Correlation energy between surface and borehole stations at the Valhall field

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ABSTRACT

Ocean-bottom cables at the Valhall field have provided an abundance of passive seismic data for testing the potential of seismic interferometry. We cross-correlate recordings from surface stations and 2-km deep borehole stations. Results show correlated energy at frequencies between 0.175 Hz and 1.75 Hz. However, the signal we retrieved is not time-symmetric, as there are multiple arrivals at acausal correlation time lags compared to the one arrival visible at causal time lags. The apexes of the causal events are found at acausal time lags rather than at zero time lag. The virtual source is centered northwest of the borehole stations at the offshore platform. We conclude that these observations are due to the borehole acting as a wave-guide. Because this mechanism does not satisfy the conditions of seismic interferometry, we cannot interpret these cross-correlation results as inter-station Green's functions.

INTRODUCTION

Traditional seismic surveys for subsurface imaging deploy a collection of receivers and a controlled source. These surveys are often expensive to deploy and require much effort to oversee. Passive seismic interferometry does not require a controlled source. Cross-correlating recordings of ambient seismic noise at two receivers turns one of the receivers into a virtual source and extracts the time it takes the energy from that virtual source to reach the other receiver of interest. This travel-time information can then be used for purposes such as velocity modeling.

Tests of the practicality of passive seismic interferometry for these purposes has been ongoing with ambient seismic noise data provided by the permanent ocean-bottom cable (OBC) array at the Valhall field. Artman (2007) and Landes et al. (2009) showed that virtual omnidirectional point sources could not be captured at frequencies typical of seismic exploration (3-60 Hz). Later, de Ridder and Dellinger (2011) showed that virtual low-frequency (0.35-1.75 Hz), omnidirectional Scholte waves along the ocean floor could be generated from seismic noise. They were able to use the Scholte-wave travel-time information for tomographic imaging of structures in the near-surface (0-150 m).

In previous studies of passive seismic interferometry for seismic exploration at the Valhall field (Artman, 2007; Bussat and Kugler, 2009; de Ridder and Dellinger, 2011) correlations were performed between stations on the ocean floor. In this study we correlate ambient seismic noise recorded over the same time period by the OBC array and by five downhole stations at nearly 2 km depth. Our goal is to test whether Green's functions can be extracted between the borehole stations and the surface stations. In this report, we present the results for low frequencies (0.175-1.75 Hz).

PASSIVE SEISMIC INTERFEROMETRY

In passive seismic interferometry, receivers record data from passive sources such as ambient seismic noise. Under appropriate conditions, cross-correlating two receiver recordings recovers a Green's function and its time-reversed version between the two receivers, convolved with the autocorrelation of a source function such as noise (Wapenaar et al., 2010). In equation form

$$[G(x_B, x_A, t) + G(x_B, x_A, -t)] * S_N(t) = \langle u(x_B, t) * u(x_A, -t)\rangle \quad , \tag{1}$$

where G is the Green's function between two receiver locations (x_A, x_B), $S_N(t)$ is the autocorrelation of the source function (here it is noise), and u is the observed wavefield at a given receiver location. Convolving the Green's function with the autocorrelation of the source function can reveal the time it takes for a virtual source signal at one receiver to reach the other receiver of interest, whether directly or after reflecting in the subsurface. If investigating direct waves, the travel-time information with the known distance between the two receivers produces an estimate of the average velocity along the path traveled. Using only surface stations and direct waves, de Ridder and Dellinger (2011) successfully constructed a velocity model of the shallow subsurface at Valhall. Now we want to incorporate recordings at borehole stations into our passive seismic interferometry. To determine whether we can extract the Green's functions between borehole and surface stations, we start by looking at spectrograms and by cross-correlating the borehole and surface station recordings.

VALHALL SURFACE STATION AND BOREHOLE STATION RECORDINGS

In late December of 2010, 2224 4-component stations on the seafloor and 5 3-component stations in a single borehole recorded ambient seismic noise at the Valhall field continuously for approximately 5 days. The ocean bottom stations were densely sampled in-line (50 m) and sparsely sampled cross-line (275 m). The borehole stations were spaced roughly 8 m apart laterally and 11 m apart vertically within a deviated wellbore at a depth of almost 2 km. They have average Universal Transverse Mercator (UTM) coordinates 525.5 km easting and 6236.5 km northing. Figure 1 shows the surface array and the surface projections of the borehole stations in map view. The borehole extends from an offshore platform, which is located at approximate UTM coordinates 524.5 km easting and 6237.0 km northing.

