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A study of the seismic disturbance produced by the wind park near the gravitational wave detector GEO-600

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Abstract

Noise emissions from wind turbines might disturb the operation and deteriorate the sensitivity of Gravitational Wave (GW) detectors. These detectors aim to an extremely precise measurement (of the order of 10^{-18}m) of the difference in path lengths between interfering light beams from two optical cavities. Seismic ground vibrations and air pressure waves in the low frequency might couple to the detector especially in correspondence to mechanical modes of the seismic isolation system. A wind turbine park exists in the vicinity of the German GW detector GEO-600 (near Hannover) and two parks are planned for construction close to the detector VIRGO in Italy (near Pisa) which has enhanced sensitivity to low frequency GW signals. We have studied some characteristics of the seismic noise emission of the wind park near GEO-600, and developed a simplified model of the attenuation of the seismic wave. We used the model to predict the excess seismic noise that a wind park might produce near VIRGO, and to set a safety distance from the detector for the location of the new wind parks.

Introduction

Several detectors are nowadays operative to reveal the space-time deformations which, according to Einstein theory of general relativity, are produced when large massive objects undergo fast acceleration variation. Detectable gravitational waves are expected to be produced in astrophysical processes, like supernova explosions, coalescence of binary systems, spinning neutron stars. A class of GW detectors works on the principle of the Michelson interferometer [1]. A laser beam is split in two by a semi-reflective mirror. The two beams are made to resonate in two long orthogonal optical cavities (arms) consisting of one pair of "free falling" mirrors. A gravitational wave would cause a differential variation of the length of the two arms (one stretches a tiny bit, while the other compresses). This results in a phase difference of the two beams which is measured with a photodiode looking at the interference of the beams out of the two arms. Detectors of this kind are: GEO-600 in Germany, VIRGO in Italy, LIGO detectors in USA, TAMA in Japan [2]. These are able to measure a length variation of the order of 10^{-18}m over a 3km distance, and over a frequency band of 10Hz to 10kHz. Second generation detectors, now in construction phase, aim to measurements at least ten times more accurate.

Optical cavity mirrors and benches (carrying optics used for readout and control) are decoupled from ground through seismic isolation systems. These are typically effective above about 10 Hz. Intense low frequency seismic noise might overcome the isolation system and deteriorate the detector sensitivity. A major concern is that low frequency periodic disturbances might match and excite the low frequency modes of the isolation systems, seriously compromising its operation.

In 2004 the EGO laboratory (hosting the VIRGO detector) was notified that two wind parks were planned for construction in its vicinity (few km away from VIRGO experimental buildings). A concern arose about the possible effects of such plants on the detector operation. In particular, the EGO laboratory was interested to asses which would be the effect of such plants in terms of increase of the local anthropogenic background noise, and of the frequency content of the noise which might match critical resonant modes of VIRGO.

A work by Schofield (2001, [3]) had shown that wind turbines produce intense low frequency seismic disturbances that might be still effective (above the local anthropogenic seismic background) at considerably large distance (10-20 km) from turbines. This is confirmed also by the comprehensive and detailed work by Style (2005, [4]) whose report is successive to the time of our study.

Indeed, the seismic excess as function of distance from the plant does depend on the absorption characteristics of the soil, i.e. its composition (rocks or limes) and on the anthropogenic background noise level. A wind park ("Schliekum") does exist in the vicinity of the GEO-600 detector. Its effect on the site seismicity and on the detector had not been studied, although no significant effect had been ever noticed. However, the VIRGO has enhanced (ten times better) sensitivity in the low frequencies (10-100Hz) and a different isolation system design, and the impact of wind turbines noise might be more relevant.

The authors performed a study of the seismic noise emissions of the wind park near GEO-600. The soil composition of the GEO site (cultivated soil, and layers of lime and sand deposits) and its seismicity (industrial area, with high density population and road traffic) are similar to those of the VIRGO site. This fact permits a reasonable extrapolation of the data to the VIRGO case. Measurements were carried out during four days in July 2005. A first report was presented at [5]. The study had two main goals: (i) asses and quantify the presence of a seismic wave field from the wind park at the GEO site, (ii) derive a model of the seismic wave absorption which would permit to reasonably quantify the impact of the planned wind parks near EGO, and eventually to define a distance of respect from EGO for the turbines location.

Here below: Section 1 describes measurement location and equipment; Section 2 describes some characteristics of the wind park seismic emissions; Section 3 describes the study of turbines-induced seismicity at GEO site and measurements of the velocity of the seismic wave field derived from correlation measurements with an array of seismometers working in coincidence; Section 4 describes a measurement and modelling of the attenuation of the seismic wave with distance; Section 5 describes the use of the model to predict the turbine noise impact for VIRGO.

1. Measurement sites and equipment

The GEO-600 site is located 25 km South of the city of Hannover in Germany (Figure 1). The detector is surrounded by agricultural cultivated soils. Soil is composed, up to a depth of 20-50m, by lime and sand sediments. Figure 2 shows the site seismicity compared to Peterson LNM, which indicates it to be a relatively high seismicity site. The EGO laboratory site, hosting the VIRGO detector, is located 10 km from the city of Pisa, Italy. The EGO site characteristics are similar to GEO-600 with respect to all mentioned aspects. The seismicity of EGO site is depicted in Figure 2 as well.

The “Schliekum” wind park consists of 8 turbines placed at a distance of 220m to 370m from each other. Turbines are aligned approximately along the North-South direction, at an average distance of 1.0 and 1.6 km respectively from the GEO-600 North and Central experimental buildings (Figure 3).

Schliekum turbines are of different manufacturer and model and differ to some extent in size and power (Table 1). Common relevant features are: (i) a three-bladed rotor head mounted on a steel tower sitting on a concrete foundation; (ii) an active control on the blades pitch angle assure an optimal and constant power output against wind speed changes in the range from 3 to 25 m/s, outside this range windmills are automatically stopped to avoid damage or reduced efficiency. The blades pitch control changes the rotor speed approximately between 9.5 and 20 rmp; (iii) an active control of the nacelle yaw angle keeps the rotor head aligned to the wind direction; (iv) the power generator (asynchronous type, located in the nacelle) runs at variable speed between 700-1400 rmp [6].

Figure 1. Geographical location of the GEO detector (three house markers at center of figure) and wind parks around it: Schliekum wind park (red crosses) and other seven ones (green flag markers).

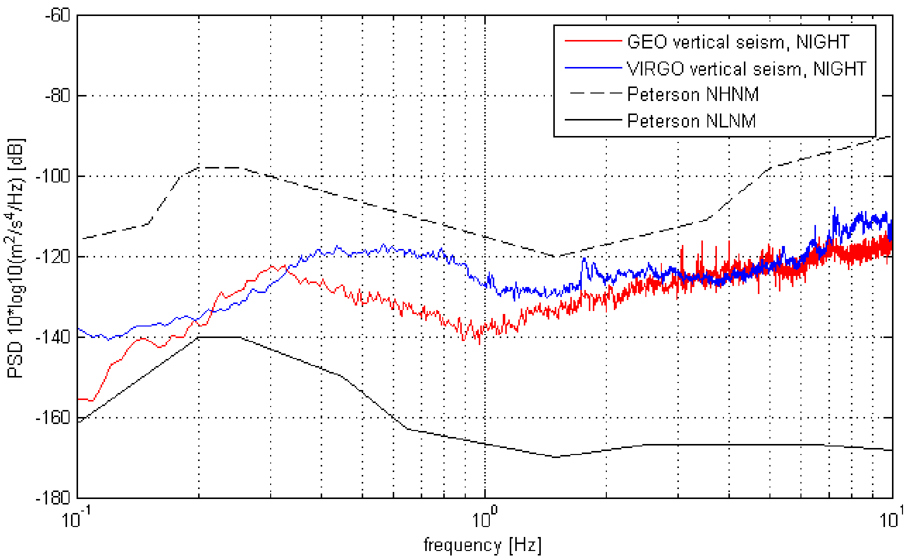


Figure 2. Typical vertical seismic spectra recorded at GEO-600 (red) and VIRGO (blue) experimental buildings during quiet night time periods, compared to Peterson Low and High Noise Models [7].

Manufacturer and Model	N. of turbines	Names	Power [MW]	Tower height [m]	Rotor diameter [m]
Nordex N90	3	Domink, Ole, Malte	2.3	100	90
Nordex S77	2	Daniela, Kerstin	1.5	85	77
EnronWind 1.5s	2	Lutz, Robert	1.5	85	65

EnronWind 1.5	1	Isabelle	1.5	85	65

Table 1. Tech. data of Schliekum wind turbines. Names have been assigned by us to identify turbines.

A first set of measurements aimed at the characterization of the seismic noise produced by the single turbines. Recordings were taken at the basement platform of each windmill using two geophones (Sercel L-4, 1Hz) laid along the vertical and one horizontal directions. Results are discussed in Section 2.

A second set of measurements aimed at the investigation of the seismic wave-field by the turbines. These data were recorded during July 25th through 28th 2005. We used: (i) two portable seismic stations, each consisting of one tri-axial low frequency seismometer (Lennartz 3D/5s, 100mHz), AD converter, hard disk, and GPS receiver; and (ii) three fixed tri-axial low frequency seismometers (STS2, 8mHz) permanently deployed on the floor of each GEO-600 experimental building. Seismometers were GPS synchronized, and the 3-axes were aligned along geographical NS, EW and vertical directions (±2°). Seismometers were used for coincidence measurements described in Section 3.

