ATTENUATION OF WIND NOISE BY SEISMIC SURFACE ARRAYS AND NODES

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Summary

Land seismic recordings are susceptible to wind noise which can be effectively attenuated by surface arrays. Seismic nodes and point-receiver acquisition methods have to rely on different noise attenuation methods. We analyze wind noise recorded by a surface array and a shallow vertical array. We show that the wind noise consists of interfering Rayleigh wave modes with a wavelength less than 1 meter for frequencies above 40 Hz. We also show that the wind noise measured at an interval over 1 m appears as incoherent noise whose amplitude in n summed traces reduces by $1/\sqrt{n}$. We propose an empirical model for wind noise spectrum as function of wind speed and depth and this model to both data-sets. The model shows that the wind noise spectrum increases by the wind speed to the power of 1.8. Furthermore we show that at this location, the attenuation of wind noise for frequencies between 40 and 100 Hz by a n geophone surface array is equal to a single geophone buried at depth $z=\sqrt{n}/20$. A geophone or seismic node buried at 20 cm depth is expected to attenuate wind noise by 12 dB, similar to a 16 element surface array.

Attenuation of wind noise by surface arrays and seismic nodes

Introduction

The main purpose of seismic surface arrays is to attenuate ambient and shot-generated noise. Seismic nodes have a number of advantages over seismic surface arrays including requiring significantly less equipment but require additional methods to reduce the higher noise levels on their data. Point receiver processing methods combined selecting suitable survey parameters have been demonstrated to be successful in attenuating the shot-generated ground-roll noise (Baeten et al., 2000). Ambient noise, in particular wind noise is however more challenging to attenuate in point receiver data and node data. Here we focus on the attenuation of the wind noise by burying the seismic node under the surface and compare it with its value at the surface.

Wind noise typically appears in the seismic record at frequencies above 40 Hz. Its amplitude increases strongly with the wind speed, see Bland and Gallant (2001). Wind noise often has an apparent random appearance in shot gathers due to its very short wavelength. Various mechanisms have been proposed for wind noise including sand grains hitting the geophone casing, through mechanical coupling through the cable and local coupling of wind energy into the ground by surface features such as trees, buildings and wind turbines (Saccorottie et al., 2011, Dean et al., 2015).

Here we analyse wind noise acquired by a surface array and compare it with receivers located at a range of depths below the surface. The data-sets allow us characterization of the wind noise and to derive a model for its spectral power as function of depth and wind strength. The analysis also allows us to compare the attenuation of wind noise by surface arrays of different size with noise levels measured below the surface. This analysis allows us to determine the depth below the surface where the wind noise recorded by a seismic node is comparable to that of a surface array.

Characterization of surface wind noise

A wind noise data-set was acquired in the desert area with sandy soil reminiscent like dry beach sand. The test site and the wider area were flat without any surface expressions and no external noise sources were present in the test area. The data was acquired by a cabled geophone system and the recording truck was located well over a kilometre away. A two-dimensional surface array of geophones was planted in a 24 by 25 grid with 30 cm separation in both directions. The geophones were buried just under the surface while the associated cables were covered with sand to prevent direct impact of sand particles. In total 21 noise data-sets, each 10 min long were acquired at 13 wind speeds between 2.8 and 8.9 m/s.

Power Spectral Densities (PSD) for the surface array data show an increase of spectral power with wind speed is observed over the entire frequency range of at least 10 dB and an increase to 16 dB is observed for frequencies over 100 Hz, see Figure 1.

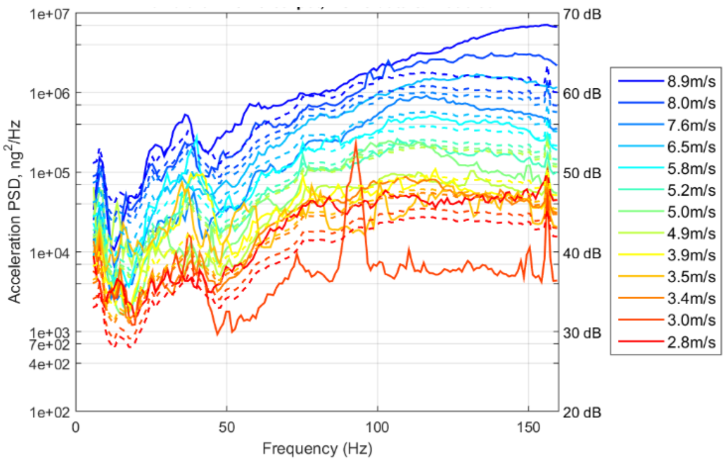

Figure 1. *Power Spectral Density of noise records recorded by the surface array at 13 wind speeds (solid). Modelled PSDs are shown by the dashed lines.*