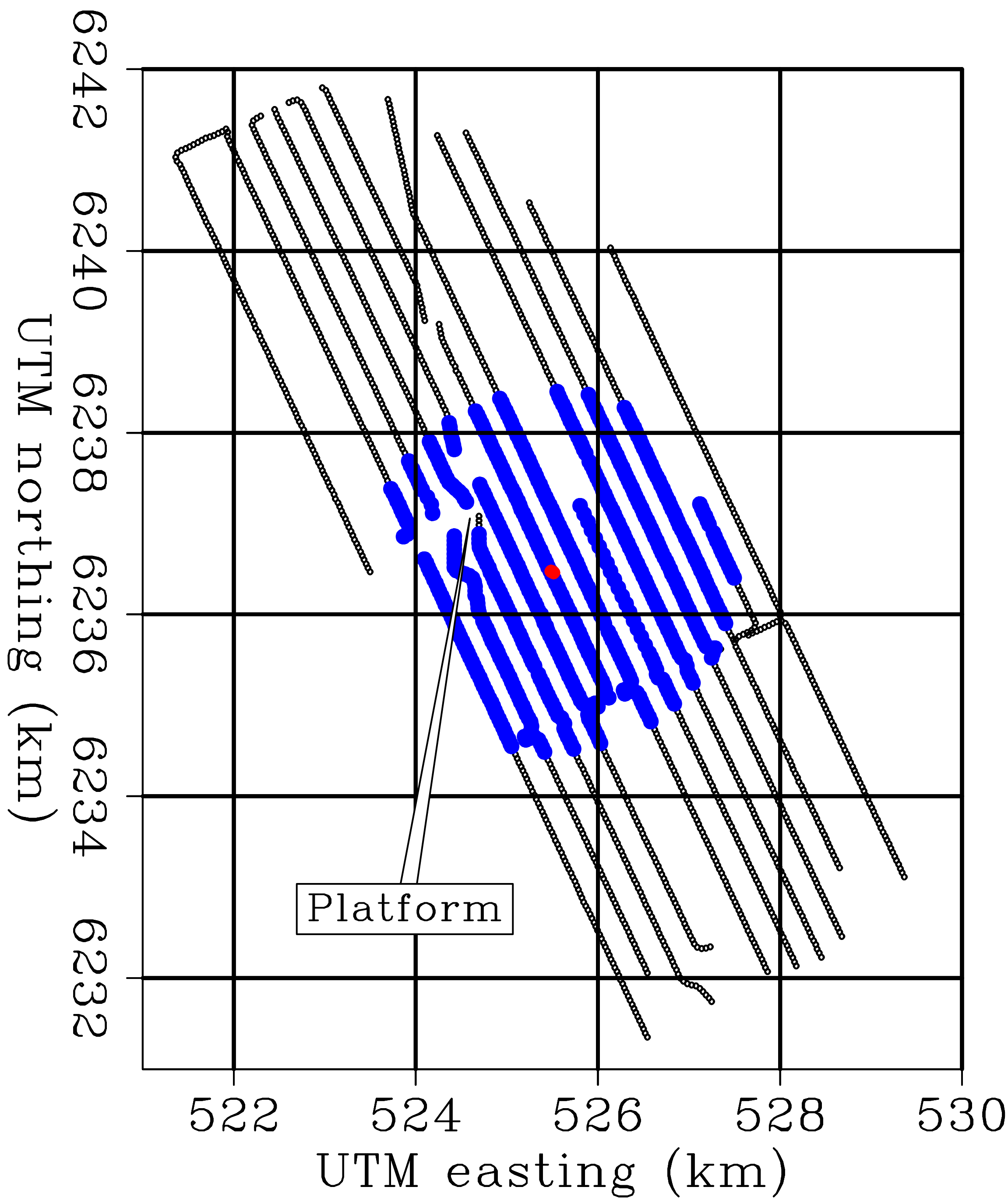

Figure 1: Distribution of seismic stations at Valhall. Black and blue circles are surface stations, with blue representing those stations within 2 km of the average surface projection of the five borehole stations. Red circles depict the five borehole stations, which are all at nearly 2 km depth. The location of the platform is also shown. [**CR**]

Prior to creating any spectrograms or performing any cross-correlations, we had to adjust the borehole recordings. The three components at each borehole station were independently directed roughly north, west, and downward. Using a direction cosine matrix calculated from the provided azimuth and dip information of each component at each borehole station, we transformed these components to due north, due west, and direct downward.

