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Progress towards a Passive Shallow-subsurface Continuous-monitoring System at Valhall Using the LoFS Array

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SUMMARY

The Valhall Life of Field Seismic (LoFS) OBC seismic array was installed in 2003 for the purpose of regular long-term 4D monitoring of the Valhall oil field. With academic collaborators, BP has investigated whether it could be used to synthesize virtual sources using passive seismic interferometry, allowing continuous monitoring of the field. The ambient noise background consists of Scholte waves, which propagate with a limited depth of penetration below the subsurface. Furthermore, although the noise is broadband, it only has the necessary statistical properties required for interferometry over a frequency range of about 0.18 to 1.75 Hz. At such low frequencies, however, Scholte waves do penetrate the top few hundred meters. Preliminary results give hope that it may be possible to use the Valhall OBC array to monitor the shallow subsurface in near real time.

Introduction

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Learning to use passive data

Artman (2007) was the first to attempt virtual-source interferometry on passive data from the ungimbaled 4C Valhall OBC array. He found that the noise on the hydrophone component of a 2004 dataset predominantly came from a few discrete sources, and did not have the necessary full coverage of propagation azimuths required for successful interferometry. Landès et al (2009) instead examined the rotated vertical component of a 2005 dataset. They successfully demonstrated 2D surface-wave inversion to a depth of 20 meters along radial lines emanating from the platform, their noise source. Dellinger and Yu (2009) also examined the 2005 dataset and found that it could be broken into three distinct frequency regimes: swell noise below 0.18 Hz (primarily on the hydrophone component), microseismic noise between 0.18 and about 1.75 Hz, and manmade noise above 1.75 Hz. This pattern appears to be a consistent feature of all Valhall data. Figures 1-3 demonstrate these three regimes.

Below 0.18 Hz swell noise dominates the energy in the hydrophone component. It has a dominant period of about 10 seconds, about the length of a typical seismic record. Low-cut recording filters are designed to strongly attenuate this "noise", but in fact it is still present even in low-cut filtered data and can be recovered by careful bandpass filtering of continuous data, as in Figure 2. Under calm conditions this energy can be seen to consist of dispersive plane waves of ocean swell, slowly moving (at ~10-18 m/s) across the array in parallel ranks (e.g., the dashed line in Figure 2). Above 1.75 Hz, the spectrum in Figure 1 develops a characteristic "thick line" appearance. Figure 2 shows that this energy is loudest around the platforms. This "rig noise" primarily comes from repetitive manmade sources such as pumps, each source creating a forest of narrow spikes in the frequency domain, which when all summed together "thicken" the spectrum. On the vertical component or on a low-cut-filtered hydrophone component, this "rig noise" is the dominant energy in the data, easily overwhelming everything else. This was the component used by Artman (2007) and Landès et al (2009).

In between these two frequency ranges is a weaker band that well approximates "random noise", as required for successful interferometry. This is the "double frequency microseismic peak" (Longuet-Higgins, 1950). It is excited by ocean swell interacting with the Earth's crust. A clean interferometry result can be obtained using one or more days of these data, as demonstrated in Figure 4.

Discussion

Virtual-source data can be used with the same surface-wave inversion techniques used with active-source data. The inverted passive surface-wave velocities shown in Figure 5 (left) (de Ridder and Dellinger, 2011) match P-wave velocity features found by performing FWI on conventional active-source data (right) (Sirgue et al, 2010). The passive data can also be used to image shallow surface-wave azimuthal anisotropy (Figure 6), a proxy for mapping shear-wave splitting (Mordret et al, 2013).

Why hasn't passive OBS data been more widely used? One obvious limiting factor is the need for an ocean-bottom array! Less obviously, passive data require greater care in their processing: 4C passive data rotated correctly looks like noise, just like passive data rotated incorrectly. Long data records and ultra-low frequencies can tickle unsuspected (and unrecognized) subtle bugs in long-stable programs.