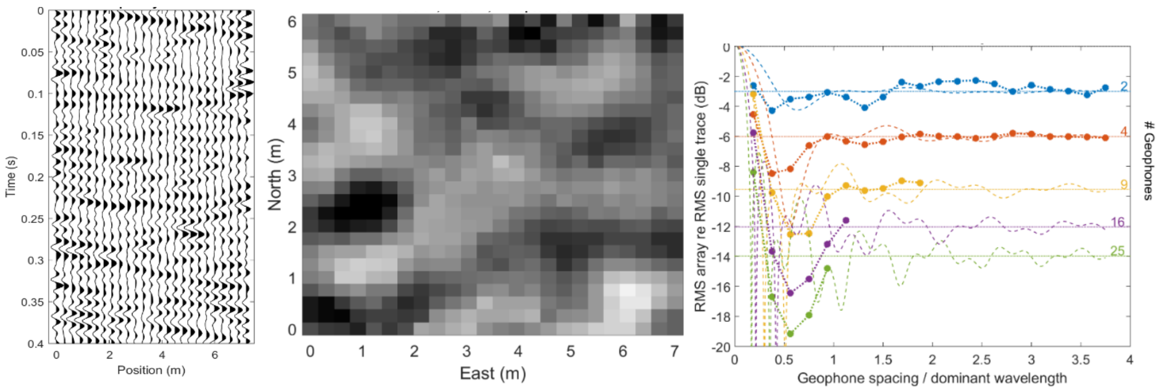

Figure 2. *Waveforms (left) and a time slice (middle) for data recorded at 6.5 m/s wind speed. (right) The RMS of the summed traces within various arrays with respect to the mean RMS of all input traces to the array for seismic wind noise records between 40 and 100 Hz (colored circles). The arrays vary in number of geophones and size expressed as the ratio of geophone spacing over dominant wavelength, d/λ. The theoretical coherent noise attenuation improvement by Denham (1963) is shown by the thin dashed lines.*

Visual inspection of the seismic wind noise shows that the noise manifests itself as interfering events that are coherent over the length of the surface array (6 m) and are traveling in multiple directions, see Figure 2. Analysis of the wind noise in the wavenumber domain shows that the energy is confined to two rings that are interpreted as a Rayleigh wave fundament and higher modes. Dispersion curves were picked in the frequency-wavenumber domain and their inversion resulted in a realistic a shear velocity profile.

While the observed wind noise is coherent over a short distance (less than 1 m), its coherency decreases with distance. The dense surface array allows us to test the attenuation of wind noise for a large number of surface array geometries with *n* geophones and separation *d*. We restrict ourselves to regular square arrays with *n*=4, 9, 16 and 25 elements and a 2-element line array. For each array the ratio of the sum of the RMS of the input traces over the RMS of the summed traces was calculated over the frequency band of 40-100 Hz that includes the wind noise. It is found that the reduction in the RMS of the *n* summed traces for geophone separations larger that the wavelength, d/λ >= 1 converges to $1/\sqrt{n}$, see Figure 2. This is in good agreement with the theoretical array response function that for d/λ > 1 converges to the value for uncorrelated noise, $1/\sqrt{n}$ (Denham, 1963).

Characterization of wind noise with depth

A small vertical array was positioned around 20 m from the surface array and had six geophones buried between 10 and 100 cm depth. The geophones in the vertical array were a prototype three-component geophone unit using the same geophone element as the surface array. Data was recorded and analysed in the acceleration domain.

PSD's for the vertical array show a systematic decay of the noise with depth down to 40 cm below surface below which it does not further decay observed. The shape of the PSD differs between the surface array and vertical array. This may be the result of the experimental housing of the prototype 3C geophones or the conditions of the sand within the hole of the vertical geophone array which had not been compacted to the same degree as the undisturbed sand.

An empirical model for wind noise is proposed and consists of three different terms, a frequency dependent source term S(f), a power law dependence on wind speed W and a frequency dependent exponential decrease with depth z:

$$U(f) = S(f)\, W^{w} \exp\left(-k(f)z\right) \quad (1).$$

The source term S(f) depends on frequency only, which is motivated by the observation that the spectral shape does not change much with wind speed W. The source term describes the amount of wind energy that is transmitted into the ground at surface level and is expected to be site specific. The second term describes the dependence of the spectrum on the wind speed W to the power *w*. A power law relation is proposed as this includes a linear relationship and equals to zero for zero wind speed contrary to for

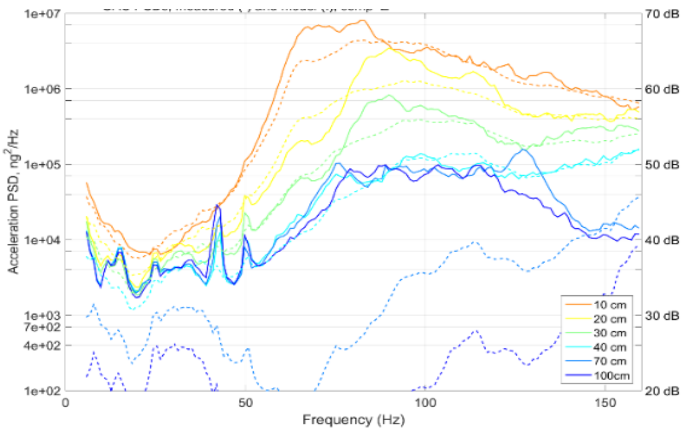

Figure 3. *PSDs for the vertical array calculated from noise records acquired at different depth for a wind speed of 6.5 m/s. The solid lines show the median PSD at each depth. The dashed lines show the PSDs at the depth modelled by Equation 1.*

instance an exponential dependence on wind speed.The third term describes the exponential decay with depth, where the decay rate *k(f)* is frequency dependent and is interpreted as the inverse of the characteristic depth or skin depth.

