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# Passive Time-lapse of Valhall Subsurface From Correlation of Ambient Seismic Noise

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## SUMMARY

We used two "vintages" of ambient seismic noise recorded at the Valhall Life of the Field Seismic network in 2004 and 2005 to perform a passive time-lapse of the subsurface. First, the cross-correlations between each pair of stations separated by less than 1 km are computed for each year. Second, the relative velocity variations between the 2004 and 2005 cross-correlations are computed using the Moving-Window Cross-Spectral technique. Finally, the relative velocity variation measurements are regionalized using a tomographic technique. The results show a strong decrease of velocity on the eastern side of the Valhall network as well as large patch of increased seismic velocity on the southern part of the network. This increase of velocity can be attributed to the exploitation of the southern flank of the Valhall reservoir with new wells and is in good agreement with a previous time-lapse study using Scholte waves from an active experiment.

## Introduction

Deterministic signals extracted from cross-correlations (CC's) of seismic noise (e.g., Gouédard et al., 2008, and references therein) provide a very attractive alternative to earthquake or active sources. For receivers installed on the earth surface, these noise CCs are dominated by fundamental-mode surface waves (Shapiro & Campillo, 2004). This technique provides two families of applications: the first one is made of noise-based surface-wave imaging methods (e.g., Shapiro et al 2005). The second family of application is based on the permanency and repeatability of the seismic noise and allows the emergence of continuous monitoring methods. CCs of noise can be computed, for example, on a daily basis and the comparison of the daily waveforms with respect to a reference one permits to track the temporal variations of the seismic velocity of the medium between the stations. Noise-based monitoring methods have a better temporal resolution and repeatability compared to methods based on earthquakes doublets or repetitive active sources comparison. These monitoring methods have been successfully applied to monitor volcanoes (e.g., Brenguier et al., 2008b) and active faults (e.g., Brenguier et al., 2008).

Such a method is of major interest for industrial applications and very few studies have been undertaken in this context so far (e.g. Corciulo et al., 2012; Delatre & Manceau, 2013). In the present paper, data of the Valhall Life of Fields Seismic network are used to extract Scholte waves (i.e., interface waves travelling between a water layer and the subsurface) from cross-correlation of ambient seismic noise. We use two datasets, the first one was recorded in 2004 during 29 hours and the second one was recorded in 2005 during 6.5 hours, to compute a time-lapse image of the velocity changes during this year.

## Methods

We analysed the continuous signals recorded at 250 Hz from 2320 sensors of the LoFS network. The CCs computation is described in detail by Mordret et al. (2013a) for the 2005 dataset and partly follows the workflow of Bensen et al. (2007), involving down-sampling to 10 Hz, spectral whitening between 0.5 and 2.85 s before computing the CCs. The same processing has been applied to the 2004 dataset. Because the data do not present strong amplitude variations, we did not used temporal normalization. In this study, we focused on Scholte waves and used the ZZ CCs from station pairs separated by less than 1 km. We only analyse here the CCs below 1.65 Hz that contain reconstructed Scholte waves from natural ambient noise.

The Moving-Window Cross-Spectral technique (Poupinet et al., 1984; Brenguier et al., 2008b; Clarke et al., 2011) is used to infer the velocity changes between 2004 and 2005. Unlike most of studies using noise CC for monitoring velocity changes, the time delays are computed only within the direct arrival windows defined by velocities between 200 m/s and 1000 m/s. The moving window used for the measurements is 4 s wide and moves with 0.05 s steps. The measurements are done in the 0.8 to 1.6 Hz frequency band where the signal-to-noise ratio is the highest. To infer the relative velocity variation, a linear regression is fitted to the time-delay measurements from windows exhibiting a coherency higher than 0.875. The relative velocity variation is then the opposite of the relative time delay. Figure 1 shows two examples of relative velocity variation measurement and their errors. Despite the relatively poor coherency of the CCs waveforms it is possible to measure relative velocity variations with small uncertainties.