SURFACE AND BOREHOLE STATION SPECTROGRAMS

A spectrogram is a plot of spectra versus time. Here we created three of them to compare the average spectral content of the data recorded by the OBC array and by the borehole stations. These spectrograms provide a first look at whether there is seismic energy at the low-frequency (0.175-1.75 Hz) range we are interested in. We calculated spectrograms for the vertical components of the surface stations within 2 km of the average borehole station location, the vertical components of the five surface stations nearest the platform, and the vertical components of four (out of five) borehole stations. The locations of these sets of stations are shown in Figure 1. We chose surface stations within 2 km of the borehole stations because it was a range comparable to the depth of the borehole stations. We chose surface stations closest to the platform because we wanted to compare signals in the borehole and signals at the entrance of the borehole. We considered only four borehole stations because one of the stations had much lower amplitude correlation results (Figure 4), which might be caused by processing errors.

To generate the spectrograms, we divided recordings at all stations into 2.5-minute overlapping segments. The mean was removed from each of the time segments prior to calculating the frequency spectrum. We then averaged the resulting spectra for each time segment over the selected stations and plotted them over the entire 5-day recording period.

Figure 2 shows the three spectrograms that we calculated. It is evident from Figure 2(a) that frequencies from near 0 Hz to 1.75 Hz consistently contain an abundance of energy at the surface stations. The surface stations nearest the platform, as seen in Figure 2(b), show similar trends over time but with weaker energy. This low-frequency energy is least evident in Figure 2(c), where there is high energy at very specific frequencies at the borehole stations. These dominant frequencies at the borehole stations are likely hiding the low-frequency energy that is clearly visible in the spectrograms of the surface stations.