We took our own record of the wind speed. We used one anemometer, positioned at 5m height close to GEO-600 central station. However, it is known that wind speed increases logarithmically with height up to some hundreds meters from soil. Therefore, the wind speed values we measured and we quote thorough this report note are systematically lower than wind speed at the turbine blades (80-100m height). Nevertheless, they provide a useful reference for correlation studies (see section 3); but in case we need to compare to wind turbines working set point a scale factor has to be considered.

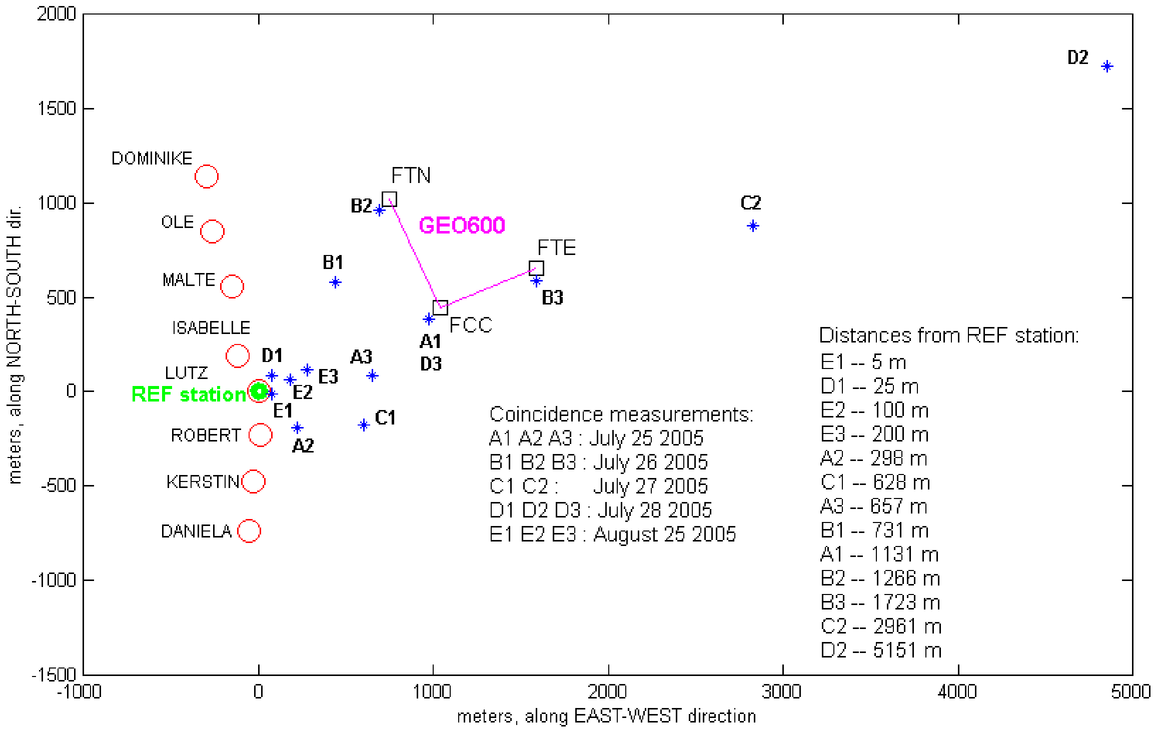


Figure 3. Location of: Schliekum wind turbines (red circles), GEO-600 experimental buildings (black squares), sites of seismic recordings (blue stars), and reference site at turbine "Lutz" (green circle).

2. Characteristics of wind turbine seismic emission

Seismic tracks recorded at turbine platforms contain intense and persistent spectral components which can be associated to structural or functional resonances of the windmills. Figure 4 shows the time evolution of the spectral composition of one seismic record. Figure 5 compares spectral composition of seismic records of different turbines. Figure 6 compares the spectral composition of tracks recorded during different wind speed conditions. Figure 7 shows seismic excitations associated to reorientation of one turbine head.

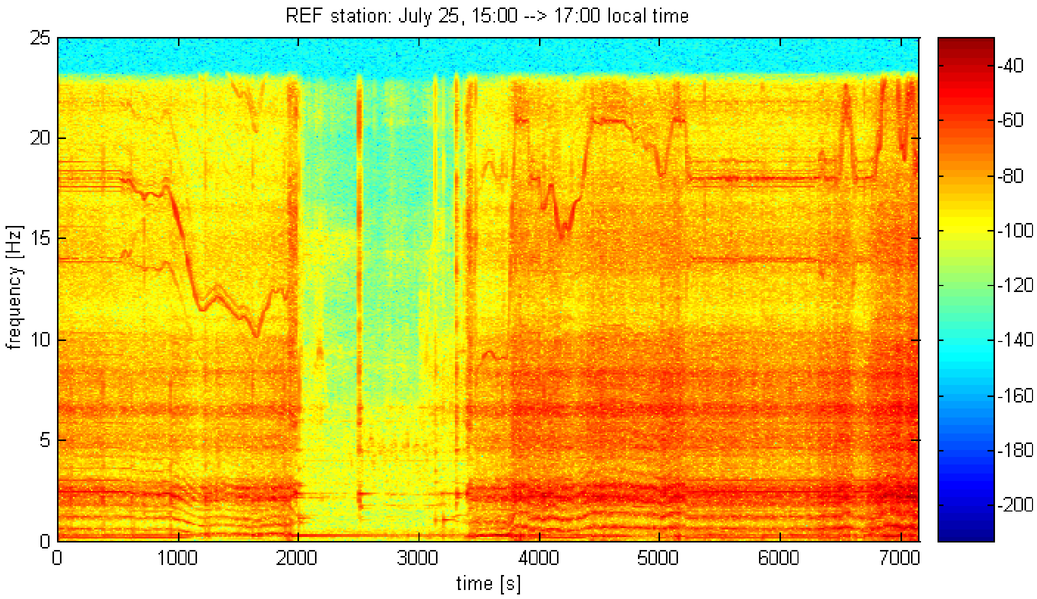
A family of equally spaced and stationary frequency components (we name "functional" peaks) are associated to the revolution frequency of the rotor (around 0.2 Hz) and to the rotor blade-pass frequency (three times the rotor frequency, 0.6 Hz) and its harmonics (1.2Hz, 1.8Hz, 2.4Hz, etc…). Peaks up to the 10^{th} harmonic are clearly distinguishable. Often peaks are broad. But sometimes, particularly in conditions of low wind speed, they are very sharp and steady (we suspect that this is associated to a peculiar regime of operation of the turbine feedback control but we do not have records of turbines operation status to investigate further). One intense, always sharp peak sweeping between 10Hz and 20Hz seems associated to the generator frequency (Figure 4, top). All these peaks sometimes do coherent sweeps (frequency changes up to 20%), which look associated to variations of rotor and generator speed (we hypothesize that this occurs when blades pitch angle changes to follow variations of wind speed or direction). Functional peaks disappear when the turbine is stopped (Figure 4).

A few other peaks persist when the turbine is stopped and never change their frequency: the most intense one is around 0.3 Hz (0.37 Hz for the two N77), less intense ones are at 2.5Hz, 4Hz and 6 Hz (Figure 4 and Table 2). These frequencies seem associated to turbine structural modes. According to a simulation study by Shaumann and Seidel [8] the 0.3 Hz frequency might be associated to the pendulum mode of the heavy rotor head and tower, and higher frequencies to flexural modes of the tower.

We took seismic records of the motion of all turbines base platform. We found the amplitude and spectral composition of records of same type turbines are indeed quite similar, while the frequency and shape of peaks differs slightly but significantly among different turbine models (Figure 5).

The root mean square (RMS) of seismic amplitude of the functional peaks increases proportionally to wind speed, and the scaling factor seems the same for all frequencies (Figure 6). Approximately a factor ten variation of RMS is associated to the operation of the turbine at different wind speed conditions within the working range. On the other hand, the amplitude of structural peaks looks independent on wind speed.

Intense seismic bursts with a typical exponential decay (decay time of 1 to 2 minutes) are produced when the turbine head is reoriented in correspondence of wind direction variations. A spectral analysis of the burst signals show that the structural modes are largely excited (2 to 5 times more than during typical conditions). Also some other frequencies (1Hz, 3Hz, and a few above) are excited, which might correspond to other structural modes not much excited during the normal turbine operation.



