs. These results were achieved through elimination, or correction, of the most obvious sources of 4D noise, such as receiver location inaccuracy, coupling variation, time drift, and variations in the water column (e.g., Wang et al., 2015). Having eliminated these first order effects, the focus shifts increasingly to seemingly lower order effects such as, e.g., the variability of the seismic source. In this paper we investigate the potential impact on 4D repeatability of subtle changes in source signature and directivity of towed marine airgun source arrays. We first statistically analyse variations of source array configurations from recently acquired marine seismic surveys to obtain a measure of the magnitude and statistical properties of such effects and their dependence on environmental parameters such as sea state. Then, we forward-model time-lapse seabed seismic data with perturbed source arrays using the measured statistics as input. Finally, we quantify the impact of such effects on repeatability in the 4D difference image domain.

Statistical analysis of source perturbations

To analyse the amount of perturbations in the source array over a sail line or survey, we analyse depth sensor and firing pressure data, as well as data from GPS and the acoustic positioning network mounted on the subarrays on a shot per shot basis. From this, we can derive parameter statistics such as the mean array depth, individual gun depths, subarray separation, as well as changes in the firing pressure. As an example, Figure 1 shows the histogram for the mean array depth measured for two sail lines of the same survey acquired in different weather conditions.

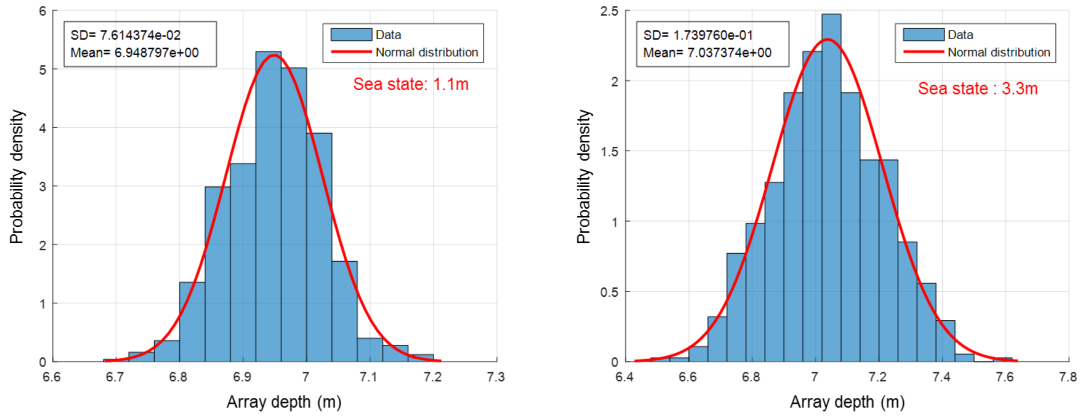

Figure 1: *Histograms of the distribution of mean source array depth for two sail lines of the same survey acquired in different weather conditions, denoted by the respective significant wave height. Red line denotes the fit of a normal distribution to the histograms represented by the blue bars.*

The observed variation follows to the first order a Gaussian distribution and can be quantified by its standard deviation as main statistical property. We also observe that the standard deviation increases with sea state. Sea state information was obtained from the vessel's observers log and is given in terms of the significant wave height. We investigate sea state dependence by comparing two different surveys acquired in different parts of the world (Figure 2). Each dot in Figure 2 represents the standard deviation (left) and mean (right) for one sail line of the respective survey. The dependence of standard deviation on sea state is more pronounced for survey 1 (blue) than for survey 2 (red), visualized by the linear regressions through the respective data points. We suspect that different apparent slopes point to different wave shape between the two regions (e.g., Hasselmann et al., 1973). A number of different source array parameters were analysed in a similar fashion for their dependence on sea state and used to define realistic source array perturbations as input for seismic modelling.