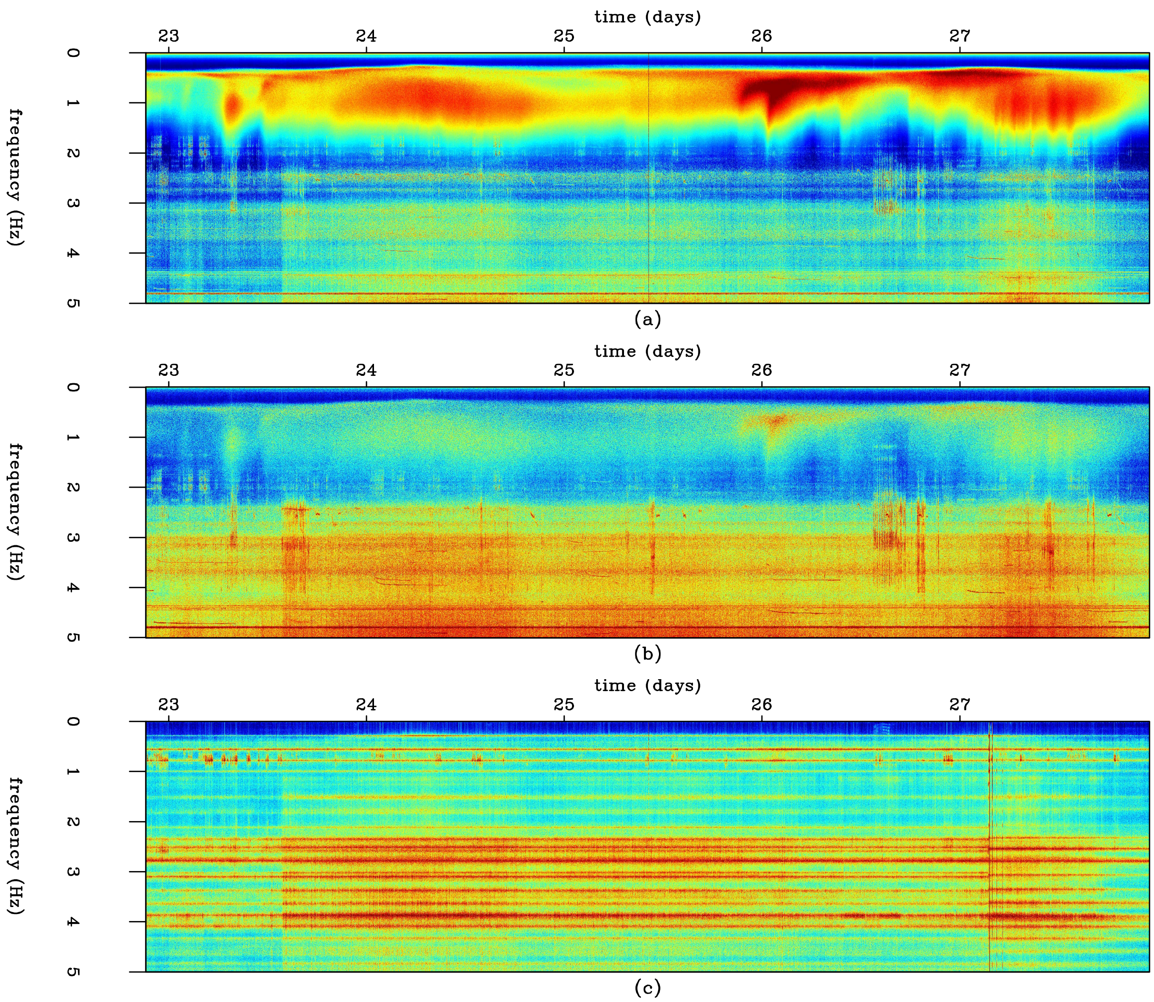

Figure 2: (a) Average spectrogram of surface stations within 2 km of the borehole stations. (b) Average spectrogram of the five surface stations nearest the offshore platform. (c) Average spectrogram of the vertical components of the borehole stations. Note the energy in the lower frequencies. [**CR**]

CROSS-CORRELATIONS BETWEEN BOREHOLE AND SURFACE STATIONS

We cross-correlate the borehole and surface station recordings to determine whether we can extract the Green's functions between them. Prior to the cross-correlations, data had to go through some processing. The five days of data at each station came in 3-hour and 15-minute segments. We tapered the first and last 15 minutes of each segment with a smooth cosine-squared taper to avoid truncation artifacts that could arise when bandpassing. We then bandpassed the segments of data recorded at both borehole and surface stations between 0.175 Hz and 1.75 Hz to be similar to the virtual Scholte-wave frequencies seen in de Ridder and Dellinger (2011). For time sections displaying instrument malfunction, we centered a smooth notch taper at the problematic section prior to bandpassing. After bandpassing, we removed the resulting artificial spikes from problematic sections by another notch taper.

We cross-correlated all possible combinations of borehole and station recordings for each time segment. This consisted of all three components at each borehole station and the vertical component at each surface station. For each cross-correlation, we time-reversed the borehole recording before convolution. We then stacked cross-correlation results from all time patches to improve the signal-to-noise ratio.

Figure 3 displays the cross-correlation results between 2140 surface stations and the shallowest vertical borehole component (1.934 km depth). Cross-correlations between vertical components of other borehole stations and the surface stations produced similar results. There is generally one arrival visible in the causal correlation time lags but many in the acausal (negative) time lags. The event in (mostly) causal times forms a cone with the apex at a negative correlation time lag (approximately $t = -2$ s). There is a mirror event (with time-reverse symmetry) in acausal times; the time of symmetry is again approximately $t = -2$ s. The acausal time window also contains a series of copies of both events at increasing negative time lags. The coherent energy is of relatively high frequency, and the wavelength is a few hundred meters. With wavelengths this short, coherent energy between the surface stations and stations at 2 km depth cannot be explained by the skin depth of surface waves.

Figure 4 shows traces representing the correlation results between a surface station roughly 1.8 km north of the borehole stations and the vertical components of the borehole stations. The traces depict very similar results at both causal and acausal times. The main difference is that the correlation with the fourth borehole station is lower in amplitude. This might be due to an incorrect rotation of that particular borehole.