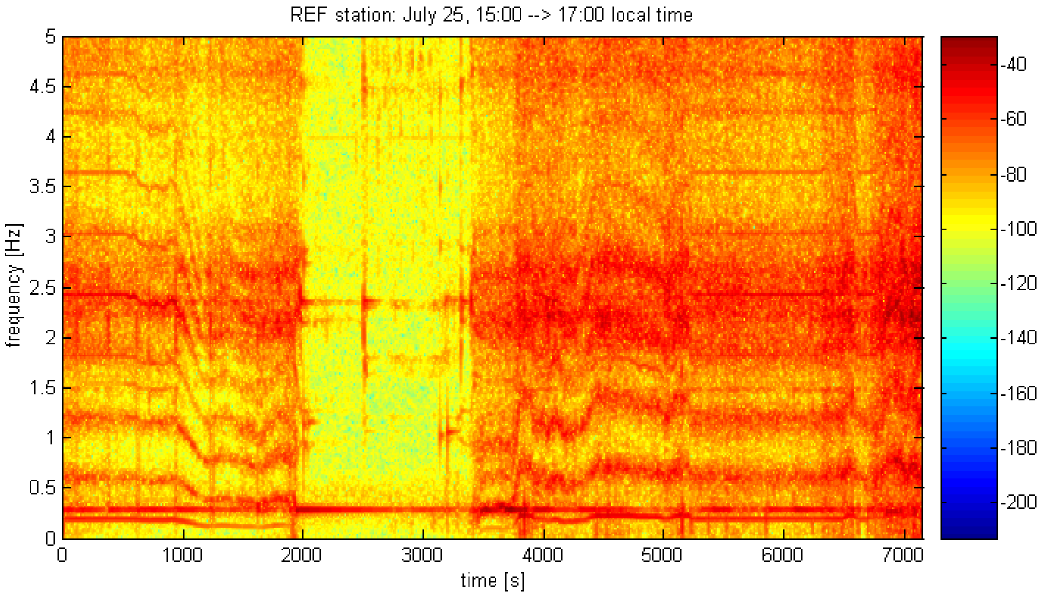
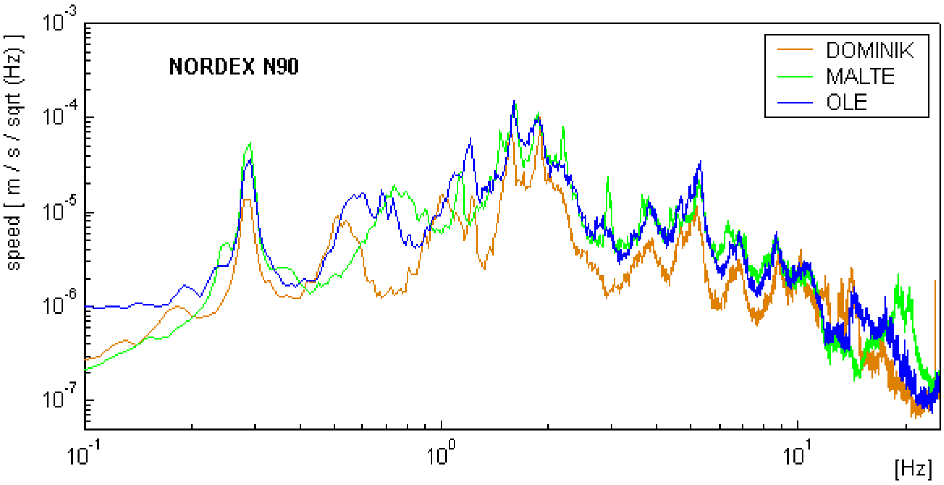


Figure 4. Spectrograms of 2hour seismic record at the Lutz base platform. In the period 2000÷3500s the turbine was stopped. The bottom plot is a zoom of the upper one in the 0÷5 Hz frequency region.

Turbine	Pendulum mode f_0 [Hz]	Flexural mode f_1 [Hz]
Nordex S77	0.37	2.45
Nordex N90	0.29	1.9
Enron Wind 1.5	0.29	2.3
Enron Wind 1.5s	0.29	2.2

Table 2. Measured frequency of the first and second structural modes of the four turbine models.



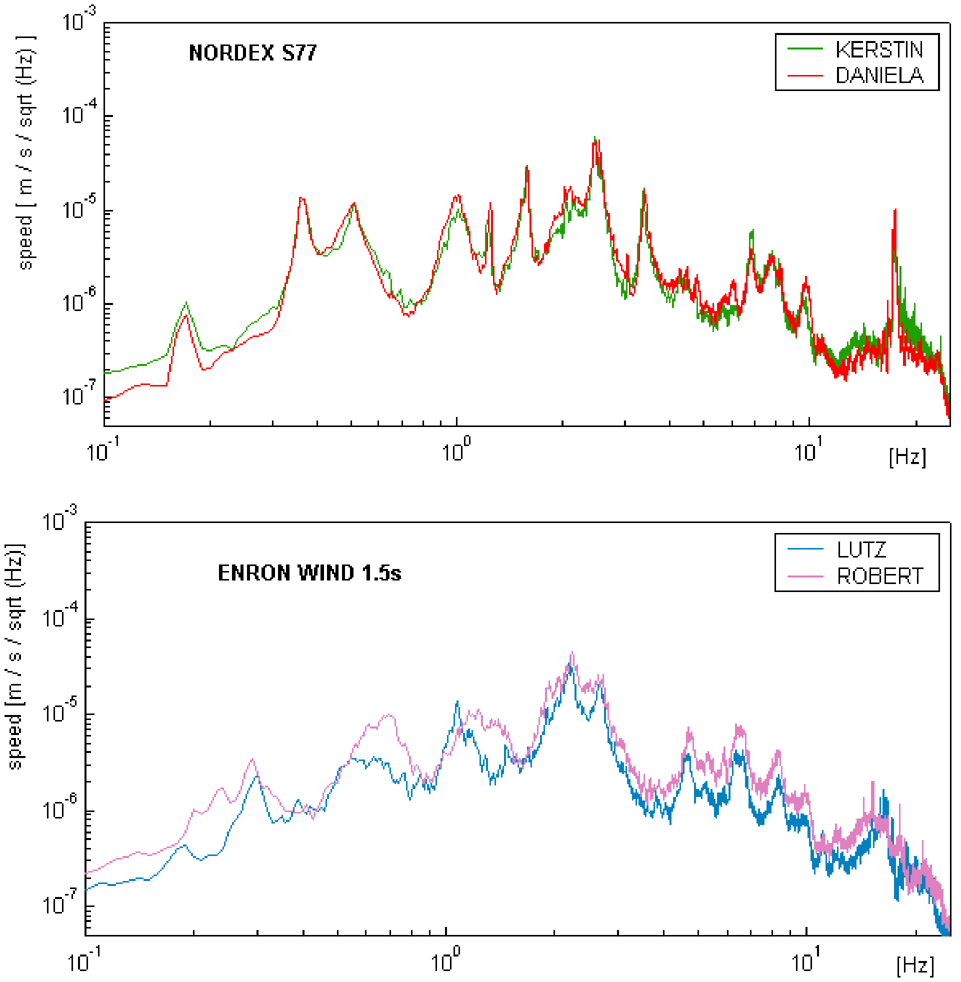


Figure 5. Amplitude of seismic vibration of turbines basement. Three turbine models are compared.

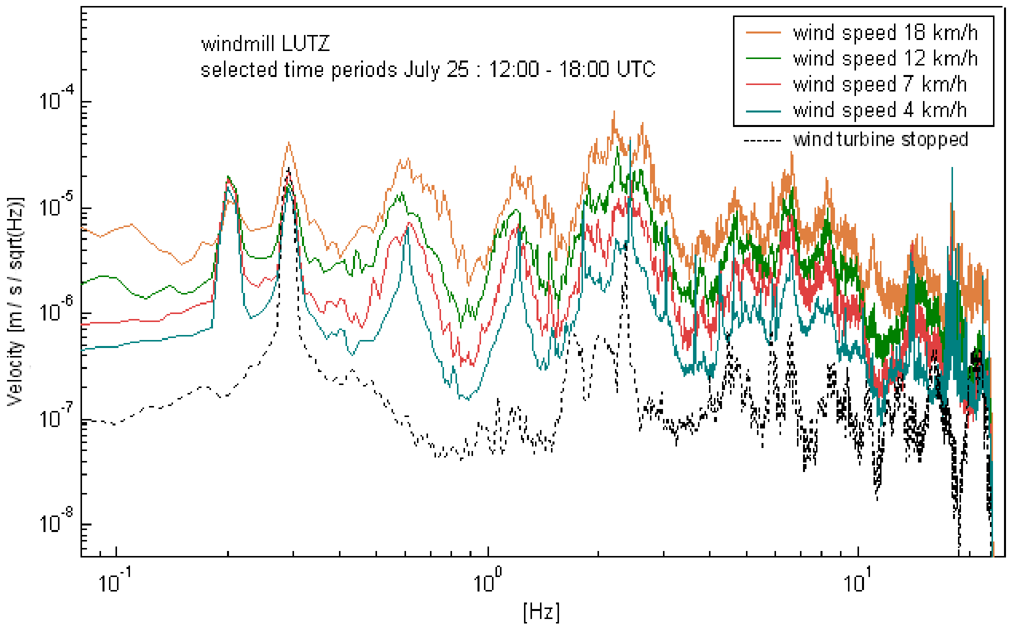


Figure 6. Solid lines are seismic amplitude spectra measured at Lutz base platform in different wind speed conditions; the dotted line is a measurement taken while the turbine was stopped. Quoted wind speeds are measured at soil level.