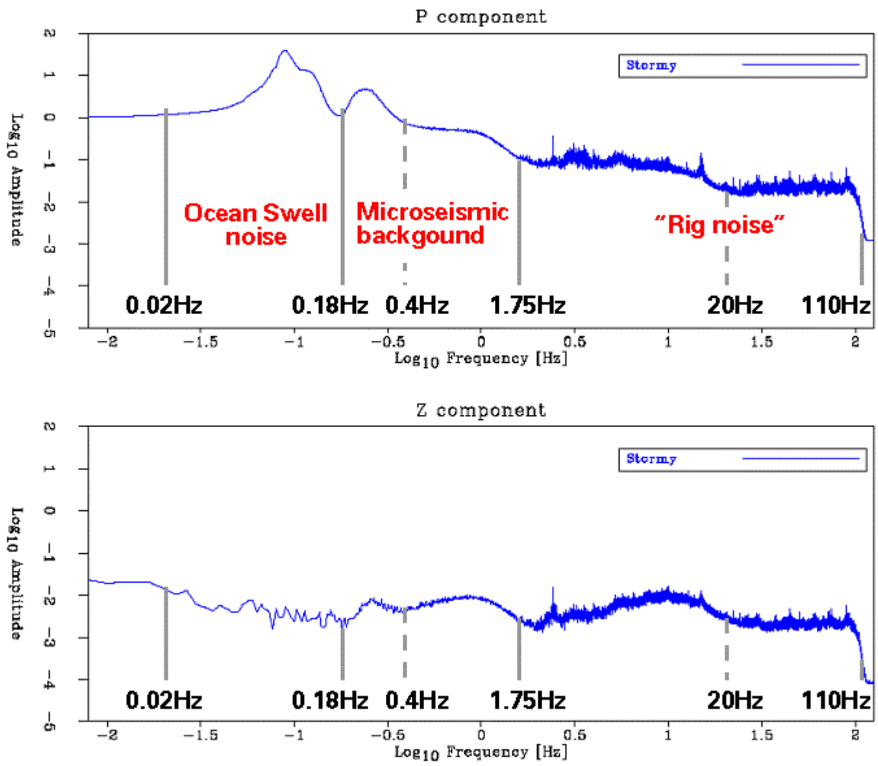

Figure 1: *Spectra for the hydrophone and vertical components of the Valhall array, recorded in 2008 under stormy conditions with the customary low-cut recording filter left off (adapted from de Ridder and Dellinger, 2011). Note the ocean swell noise is weak to nonexistent on the geophone component.*

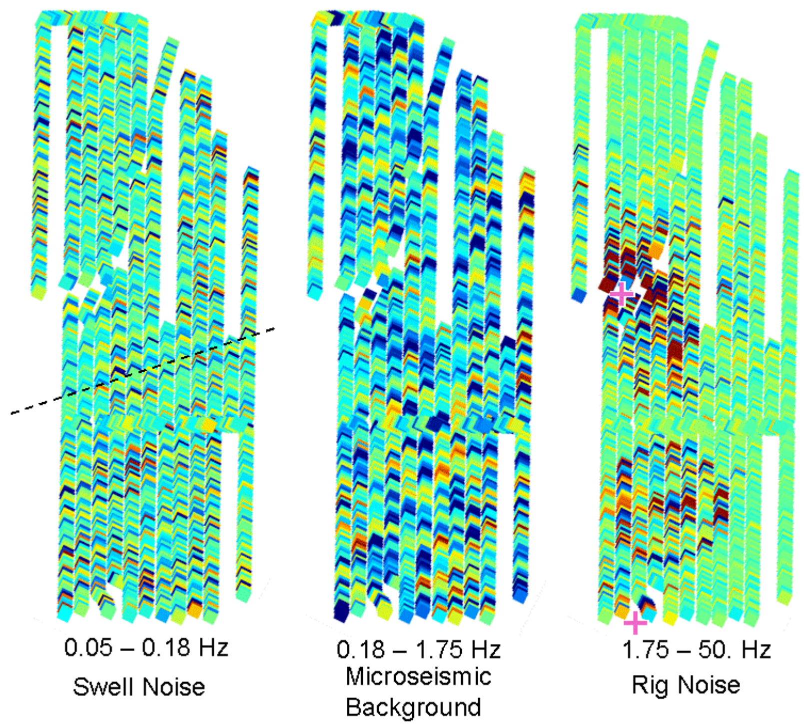

Figure 2: *Time slices of amplitudes of the hydrophone component across the Valhall array for three different frequency ranges. These 2005 data were recorded under relatively calm conditions, with the customary low-cut recording filter used for active data engaged. The "rig noise" contains repetitive signals around the platforms (marked by purple crosses) but also occasional manmade impulsive signals (e.g. the prominent expanding ring of energy in the lower half of the array).*