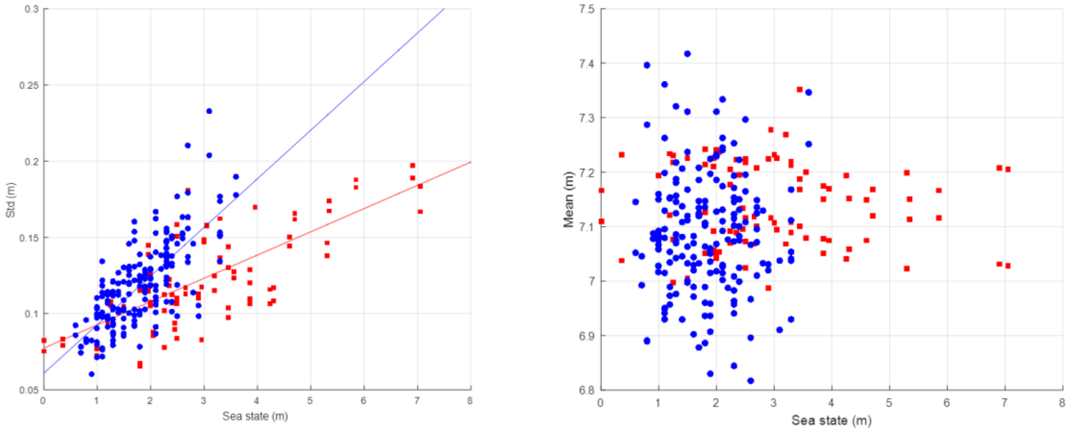

Figure 2: *Dependence of source array depth standard deviation (left), and mean array depth (right) for two different surveys (red and blue). Each point represents data from one sail line. Lines denote linear regression through the respectively coloured data points.*

Wave-induced array perturbations

Wave-induced source array perturbations can in principle have two effects on the farfield source signature: (i) variations in hydrostatic and firing pressure cause variations in the bubble period and hence the waveform of individual gun signatures. (ii) Movement of the source floats with the sea surface can cause the array to pitch and roll, which would have an effect on the array directivity. The former effect can be directly quantified from the measured depth sensor and firing pressure data, while the latter requires extraction of pitch and roll from the depth sensor data within one source float. We achieve this through a decomposition of the individual depth sensor measurements (at least three per float, but typically one per gun/cluster position) using Legendre polynomials up to the first order. This gives a mean array depth variation (0^{th} order) and a subarray pitch (1^{st} order).

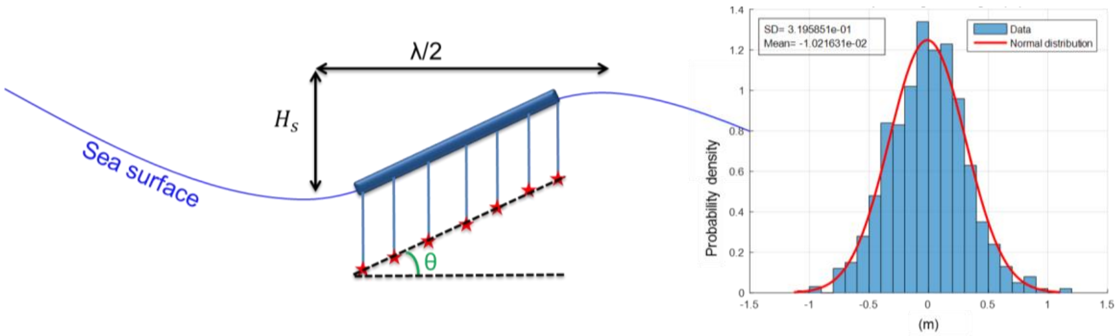

Figure 3: *Left: Sketch depicting how to approximate the array pitch as a function of sea state. Right: example histogram of the wave-induced pitch, expressed as the depth difference between 1^{st} and last gun, using the JONSWAP model with γ=5.*