Another way to look at the correlation results is in map view. Figure 5 plots the correlation results when $t = 2$ s. A strong amplitude, circular wavefront is formed by the coherent energy between the borehole station and the surface stations. This wavefront suggests that the virtual source is centered about a location quite a distance away from the lateral position of the borehole stations. This center happens

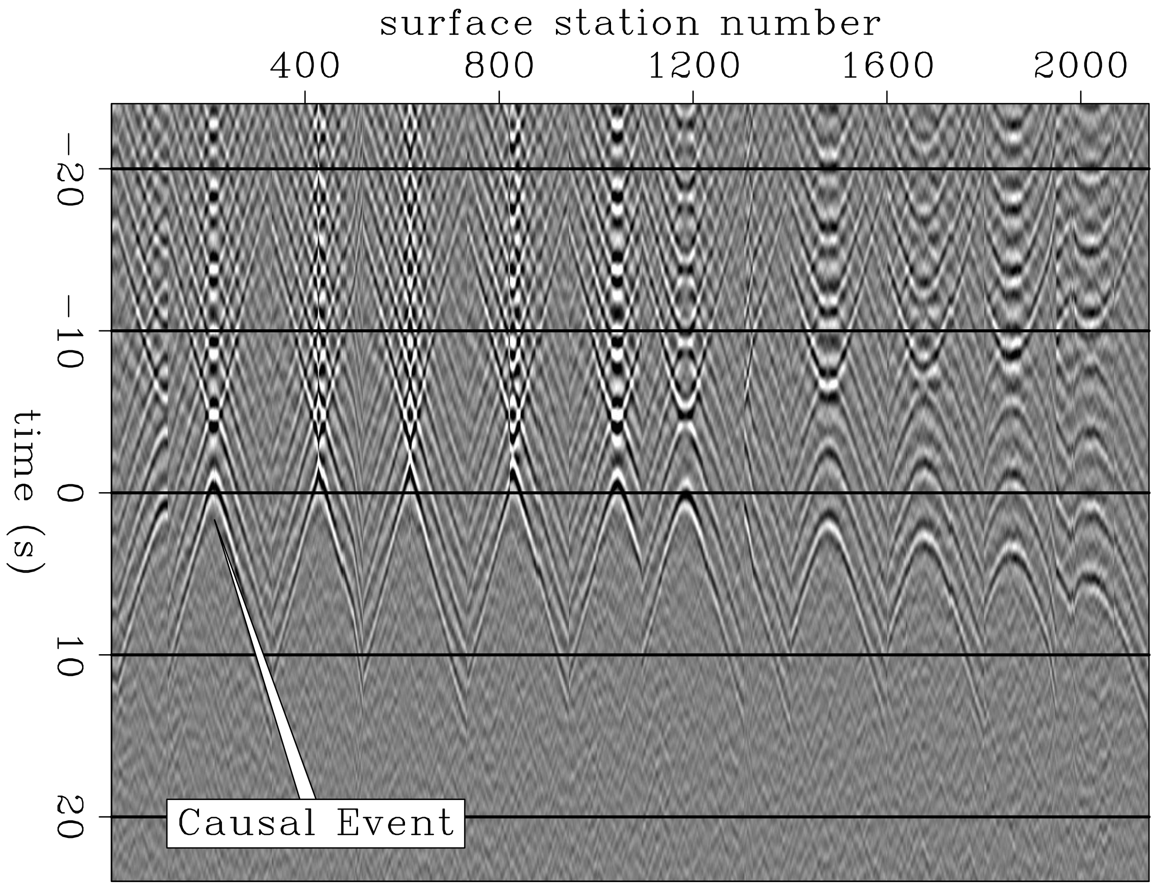

Figure 3: Result after cross-correlations between the shallowest borehole station (at 1.934 km depth) and the surface stations. [**CR**]