The coefficients of the empirical wind noise model were determined for both data-sets and the modelled PSD's for the surface and vertical array are shown by dotted lines in Figures 1 and 3 respectively. As expected, the source term *S(f)* was substantially different between the data-sets. Good agreement was found for the wind speed power coefficient which was *w=1.83* for the surface array data and *w=1.80* for the vertical array. The decay rate for the vertical array data was estimated to be k=0.70 m at 20 Hz and decreased to below *k=0.2* m at frequencies over 60 Hz. The decay rate agrees with modelled Rayleigh wave amplitude functions. The model over-estimates the reduction of noise levels below 40 cm where observed noise does not further reduce in amplitude.

Comparison of the noise attenuation by a surface array and with depth

The surface array is shown to attenuate wind noise by $1/\sqrt{n}$ for d/λ > 1, or 3 dB for n=2, 6 dB for n=4 and 12 dB for n=16, see Figure 4. The modelled spectral decay function, $(exp(-k(f)z))$ with respect to its surface shows that a geophone buried at 10 cm wind noise is estimated to be attenuated by 5 dB between 50-100 Hz, see Figure 4. Over the same frequency band, a geophone buried at 20 cm is estimated to attenuate wind noise by around 12 dB, similar to that for a 16 element surface array. Larger attenuation is obtained when planting the geophone deeper. As a simple rule we find that the depth z_n of where attenuation of wind noise by a buried geophone becomes equal to that of the surface array *n* equals $z_n = \frac{\sqrt{n}}{20}$.

Noise at frequencies below 40 Hz attenuates less well with depth as it is dominated by longer wavelength ambient ground-roll. Our data shows that 9 dB noise attenuation can be obtained at 40 cm depth, which is comparable to a 9 element surface array. Attenuation of the noise in this lower bandwidth can be approximated by $z_n = \frac{\sqrt{n}}{7}$. These results are summarized in Table 1.

Target noise attenuation	**3 dB**	**6 dB**	**9.5 dB**	**12 dB**	**14 dB**	**18 dB**
Number of elements in surface array	2	4	9	16	25	64
Noise level of a single element at depth for wind noise, 40 > f < 100 Hz	7 cm	10 cm	15 cm	20 cm	25 cm	40 cm
Noise level of a single element at depth, f < 40 Hz	20 cm	30 cm	40 cm (9 dB)	-	-	-

Table 1. *Comparison of the modelled noise attenuation for a n element surface array and a single element at depth.*

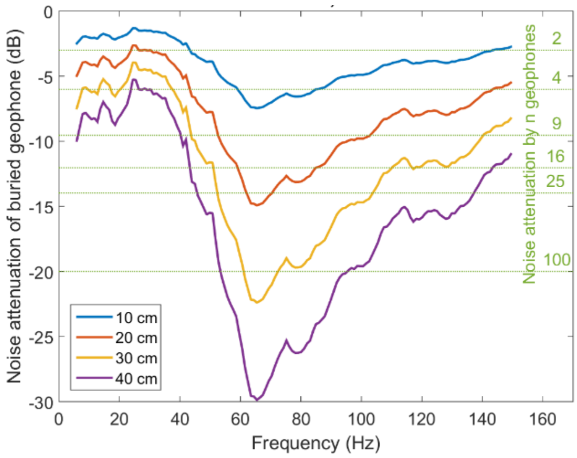

Figure 4. *The modelled spectral attenuation of noise with depth relative to its surface values, $exp(-k(f)z)$. The theoretical random noise attenuation of an array of n geophones is shown in green.*

Conclusions

Analysis of a data-set showed that at its location, wind noise can be described by a superposition of high frequency fundamental and higher mode surface waves, direct and scattered in many directions. Wind noise is found to be coherent at the surface with a wavelength less than 1 m for frequencies above 40 Hz. The spectral power of the wind noise increases with the wind speed to the power of 1.8. Attenuation of wind noise by a surface array with *n* elements spaced d/λ > 1 is proportional to theoretical value of for random noise, $1/\sqrt{n}$. Wind noise is observed to attenuate with depth by at least $exp(-z/0.2)$. At this location, the attenuation of wind noise for frequencies over 40 > f < 100 Hz by a surface array *n* is equal to a single geophone buried at a depth $z_n = \frac{\sqrt{n}}{20}$. A seismic node buried at 20 cm depth is expected to attenuate wind noise by 12 dB, similar to a 16 element surface array.

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