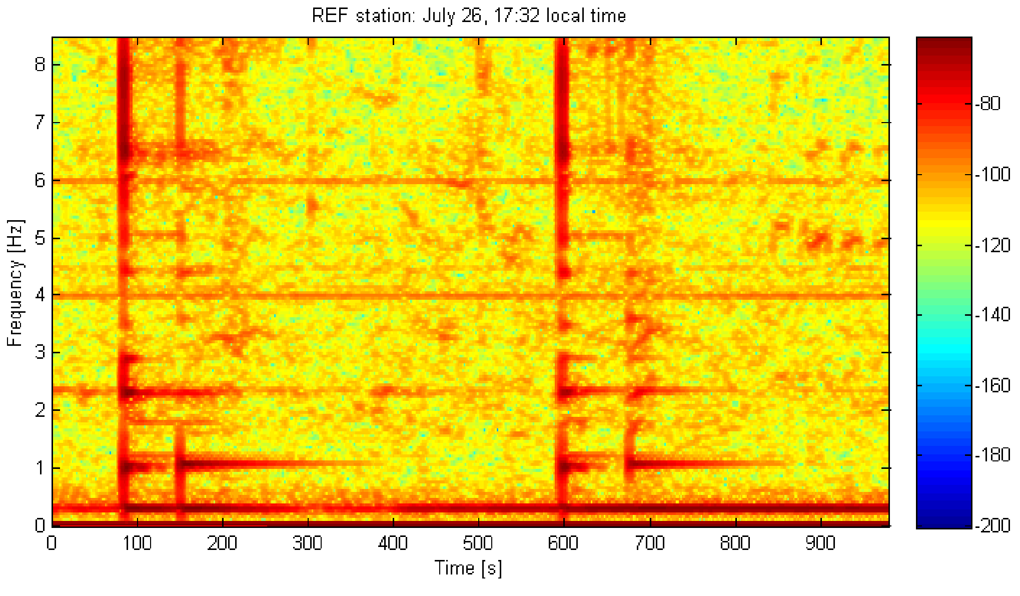


Figure 7. Spectrogram of a 15minutes seismic record at the Lutz basement. Temporary increases of seismic amplitude correspond to re-orientation of the turbine nacelle while the blades were stopped .

3. Characteristics of the seismic wave-field from turbines

It is expected that turbines vibrations transmit to the soil through basements and generate persistent seismic surface wave travelling to some distance from the wind-park. A method to detect and study this seismic wave-field, particularly in conditions of elevated background noise, is that of coincidence measurements with an array of seismometers.

We used two tri-axial seismometers, GPS synchronized and aligned. We left one seismometer permanently positioned at Lutz basement platform; while we moved the other one to 13 different out-field sites at variable distances, up to 5km away. A map of recording sites is shown in Figure 3. Three tri-axial seismometer permanently located on the floor of each GEO experimental building were also part of our seismic array.

At least 8 hours of continuous recording was taken at each site. The two most distant sites are located 3km and 5km away and there the seismometer was left recording over-night to catch more quiet times. Most sites are actually in the “near-field” with respect to the wind-park. This was dictated by the need to investigate on the noise produced at the GEO site, and also by the fact that it was not possible to find suited measurement sites, sufficiently distant from roads and houses, at farther distance from the wind-park.

The computation of coherence between the seismic signal at Lutz platform and the signal at out-field stations permitted us to track and study the seismic wave of this particular turbine.

Figure 8 compares horizontal and vertical seismic spectra recorded at Lutz and at increasing distances from it. Figure 9 shows spectral coherences between the seismic record at Lutz and at distant stations. Shown data records were taken with not too different wind conditions, wind speeds at soil ranging from 7 km/h to 11 km/h. For more distant stations (B2 and B3) night-time data are used, because day-time records are dominated by anthropogenic noise from other sources. Seismic records at the two most distant stations (3km and 5km) are dominated by anthropogenic noise also at night-times.

Below 1 Hz all spectra show a persistent seismic peak at 0.3 Hz (Figure 8), which happen to correspond to the frequency of the turbines first structural mode. Between 2Hz and 10Hz the stacked spectra give evidence of a seismic noise component whose amplitude gradually decreases with distance, and which is still detectable at 2 km from the turbines (Figure 8). This noise component is characterized by intense spectral peaks, which reasonably well associate to turbines frequencies. At these peaks, significant coherence is measured between the out-field stations and the vibrations of Lutz platform, this coherence decreases with distance from Lutz (Figure 9). Instead, quite surprising, no coherence is found in correspondence to the intense 0.3Hz spectral component (Figure 9).

The 2-10Hz seismic noise component from the turbines is sensed by the seismometers inside GEO-600 buildings. This is demonstrated by a study shown in Figure 10: comparing seismic spectra recorded during a few night-time periods when the turbines were stopped and when turbines were running. A clear excess (about a factor 5 above background) is detected between 2 and 10 Hz. Typical turbine peaks are spotted. During day-times the excess is less evident; it is partially covered by human activities related noise.

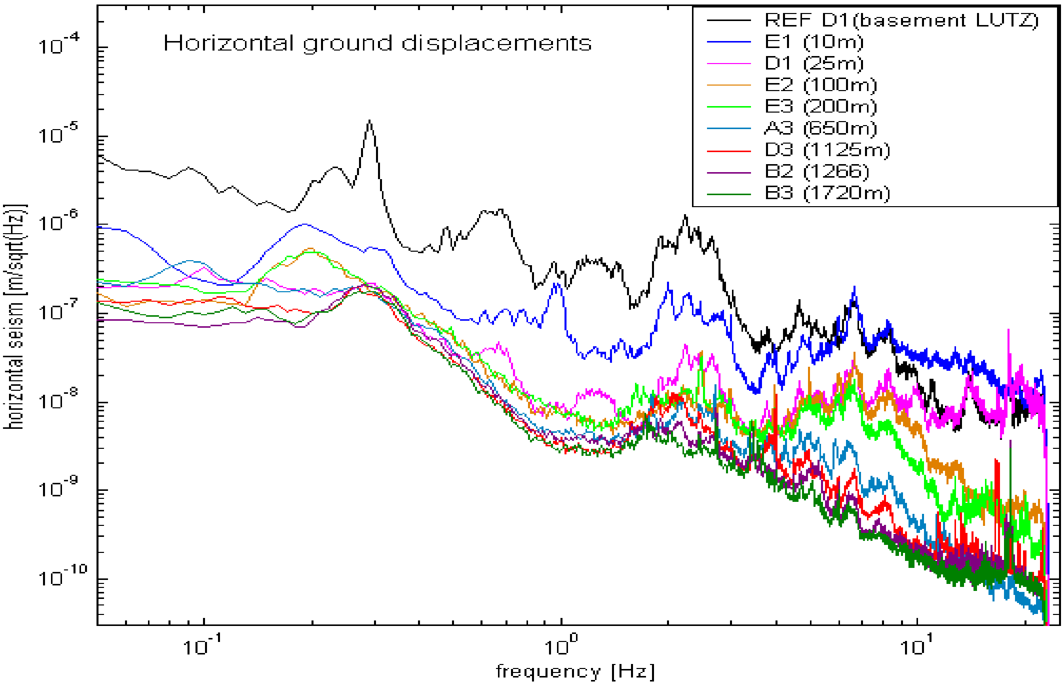
The 2-10 Hz seismic noise looks richer in horizontal than vertical components. This is shown in Figure 11, displaying the ratio of horizontal to vertical spectra recorded by station A1, deployed in the soil close to the GEO central building. This is true also for the background noise, recorded when turbines are stopped. In conditions of strong wind the horizontal to vertical ratio is enhanced in correspondence of the frequencies of turbines emission.

The presence of coherence between Lutz station and the out-field stations (Figure 9) persisting over long periods, points to the existence of a persistent seismic wave in the soil produced by the turbines. The propagation time (and thus the velocity) of this wave can be measured by looking for the maximum of the correlation function between the seismic signal at Lutz and the signals at one out-field station, for different time shifts between the two signals [9,10]. This computation is represented with a "correlogram" plot.

Figure 12 shows correlogram plots which measure the propagation time of the seismic wave between station "REF" at the Lutz platform and station "A1", located 1130m North-East from REF. The four correlograms in Figure 12 analyze the seismic wave-field in four different frequency bands (2-3Hz, 4-5Hz, 6-7Hz and 8-9Hz). This is done by band-pass filtering the signals before correlating them. The propagation times measured in Figure 12, together with similar ones measured from correlating REF signal with other stations, seem consistent with the hypothesis of a seismic wave propagating in radial direction from Lutz with a particularly slow velocity. We measured: v=(450±50)m/s for the 2-4Hz component, v=(260±50)m/s for the 4-10Hz component. We thus derive indication of a slowly propagating seismic wave whose speed decreases with frequency. These characteristics, including the fact that the seismic signal is richer in horizontal than vertical components, seem consistent with a shear type of seismic wave (also known as Love waves [11]) travelling in aerated soils as are the agricultural cultivated soils surrounding the Schliekum park and GEO.

We performed a similar correlation analysis for the 0.3Hz seismic component. This is particularly interesting since its frequency coincides with the structural mode of the turbines. The 0.3Hz signals is detected by all out-field stations; it is coherent among all stations, although it is not coherent with the seismic signal at Lutz. The result of the correlation analysis is that: (i) the 0.3Hz signal is quite stable (both in frequency and amplitude) and persistent over the four days; (ii) it is associated to a seismic wave field which travels from the North-East direction (48°±4° N, i.e. opposite to the wind park) with velocity = 800±50m/s. Indeed, the dominant 0.3Hz signal detected by out-field stations is not originating from the Schliekum wind park. We initially hypothesized the 0.3Hz might be the 1st harmonic of oceanic microseism (whose typical fundamental frequency is 0.1÷0.15 Hz [12].

A subsequent study revealed that the typical oceanic microseismic signal at GEO has a dominant 150mHz component, and propagates from North, with a velocity of the order of 6 km/s. One alternative hypothesis is that the observed 0.3Hz peak originates from another wind park. The closest one in the North-East direction from GEO is located about 4.5 km far and counts 10 turbines. This wind park is older than the Schliekum and might have more unbalanced and noisy turbines. However, the origin of the 0.3Hz seismic component, although interesting, remains unknown.