One caveat is that depth sensor data (a pressure measurement) can only measure the position of the source subarray relative to the sea surface, and hence doesn't capture the wave-induced shape changes of the sea surface which is additive to the subarray pitch determined from decomposing the depth sensor data. Lacking a direct measurement of the sea surface shape, we model sea surface tilt based on standard spectral wave models (Pierson & Moskovitz, 1964; Hasselmann et al., 1973) for each sea state. For this we need to know the length of the source float, the significant wave height H_S and the peak wavelength λ. We assume that the wavelength of sea waves is always larger than the float length such that the source float is following the sea surface and we can approximate the wave-induced pitch component $\theta = \arctan(2H_S / \lambda)$, as depicted in Figure 3. Since both λ and H_S depend on the square of the wind speed for fully developed seas, the wave steepness, i.e., the ratio of the two will in theory be independent of sea state. In practice, however, the wave steepness can be highly variable for different conditions and in different regions (Chakrabarti, 2005). We account for this by considering the JONSWAP wave model (Hasselmann et al., 1973) with a varying peak shape parameter γ. The resulting wave-induced pitch component is typically larger than the pitch component extracted from the decomposed depth sensor data. The example histogram in Figure 3 amounts to a standard deviation of 0.3 m difference between 1st and last gun for a subarray float length of 15 m.

Modelling of 4D noise

To investigate the effect of source array perturbations on 4D data, we create a synthetic seismic 4D dataset for an ocean bottom receiver configuration. The survey geometry consists of 50 receivers with 50 m spacing and 200 shot points with 25 m spacing. For simplicity, but without loss of generality, we restrict ourselves to a 2D line with 3D wave propagation (2.5D case). The geologic model shown in Figure 4 is representative of the North Sea with an oil reservoir at 2 km depth. To obtain a realistic 4D scenario for a one year repeat cycle, we have introduced a very subtle change of 1 m in the oil-water contact (OWC) and a 1% saturation-induced velocity change in the reservoir (red arrow in Figure 4).

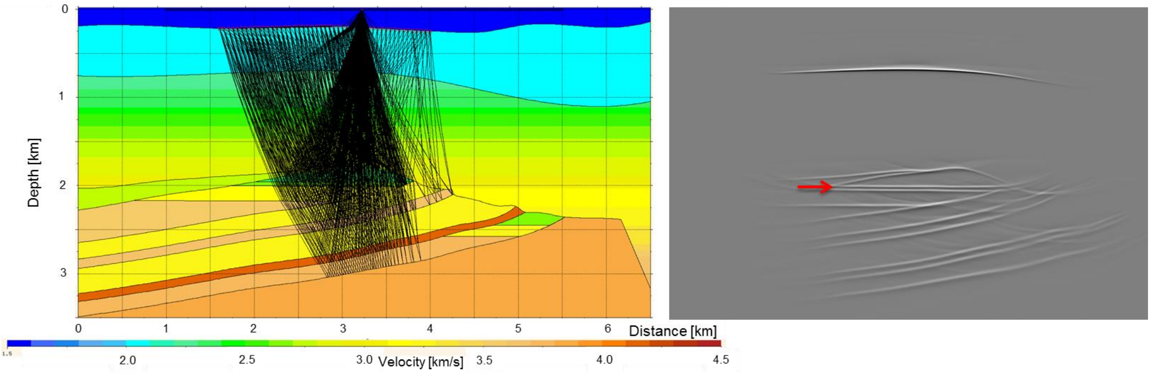

Figure 4: *Left: P-wave velocity model used for modelling. Rays are shown for one shot point into all 50 receivers. The reservoir is located below an unconformity at 2 km depth in the centre of the model. Right: depth-migrated image obtained from primary reflections. Arrow points to reservoir.*