## Results

Figure 2a shows the relative velocity variation measurements for the station pairs use in this study and Figure 2b the errors of the slope associated with these measurements. The areas around the platforms exhibit strong relative velocity variations (both positive or negative) as well as strong errors. Far from the platforms, the average relative velocity variation is between +0.5% and -1% with errors on the order of 0.2 %.

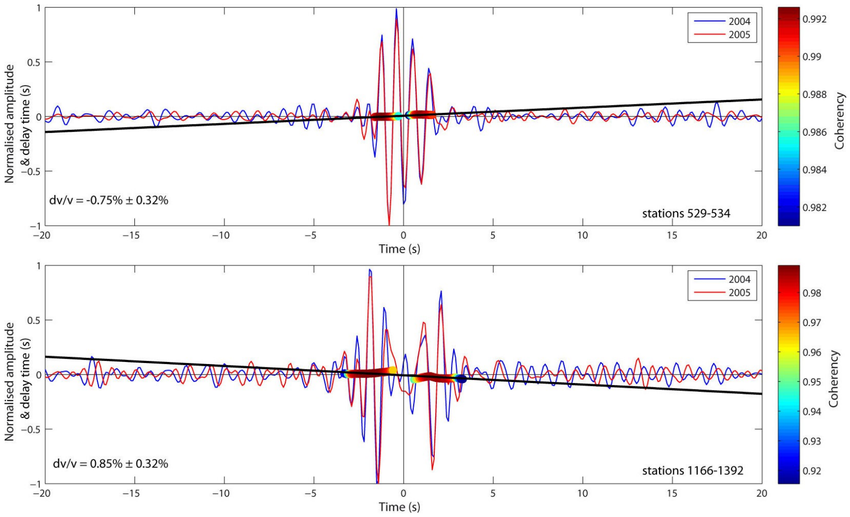


***Figure 1*** *Doublet measurement for two cross-correlations. a): cross-correlation between station 529 and 534. b): cross-correlation between station 1166 and 1392. The large dots are the time delay measurements and their colors represent the coherency of the waveforms in each moving window. The black line shows the linear fitting to the delay measurements. The value of the inferred relative velocity variation and its error is shown in each panel.*

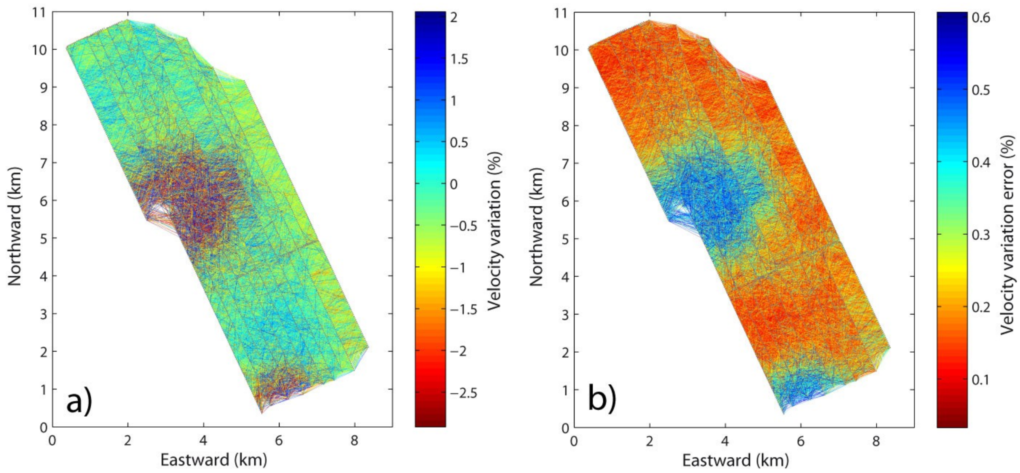


***Figure 2*** *Results of relative velocity variation measurements for every cross-correlations used in this study. Left : relative velocity variations. Right : Error of the relative velocity variations*

The main features observed in the relative velocity variation map are the strong velocity decrease on the eastern side of the Valhall network which reaches -1% and the patch of increased velocity in the southern part of the field which reaches +0.5%. The platform areas are not well constrained, as already observed by Mordret et al. (2013a) for a group velocity tomography. To have a better estimate of the spatial distribution of the velocity changes a tomographic technique is used to regionalize these values (Takagi et al., 2012). Because the measurements are done on the direct arrival waves, it is possible to use the ray-based tomographic method of Barmin et al. (2001) to map the relative velocity variation measurements.