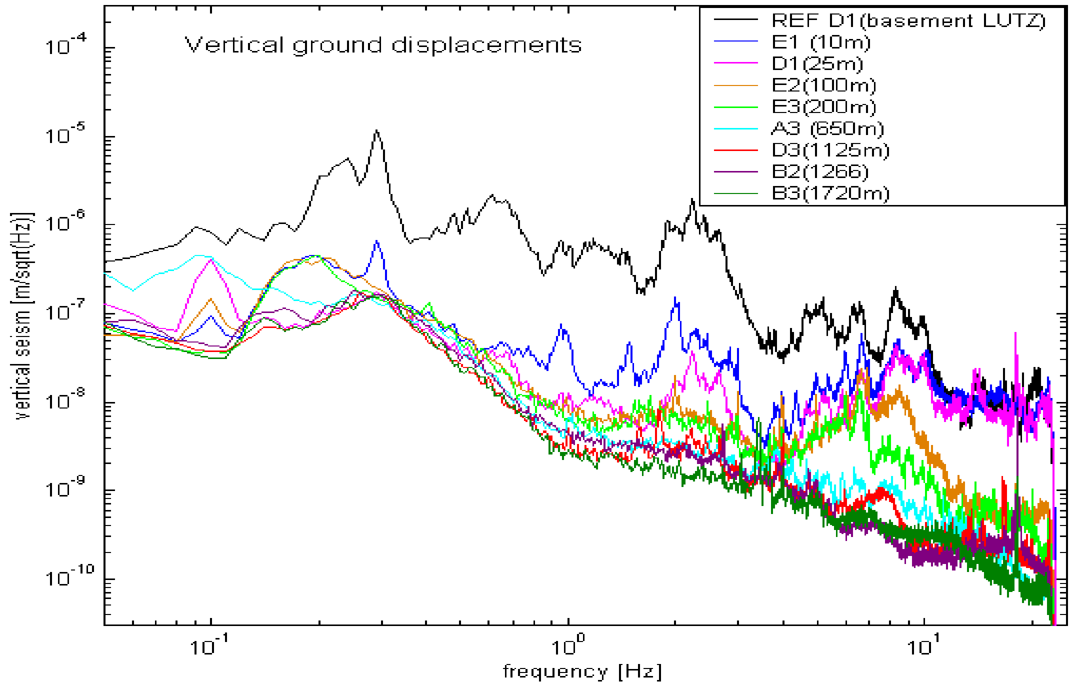
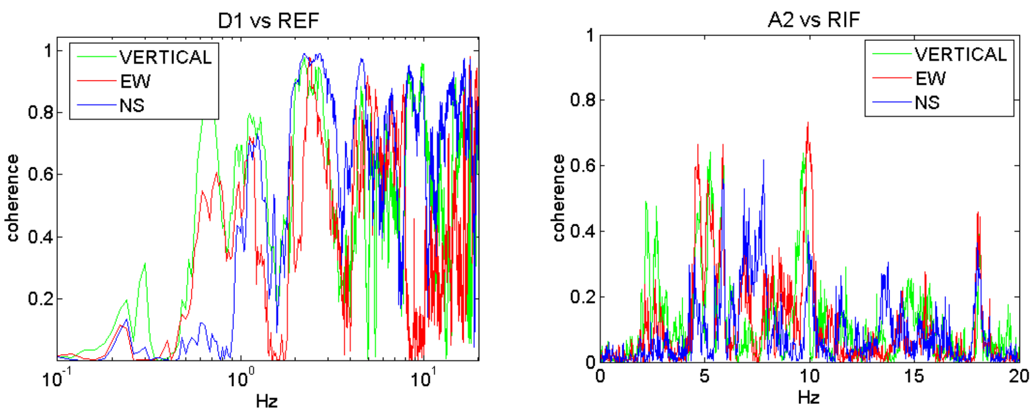


Figure 8. Displacement seismic spectra at Lutz platform (black), and at increasing distance towards GEO-600 and beyond (in colors). Each spectrum is averaged over about one hour. Top plot shows the average soil displacement noise measured along two orthogonal horizontal directions; Bottom plot shows soil vertical displacements.



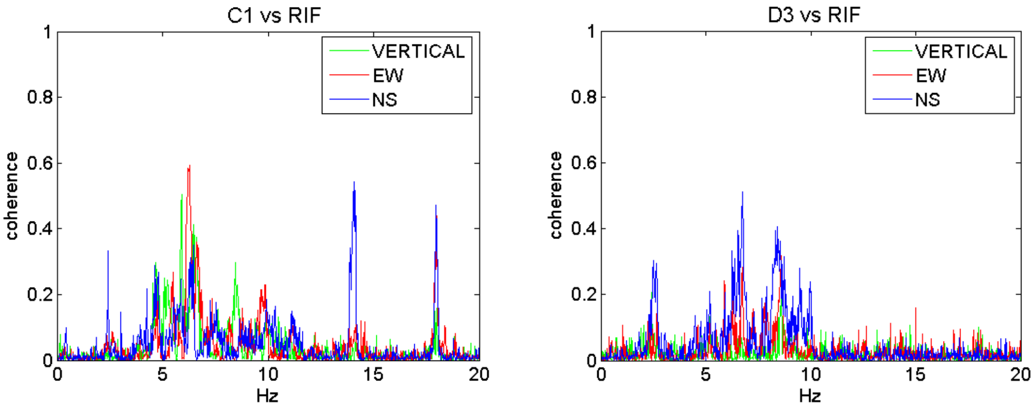


Figure 9. Coherence between the seismic signals at Lutz and at four locations at increasing distance from it: 25m, 300m, 630m and 1130m (clock-wise from top-left). The first plot is displayed with a logarithmic x-axis, to evidence the absence of coherence at the 0.3 Hz peak.

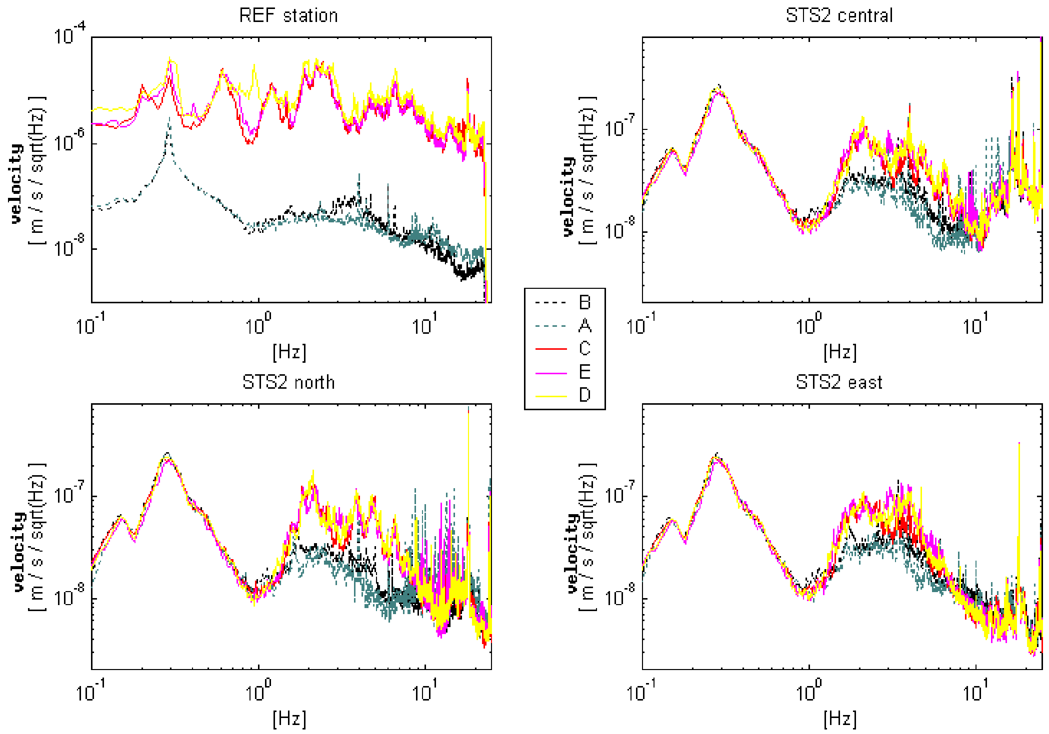


Figure 10. Seismic spectra at windmill Lutz and three GEO buildings corresponding to two night-time periods with all turbines stopped (A,B) and three night-time periods with turbines running (C,D,E).

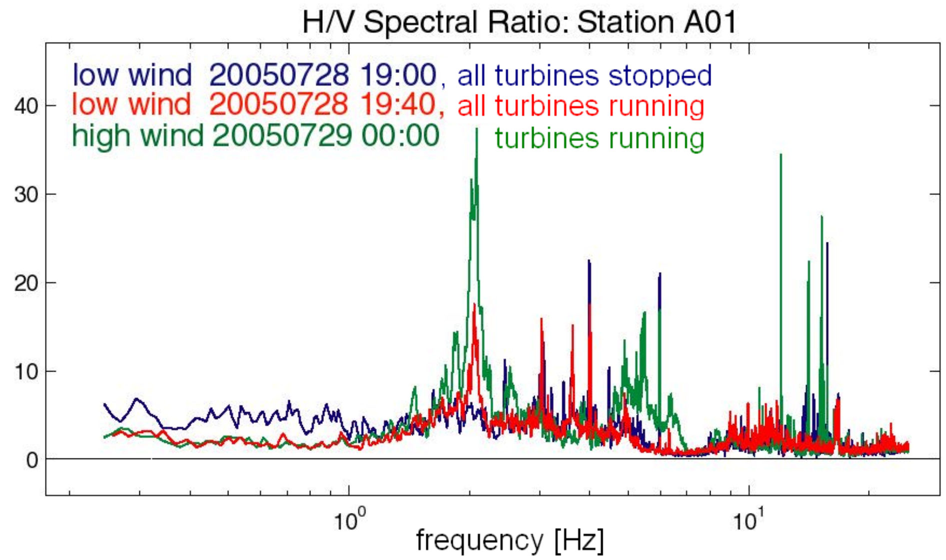


Figure 11. Ratio of horizontal and vertical seismic spectra measured by station A1. Three conditions are compared: all turbines stopped (blue), all turbines running with low wind (red) and all running with strong wind (green).