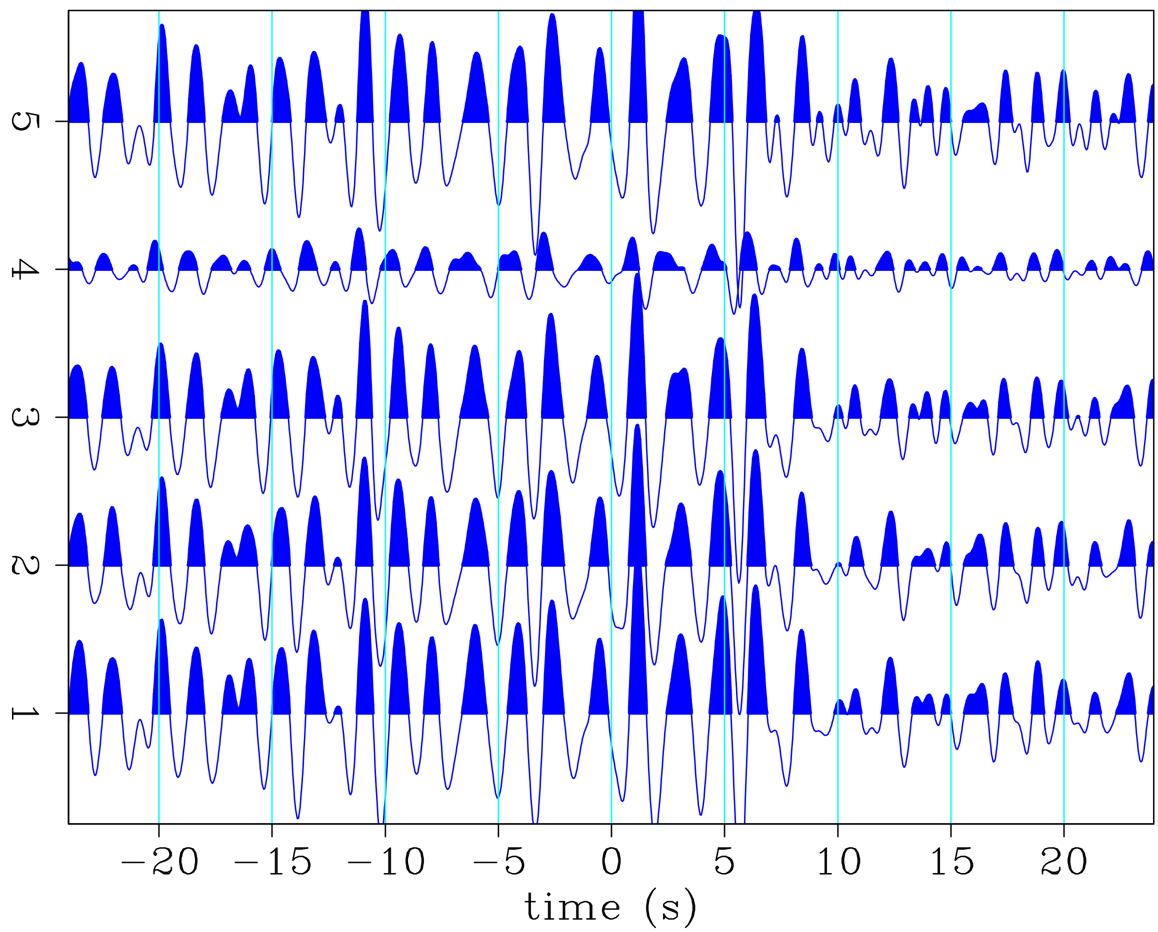

Figure 4: Correlation results of surface station number 1785 with the five boreholes. This surface station is located roughly 1.8 km north of the borehole stations. Trace 1 is the correlation result with the shallowest borehole, and trace 5 is the correlation result with the deepest borehole. Note the similarity of the shapes of the traces but the drastic decrease in amplitude of borehole station 4. [**CR**]

to coincide with the location of an offshore platform, which is where the top of the borehole is located.

DISCUSSION

There is definitely coherent correlated energy between borehole and surface stations. Although the results in Figure 4 appear noisy, the correlations between a single surface station and all five borehole stations are very similar to each other. However, a resemblance between the cross-correlation signal and the Green's function remains to be discussed. As previously mentioned, seismic interferometry says that, under certain conditions, the Green's function between two stations can be extracted by cross-correlating recordings of the ambient seismic field at both stations. One of the primary conditions is that the ambient seismic field satisfies energy equipartition, which means that energy propagates equally in all directions. This seems to be more or less satisfied for wave modes along the surface but does not usually seem to hold in 3D for body waves (Artman, 2007).