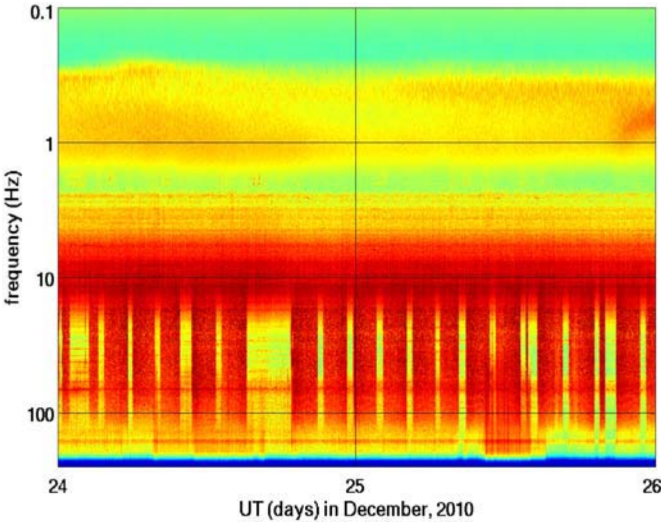

Figure 3: *A spectrogram of an unfiltered 2010 vertical-component dataset spanning two days. Amplitudes and frequency are plotted on a log scale. Above 2 Hz these data are dominated by noise from airguns at the nearby Ekofisk field (vertical stripes) and monotonously droning locally generated "rig noise" (horizontal stripes). Note the noise between 0.18 and 1.75 Hz slowly varies with changes in the sea state.*

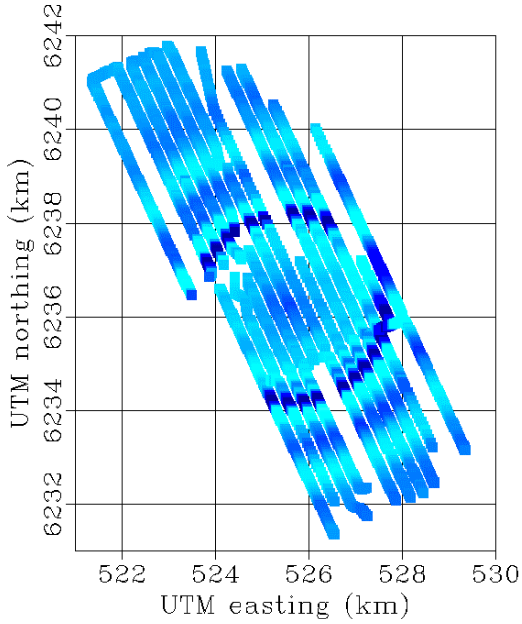

Figure 4: *A snapshot of a 0.18-1.75Hz Scholte wave after 6 seconds of propagation from a virtual source near the centre of the array (Z component, 2010 dataset). Note the frequency dispersion, with lower frequencies travelling at twice the velocity of higher frequencies.*