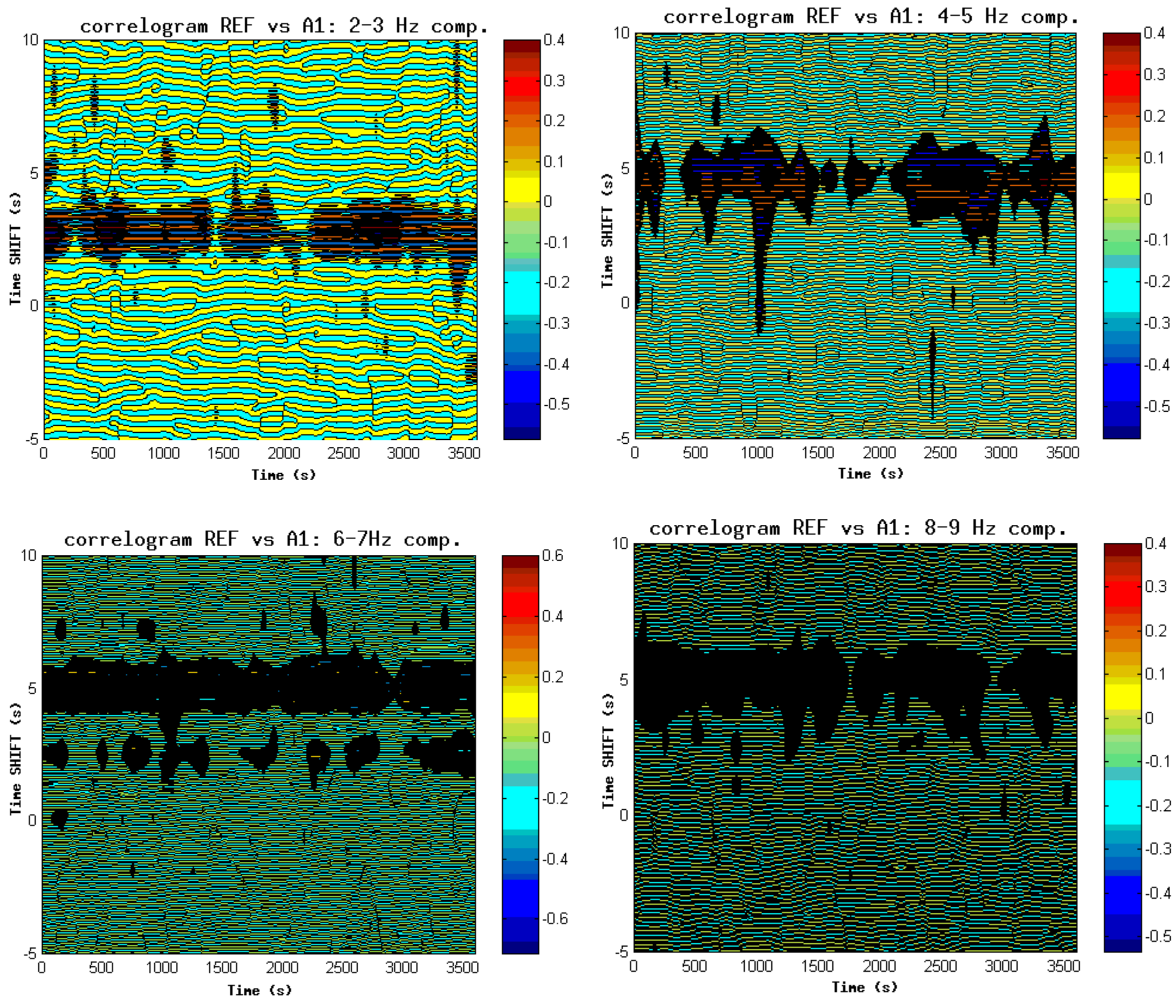


Figure 12. Correlation analysis of seismic tracks recorded by stations REF and A1 (1130m away). Signals were first band-pass filtered. The four correlogram plots are produced correlating the REF and A1signals filtered in four different frequency bands (clock-wise from upper left: 2-3Hz, 4-5Hz, 6-7Hz and 8-9Hz). In each plot the dark region identifies the maximum of the correlation function of the two signals as function of time. For the upper left plot, the maximum correlation occurs when the REF signal is delayed by +2.5s with respect to REF. This measured delay is constant as function of time (over 1 hour). This indicate for a persistent wave-field propagating from REF to A1 with a velocity of 450 m/s. Similar considerations apply to the other plots.

4. A model for seismic wave absorption

We used coincident records to measure the attenuation of the seismic wave-field as a function of distance from the wind park. As discussed in Section 3, the measured wave-field does not contain well identified spectral peaks which could be tracked in all recording sites. On the other hand, both the coherence studies (Figure 9) and the comparison of distant seismic spectra (Figure 8), indicate that the seismic wave field from the turbines is richer in frequency components between 2Hz and 10Hz. Thus, we measured the attenuation of this composite wave-form. The advantage is that we maximize the signal to noise ratio by including all the most intense signal components. The drawback is that we average over a possible frequency dependence of the absorption law.

We proceeded by selecting, for each measuring site, about 4 hours of clean data, having excluded periods with turbine stopped or transients (transient events, like those caused by passage of cars, are identified with visual inspection of the data in the time frequency domain by means of spectrogram plots). We then extracted the wave form component by filtering the data with one Butterworth band-pass filter with 2Hz and 10Hz cut-offs. We did the same for the coincident recordings of the REF station and of the far station. We then computed the amplitude root mean square (RMS) of both filtered signal. We analyzed separately horizontal and vertical components (we averaged the two orthogonal NS and EW components to one effective horizontal component). We then computed the ratio of the RMS at the far station over that of REF station. In the reasonable hypothesis that the amplitude of seismic emission of all Schliekum turbines is affected by wind speed in the same way, this operation factors-out the effect of variations of the wind speed during measurements. Finally, we normalized the RMS ratios to the horizontal seismic RMS value recorded at station E1 (Figure 3), which was buried in the ground close to Lutz foundation[1].

The normalized RMS ratios are plot in Figure 13, separately for the horizontal and vertical components. We find indication that the horizontal and vertical components

[1] The seismic signal measured onto the turbine platform appears not to be a good reference for measuring attenuations, since the basement can amplify seismic vibrations. Qualitatively this effect can be observed in Figure 8, comparing the seismic spectrum measured by the REF station on the concrete with spectra measured by station E1 deployed in the soil but very close to the basement edge. It seems that vertical vibrations are amplified by about a factor two more than horizontal ones. In addition, the basement seems to enhance low frequencies up to 5-6 Hz.

of the seismic wave-field from the wind park follow the same attenuation law, although the amplitude of the vertical component is about a factor 1.75 smaller than the horizontal component at any distance from the turbines (this is consistent with measurements discussed in Section 3). At distances greater than 1.5km we note a saturation effect. This indicates that the turbines RMS noise is overcome and masked by anthropogenic noise from other sources.

A simple model for the propagation of a seismic wave from a surface source, as for example the wind turbine, assumes that the seismic energy is radiated uniformly from the source along a circular wave-front. The attenuation of the wave amplitude with distance is then described by the formula [11]:

(1) $$A_R = A_r \frac{\sqrt{r}}{\sqrt{R}} \cdot \exp(\frac{-\pi \cdot f \cdot (R-r)}{Q \cdot v})$$

Where: R is the distance from source where the signal amplitude is A_R, r is the distance of a reference nearer (r<<R) location where the signal amplitude is A_r. The exponential term accounts for the energy dissipation in the soil. This is parameterized with a quality factor Q which …, v is the wave velocity and $\omega=2\pi f$ is the wave frequency.

We applied this model to the multiple incoherent sources of the Schliekum wind park. We computed the total seismic (A_j) amplitude at one measuring location *"j"* as the quadratic sum of the seismic amplitude at *"j"* of the seismic waves from each turbine, $A_{i,j}$ (the index *"i"* identifies the turbine: *"i"*=1,…8):

(2) $$A_j = \sqrt{\sum_i A_{i,j}^2}$$

(3) $$A_{i,j} = \frac{K}{\sqrt{R_{i,j}}} \cdot P_i \cdot \exp(\frac{-\pi \cdot f \cdot R_{i,j}}{Q \cdot v})$$

(4) $$K = A_0 \sqrt{r_0} \frac{1}{P_0} \exp(\frac{\pi \cdot f \cdot r_0}{Q \cdot v})$$

Where: $R_{i,j}$ is the distance of turbine *"i"* from location *"j"*, P_i is the power of turbine *"i"* (see footnote [2]), and K is a constant factor which accounts for the seismic amplitude measured at one reference distance from one reference turbine.