The seismic Green's function between borehole stations and the surface stations is unknown, especially at these low frequencies. The wave propagation between stations in the borehole and stations at the surface is obviously affected by the presence of the borehole, as it can act as a wave-guide. It is not inconceivable that the waves propagate from a virtual source in the borehole, first moving up to the surface along the borehole and then outward along the surface. This would explain why the apex of the event at causal times lies at the platform rather than at the surface coordinates of the borehole stations. However, this does not explain the non-physical nature of the apex not lying at $t = 0$ s but at approximately $t = -2$ s, nor why the signal we retrieve is not time-symmetric (not even around approximately $t = -2$ s).

The diagram in Figure 6 shows a possible mechanism for the coherent energy observed at low frequencies between the borehole and surface stations. The diagram depicts energy, excited by distant sources, in both directions along the surface. Energy that reaches the entrance of the borehole both excites the waves down to the borehole stations and continues to the surface stations. This would account for the apex of the (mostly) causal events lying at a small negative correlation lag. Energy that enters the borehole under the platform and travels down can lead to multiple bounces up and down the borehole, which would cause the repetitive signal in the acausal time window. This mechanism of seismic energy does not satisfy the conditions of seismic interferometry, thus we cannot interpret the cross-correlation signals as inter-station Green's functions.

CONCLUSIONS

We have demonstrated that there is correlated energy at frequencies between 0.175 Hz and 1.75 Hz between 2-km deep borehole stations and surface stations at the Valhall