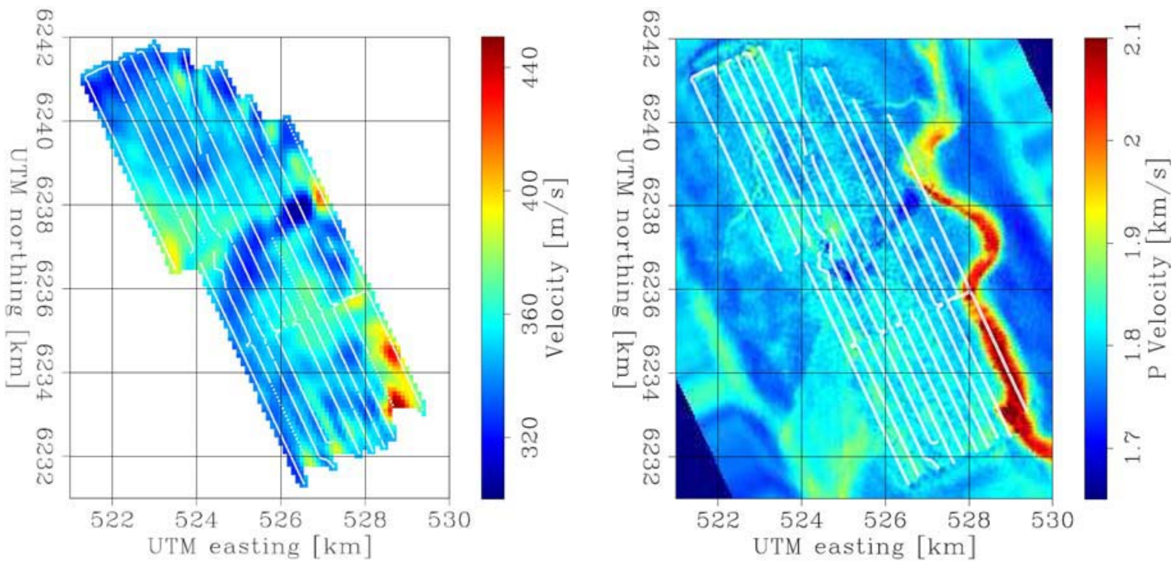

Figure 5: *Ambient-seismic-noise Eikonal surface-wave tomography (left) over the frequency range 0.35-0.95 Hz, showing surface-wave velocity anomalies that appear to correspond to anomalies in a P-wave velocity model created by FWI of conventional airgun data, averaged over 150-195 meters below the sea floor (right, reproduced from de Ridder and Dellinger, 2011). Note that active sources, unlike virtual ones, can sample areas outside the array footprint.*

Any nonlinear process (including those caused by subtle bugs) applied to the data will act to mix the data over frequency and can destroy the useful microseismic frequency window. Passive data is also low-grade ore, requiring huge volumes to be useful. Valhall can produce ~1 Terabyte / day, a strain to transmit and store on an ongoing basis. Yet images like Figures 5 and 6 are tiny! For this reason, BP is currently implementing a system that will process Valhall passive data in a streaming manner.

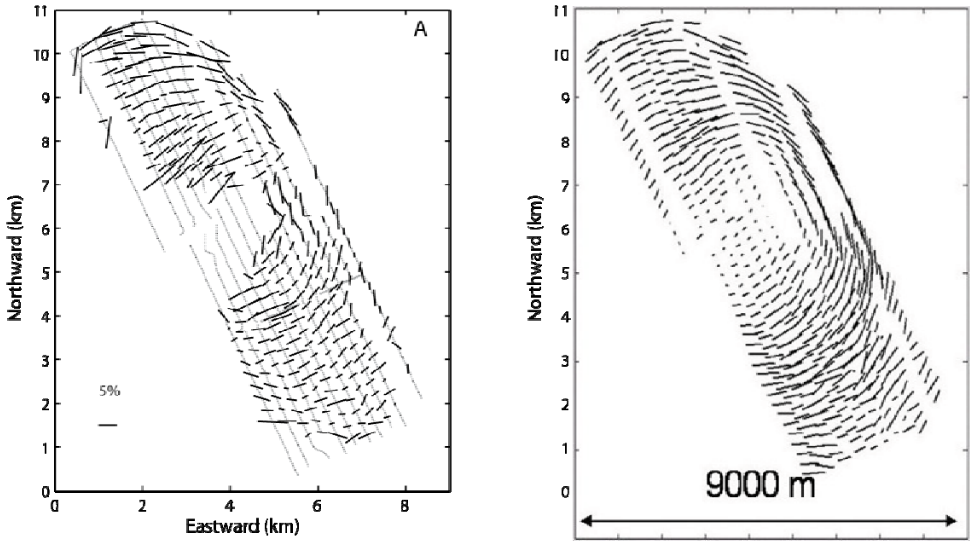

Figure 6: *Maps of shear-wave splitting at Valhall derived from 2005 passive data (left) and from active-source data (right, adapted from Barkved and Kristiansen, 2005).*

Conclusions

Using four trial datasets, recorded under differing weather conditions, with different filter settings, and at different times, we have demonstrated that we can use passive data to make preliminary images of the subsurface at Valhall down to about ~200 meters. The next step is to finish constructing a system that will automate this process, allowing new processed passive datasets to be generated approximately daily, an orders-of-magnitude increase in the passive data previously available from Valhall. This should make continuous 4D surveillance using passive data possible at Valhall for the first time. Yet to be discovered is how stable these images will be against irrelevant perturbations such as changes in the weather, seasons, or local human activity, and how sensitive the images might be to relevant 4D signals such as changes in the subsurface state of stress or moving fluids.

Acknowledgements

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