The parameters we use in the model are the following:

- f = 6 Hz, is the central frequency of the chosen RMS frequency range;
- v = 310 m/s, is the weighted average of the measured velocity (Section 2);

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[2] Our measurements indicate the turbine seismic amplitude is proportional to wind speed (Section 2 and Figure 6), on the other hand, turbines power is approximately proportional to wind speed in the rated working range. We thus assume seismic amplitude to be proportional to turbines power.

- According to literature [11] a value of Q in the range 20 to 100 is reasonable for a sandy clay type of soil. We tested our model with values of $Q \cdot v$ = 6000, 15000, and 30000.

The hypotheses of uniform radiation and of linear superposition indeed are not strictly valid in the near field of the sources. In fact, the presence of obstacles (buildings, other turbines) or soil non-homogeneities on the wave-field path can cause local build-ups or dilutions of seismic energy. Therefore we do expect the model to have some degree of uncertainty when applied to measurements done in the vicinity of the turbines, at distances smaller that a few times the signal wavelength (in our case $\lambda \approx 50$m).

Figure 14 compares the measured horizontal attenuation to the prediction of the attenuation models. Values of $Q \cdot v$ in the range 15000 to 30000 appear to adequately reproduce the data. This poor estimate suffers mainly of the fact that we could not perform significant measurements beyond 2 km from the windmills, because there the windmills signal was overcome by anthropogenic noise of different origin.

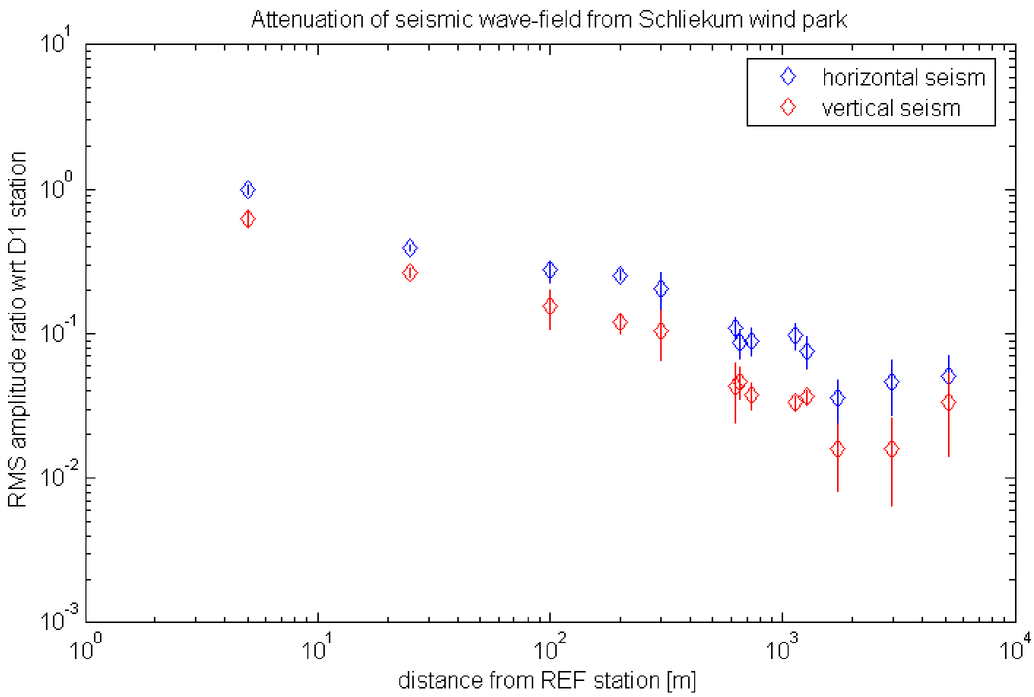

Figure 13. Attenuation of the amplitude of the seismic wave-field from the Schliekum wind turbines: horizontal (blue) and vertical (red) components. The plotted dots are the ratio of the 2-10Hz RMS amplitude measured at out-field stations (A1 to D3), corrected by wind speed, to the horizontal RMS measured at station E1 (5m). On the horizontal axis is reported the distance of out-field stations from REF station on Lutz platform. Each RMS is computed over four hours of data (cleaned from transients

and turbines off periods) at 100s steps. The bars show the statistical uncertainty associated to the variance of RMS values.

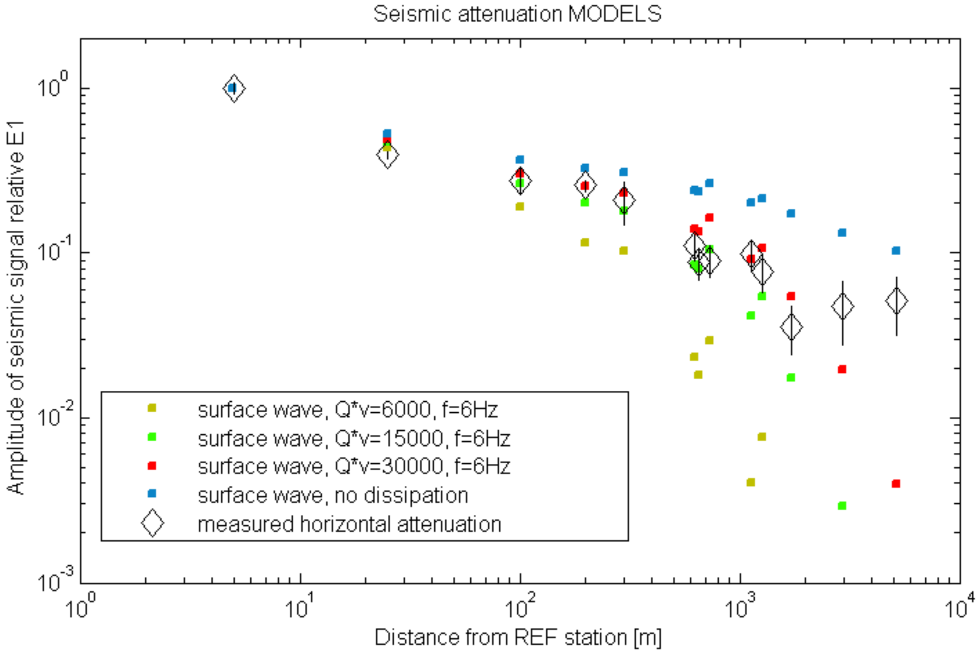

Figure 14. The measured horizontal attenuation as function of distance (blue diamonds) is compared to the predictions of the attenuation model. Squares of different colours correspond to four different values of the $Q{\cdot}v$ parameter, or, assumed a velocity v=*300 m/s*, four different values of the soil attenuation factor: Q=20, 50, 100. Also the ideal case of a non-dissipative soil is represented.

5. Prediction of seismic noise at VIRGO by "il Faldo" wind park project.

The final goal of our study is to derive an estimate of the seismic disturbance (RMS noise level and spectral composition) produced at the VIRGO site from the wind park "il Faldo" proposed for construction in the vicinity of the site. Figure 15 shows the proposed layout of "il Faldo" composed by 9 turbines, Enercon E82, 2.0MW [13]. The turbines are located approximately S-W of VIRGO at distances between 3 and 4.5 km from the (closest) VIRGO West experimental building.

We used the model described in Section 5, with the following assumptions:

(1) VIRGO and GEO soils have similar transmission properties for mechanical waves, so that the attenuation model we derived for GEO reasonably applies to VIRGO. This assumption is supported by the similar morphology of soils (sandy clay), and by the fact that the velocity of propagation of 2-4Hz surface seismic waves measured at GEO (Section 3) and at VIRGO [14] are similar.

(2) We assume similar characteristics of the seismic emissions by Schliekum and "il Faldo" wind turbines. We indeed expect the coarse features of the signal spectral composition to depend mainly on the blades rotation frequency and the turbines structural parameters, which are similar for Schliekum and "il Faldo" ones. On the other hand, we expect that the relative amplitude of the

frequency components transmitted to the soil would depend mainly on the characteristics of the turbine foundations, which we assume similar.

Thus, we used formula (2), (3) and (4) (Section 4) with the following settings:

- we defined locations *"j"* where to evaluate the seismic noise of "il Faldo" (black dots in Figure 15);
- we inserted in "r_{ij}" the geometrical layout of "il Faldo" and turbines power P_i;
- being interested in a conservative estimate of the noise produced, we adopted, within the $Q \cdot v$ range determined above, the value $Q \cdot v$=30000, corresponding to a less dissipating type of soil (given a wave speed v≈300m/s, this corresponds to a soil quality factor Q=100),
- we adopted the same average frequency f = 6Hz, and RMS range 2÷10Hz;
- we adopted as reference seismic RMS amplitude (A_0) the seismic noise produced by turbine Lutz (P_0=1.5MW) measured by station E1 in conditions of an average wind speed of 8 km/h (measured at soil level).

Figure 16 shows the predicted RMS seismic amplitude (2÷10Hz) produced by "il Faldo" at increasing distances towards VIRGO, and its expected excursion associated to variations of wind speed in the range 4 to 25 km/h (at soil level). The expected noise is compared to the typical values of 2÷10Hz RMS environmental seismic noise measured at the VIRGO site. In this frequency range, the site seismicity is dominated during working hours by the noise produced by local traffic and follows a daily amplitude variation of about a factor 6 (90% C.L.) [15,14].

The result is that the wind park would produce an observable effect at the VIRGO West station (North and Central stations instead would be substantially unaffected). The increase of seismic noise at the West station would be within the range of RMS variations due to other anthropogenic sources (Figure 16). However, in order to correctly evaluate the impact of the noise on the VIRGO interferometer, we have to consider the spectral composition of the noise. In fact, seismic peaks in correspondence of the mechanical resonances of the mirror suspensions can excite high-Q modes and make the system unstable.