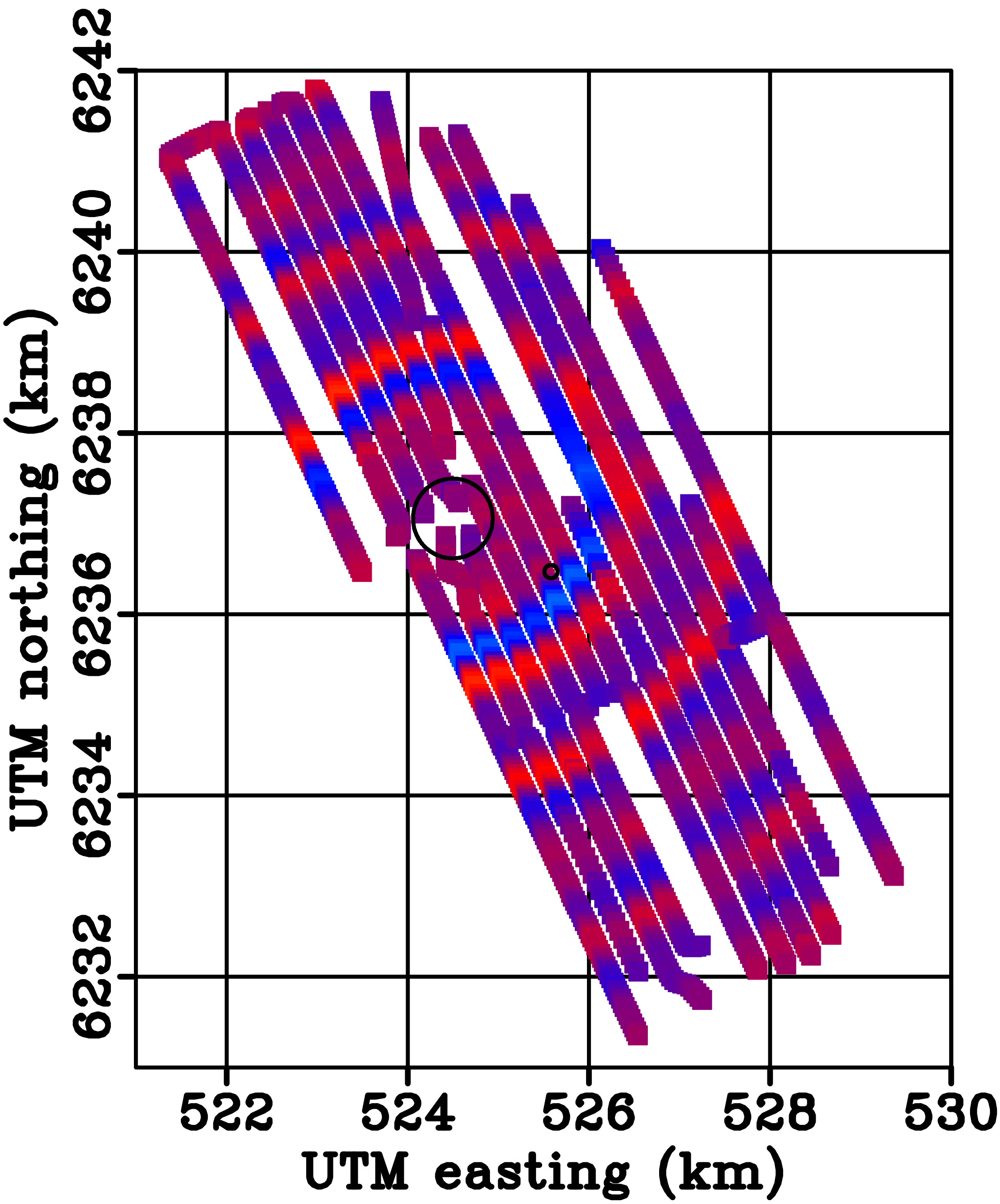

Figure 5: Snapshot of the wavefront propagating outward from the virtual source. Note how the virtual source location appears to be northwest of the borehole station location 525.5 km and 6236.5 km (smaller circle). This source location is near an offshore platform 524.5 km and 6237 km (larger circle). [**CR**]

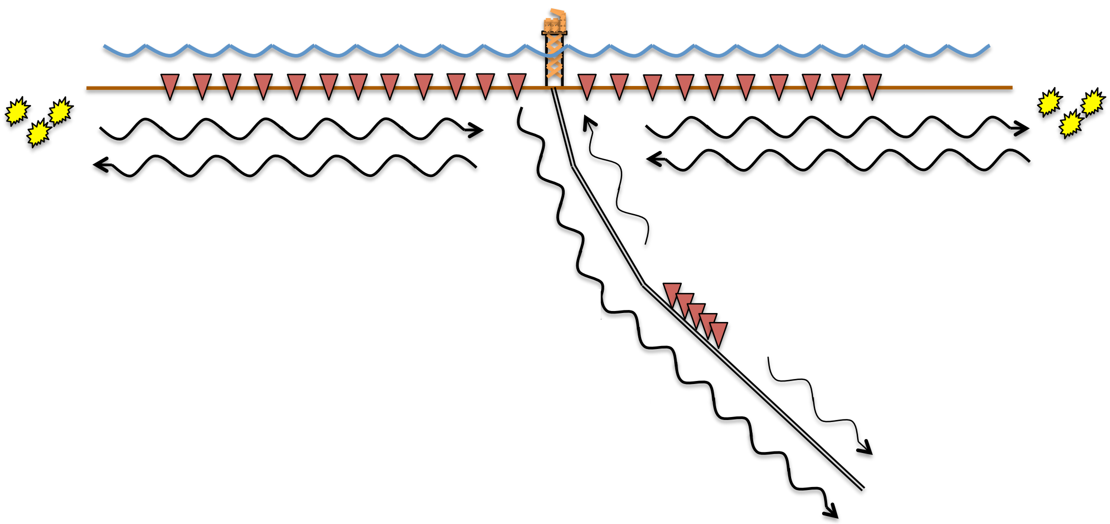

Figure 6: Illustration of the ambient seismic noise environment at Valhall. [**NR**]

field. However the results are not typical of seismic interferometry. The signal is asymmetric, not centered at zero time lag, and does not originate from the borehole stations. We have argued that these observations are due to seismic energy interacting with the borehole acting a wave-guide. In this scenario, the asymmetry would be due to seismic energy travelling up and down the borehole. The apexes would be at acausal times because seismic energy needs to enter the borehole at the surface before reaching the stations at depth. A virtual source appears to emanate from the platform because correlated energy in the borehole must reach the surface at the platform before propagating outward. Because this proposed mechanism does not satisfy the conditions of seismic interferometry, we cannot interpret these cross-correlation results as inter-station Green's functions.

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