Figure 3 shows the regionalisation of the relative velocity variations. This map is more easily interpretable that the map of the Figure 2. The main features observed in the relative velocity variation map are the strong velocity decrease on the eastern side of the Valhall network and the patch of increased velocity in the southern part of the field. The platform areas are not well constrained, as already observed by Mordret et al. (2013b) for a group velocity tomography.

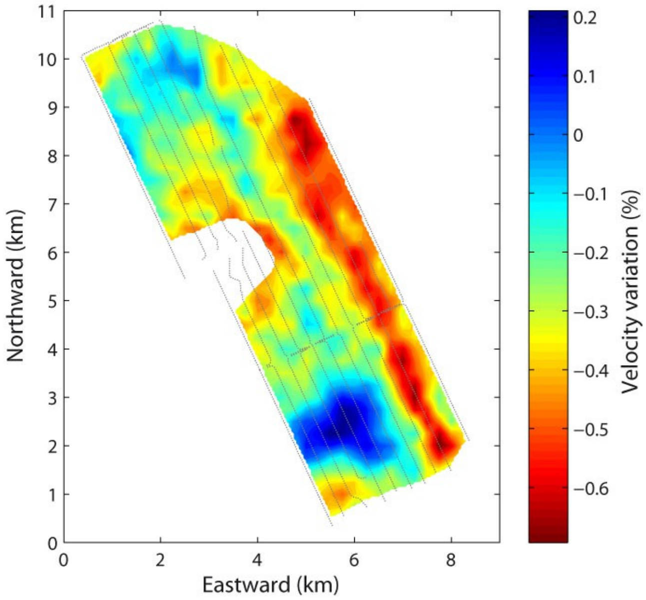


***Figure 3** Regionalization of the velocity variations*

**Discussion**

The results presented in this study can be compared with time-lapse results from Wills et al. (2008) who measured by cross-correlation the time-shift between Scholte waves acquired during active surveys in November 2003 and November 2005. Even if the methods are different and the delay between the surveys is twice longer in the case of Wills et al. (2008) study, relative velocity variation results from our study are in good agreement with results from the active surveys. The discrepancies in amplitude between the two studies can be due to the method used by Wills et al. (2008) (they measured the time-shift between the surveys by measuring the time-lag of the cross-correlation of the Scholte waves). This method may be less accurate than the Moving-Window Cross-Spectral technique. Nevertheless, the main observed features are similar in both maps. Of particular interest is the area of increased (or smaller than average decrease) velocity at the south of the field. It is related to the drilling of new wells in 2003 to exploit the southern flank of the reservoir. The previous 20 years of exploitation of the reservoir in the central area has produced a strong subsidence of the seafloor due to the compaction of the rocks in the reservoir (Hatchell et al., 2009). This subsidence ( 20 cm/y) is not uniform and creates a bowl with compaction at the center and strong extension on the edges. This extension opens concentric cracks that produce noticeable azimuthal anisotropy (Mordret et al., 2013b). When the exploitation started on the southern flank, a new small subsidence bowl started to form on the edge of the older one which closed the former cracks and tend to increase the seismic velocity.

**Conclusions**

We show in this study that the ambient noise cross-correlation method could be used in an marine and industrial environment to produce time-lapse maps of the Scholte waves relative velocity variations from datasets recorded one year apart. At Valhall, 6.5 hours of continuous noise are sufficient to accurately reconstruct the direct arrival parts of the Green's functions. At the frequency around 1 Hz where the measurements are executed, the Scholte waves in the cross-correlations have a sensitivity down to a few hundreds of meters. Providing a dense seismic network like Valhall LoFS, this passive technique could then be used to monitor the near surface in quasi real-time. We believe that this technique could have important industrial applications such as hydrocarbon or CO2 sequestration reservoir environment monitoring.

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