Figure 17 gives an idea of the spectral amplitude of the seismic signal from the "il Faldo" turbines that would be measured at the VIRGO West station. The prediction has been obtained using the amplitude spectrum recorded at E1 and rescaling it to the value of predicted RMS at the West station. An upper limit is computed increasing this spectral noise by a factor three to account for wind speeds up to 25 km/h (soil level). We compare these predictions to the spectral amplitude of the typical seismic noise from (other) environmental sources measured at the VIRGO site. We find that seismic spectral peaks from the "il Faldo" turbines would significantly exceed the present seismic noise, in conditions of moderate-high wind, but only at the Virgo West experimental hall which is the closest (≈3km) to the wind park.

Although the precise frequency position of the seismic peaks between 2 and 10 Hz might be different for the "Il Faldo" windmills, our projection indicate a significant disturbance. The frequency region above 4 Hz appears to be the most exposed. At present the day-time increase of seismic noise in the 2-10 Hz range is due to transient signals associated to road traffic [14,15]. Seismic noise from turbines would be instead of a persistent nature, thus more critical for the VIRGO detector, being capable of exciting mirror suspensions resonances.

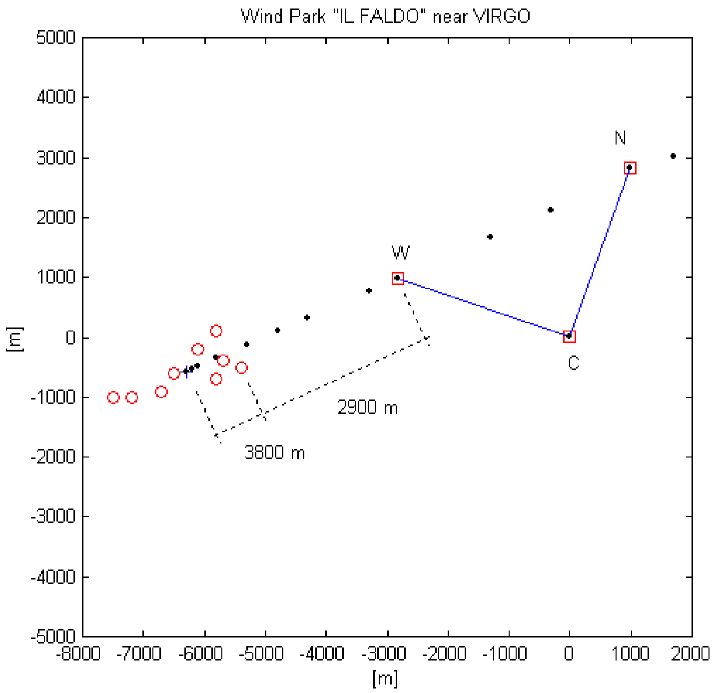

Figure 15. Proposed layout of "il Faldo" wind park. Red circles indicate turbines. Also depicted is the position of VIRGO experimental Buildings (C=central, W=West, N=North). Black dots mark the points where the model prediction was evaluated.

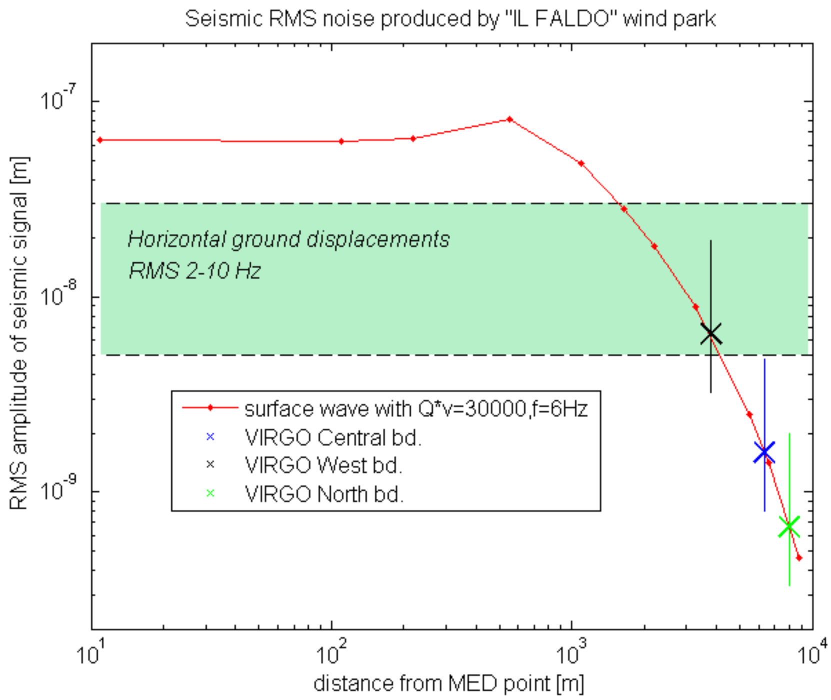

Figure 16. Prediction of seismic RMS displacement (2-10 Hz) produced by "Il Faldo" wind turbines at increasing distances towards VIRGO. Distances are measured for convenience from the geometrical barycentre of the turbines position (MED). The green rectangle delimits the range of RMS seismic noise variation measured at the Virgo site. Crosses mark the RMS noise expectation at VIRGO buildings for a typical average wind speed of 8 km/h. Vertical bars represent the variation in RMS noise we expect associated to variations of wind speed between 4 and 25 km/h. These are wind speed values measured at soil level, we assume they correspond to the minimum and maximum wind speed values of typical operational range of turbines.

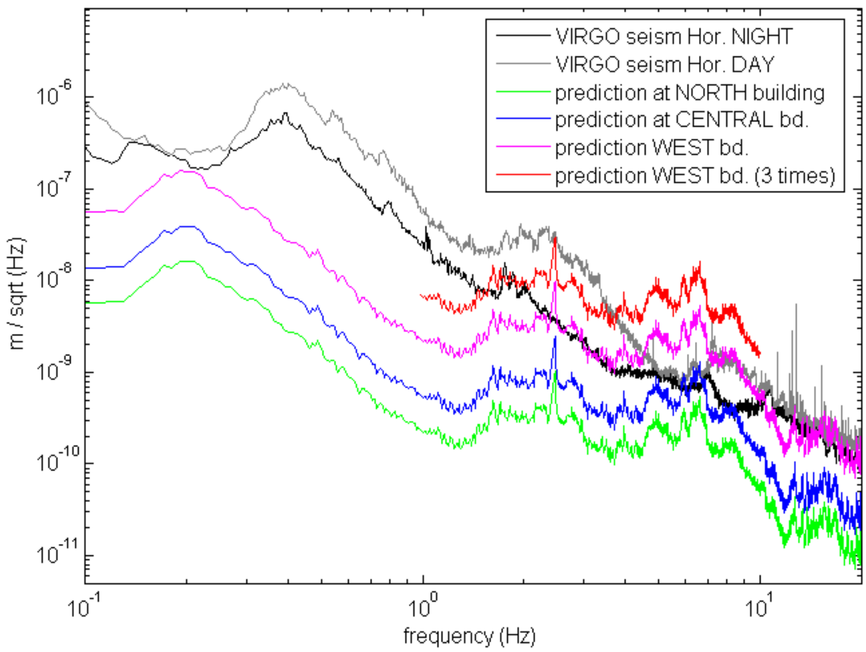

Figure 17. Black and gray curves are typical seismic noise displacement spectra at the VIRGO site, recorded during night-times (black) and day-times (gray). These are compared to the predicted spectral noise produced by the "il Faldo" turbines at the location of the VIRGO experimental buildings (in colors). The parameters used for the attenuation model are the same used in Figure 16. Magenta, blue and green curves are computed for an average wind speed of 8 km/h (measured at soil level), which we assume corresponds to the mid-range wind speed of turbines operation. The red curve shows the expected noise level at VIRGO West building in case of a three times stronger wind, which we assume corresponds to the upper limit of the operational range of turbines.

Conclusions

We studied the seismic wave-field generated by one wind park located in a not particularly quiet seismic area (25 km from the city of Hannover) on a cultivated soil and composed of lime and sand sediments (thus particularly seismically dissipative-type of soil).

We find that the seismic wave-field is particularly rich in the 2 to 10 Hz frequency components, which correspond to functional frequencies of the turbines. The surface seismic wave has the characteristics of a Love wave with a dominant horizontal component. The velocity of propagation is particularly slow, 500÷250 m/s, with evidence of dispersive effects (higher components travel slower). A qualitative indication is that at about 2km distance from the park the wave-field amplitude reduces to a level comparable to the variation of the anthropogenic seismic noise.

A simple model of incoherent superposition of uniformly radiated surface seismic waves from the single turbines seems to reproduce the measured seismic wave-field attenuation with distance, for values of the $Q \cdot v$ parameter in the range 15000÷30000. The uncertainty of the model predictions is however large because we applied it to measurements in the near-field of the wind park.

Based on this model we expect that a similar wind park proposed for construction in the vicinity of the VIRGO detector in Italy, would produce a disturbance significantly above of the typical RMS variation of the site seismicity, up to about 4 km distance.

Based on this result and conservatively accounting for the model uncertainty, we set a minimum "distance of respect" of 6km from each of the VIRGO buildings for the installation of the wind park, counting 9 turbines of 2MW. This distance scales with the square root of the number of turbines and linearly with the turbines power.

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