Source perturbations are introduced by first modelling the individual notional sources at their respective position in the source array with randomly varying input parameters such as hydrostatic pressure and firing pressure. Array geometry variations are introduced in two steps: first, we create random variations of the subarray pitch relative to the sea surface such that individual gun depths are slightly different and hence the hydrostatic pressure for notional modelling varies. This resembles the case captured by the depth sensor data described earlier and hence we use the empirically determined standard deviation as input. In a second step, we add a wave-induced array pitch and roll. This latter step will only affect the array directivity but not change the waveforms of the individual notional signatures as the hydrostatic pressure remains unaffected. To achieve an unbiased statistics, we create these perturbations on a much larger sample of 1000 shots and bootstrap a subset for the number of shot points in our example (Figure 4). We use different random seeds and bootstrap samples for the source perturbations in the baseline and monitor surveys. We have also tested different statistical parameters representing different weather conditions for baseline and monitor. Synthetic seismograms are created with a wave front construction method (Vinje et al., 1993). We apply some rudimentary pre-processing to the gathers, including a global 1D designature operator, then image the data by means of a Kirchhoff prestack depth migration using the baseline velocity model, and finally subtract baseline and monitor to obtain a 4D image (Figure 5). We quantify the remaining 4D noise on an overburden reflector (see arrow in Figure 5) by means of the NRMSD attribute. Since we are particularly interested in the influence of source signature and directivity variations, we omit all other potential sources of 4D noise, except of a small (1%) component of random white noise added to the prestack data for the purpose of stabilizing the NRMSD operator (Kragh & Christie, 2002). With the described workflow, we can now investigate the influence of source-related variations on 4D noise as quantified through the NRMSD attribute measured on an overburden reflector. The examples shown in Figure 5 correspond to the two end-member cases of no perturbation (left) and high, but realistic perturbations for rough seas (sea state 5; H_S = 3.5 m) in the North Sea (γ=5) on the right hand side. We obtain an NRMSD of 3.9%, measured along the overburden reflector (arrow 1). Between these two end-member cases we investigated various scenarios, including different sea states and wave shapes, but also the separate influence of signature variations and array directivity variations.

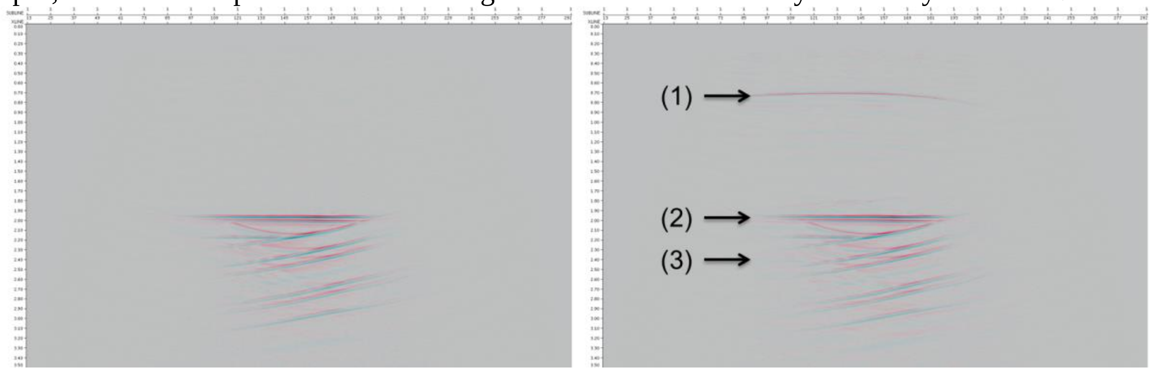

Figure 5: *Synthetic 4D difference image. Left: no source perturbations. Right: source perturbations for rough sea including wave-induced pitch and roll. Arrows (1) points to an overburden reflector used to measure NRMSD, (2) points to the 4D reservoir signal, and (3) the underburden 4D effect.*

Conclusions

Wave-induced shot-to-shot variations of marine airgun arrays can have a significant impact on the quality of 4D data. Our modelling, which we try to base on measured variations to the extent possible, suggests that up to 4% NRMSD can be attributed to the source. The two main contributing effects are variations of individual gun signatures due to pressure changes, and array directivity variations due to the wave-induced pitch and roll of the source floats. The latter effect has a larger impact on the 4D noise in our simulations and depends more on the wave steepness rather than the wave height. While waveform variations can be addressed by a nearfield-based shot-by-shot de-signature, directivity variations are difficult to correct without knowledge of the sea surface shape.

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