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PEER REVIEW OF REPORTS RELATED TO SEISMIC NOISE FROM WIND TURBINES NEAR ESKDALMUIR SEISMIC ARRAY

Limberger, F., and G. Rümpker (2025). Re-Analysis of seismological data to characterize the decay of ground motions induced by wind turbines.

For their report Limberger and Rümpker analyzed the vertical component of seismic recordings from a linear array (LA) of seismometers deployed by CWP for 6 months, and extending from an existing windfarm toward the Eskdalmuir Seismic Array (EKA). For comparison, they also looked at data from EKA from the same time interval. In data from LA stations less than about 5.5 km from the wind turbines (WT), they found strong contributions to the seismic wavefield overall between 2 Hz and 12 Hz, but especially of spectral peaks at various frequencies in that range. These contributions are considered seismic noise, as they would obscure relatively small seismic signals of interest that may be arriving at the EKA array stations. Overall, this noise increases with the windspeed. However, Limberger and Rümpker further document that the spectral peaks have mostly disappeared at a distance of 5.5 km from the WT. The peaks are neither apparent in the data for LA stations which are more than 8.6 km from the windfarm, or in the spectra from the EKA station closest to the windfarm, EKB1. The amplitude of the seismic noise caused by the WT depends primarily on the windspeed, while the levels of the noise recorded on EKA stations often exhibit a difference between working and night time hours. The seismic noise at EKA stations also increases when strong winds are present, which is a well known phenomenon (Seidl et al., 1996; Withers et al., 1996), but the particular peaks generated by the WT are currently not apparent in the spectra.

In my opinion, the conclusions that Limberger and Rümpker present are very reasonable, given their analyses. Seismic noise caused by the WT is readily apparent as spectral peaks in the frequency band between 1 and 12 Hz at distances up to 5.5 km from the wind farm. These spectral peaks are present 24-hours a day if the wind is blowing, and their amplitude changes only with changes in the windspeed (or if the WT are off). Spectral peaks are also observed in the data from the EKA stations, but they are not at the same frequencies as those from the WT and therefore cannot reasonably be attributed to the WT. The spectral peaks of the WT seismic noise cannot currently be observed at even the closest EKA stations.

Hasting Micro-Seismic Consulting, Inc. (2025). Final Technical Report CWP Eskdalemuir Seismic Station.

The HMSC Final Technical Report reviews data and analysis from the deployment of a Gaiacode 3-component (3C) Alpha model broadband borehole seismometer in a ~200 m borehole emplaced near EKA seismic station EKR4. For direct comparison, two 3C seismometers were installed at the surface next to the borehole, an ALPHA and a CMG-6T. Data from the vertical channel of the borehole seismometer show that the level of continuous, or background, noise between 1 and 15 Hz at several depths below 175 m and at a variety of windspeeds are always lower than the noise on the vertical channels of either of the two surface seismometers or at

the EKA array station EKR4. The greatest difference in the seismic noise amplitudes between surface and borehole instruments is apparent at the deepest deployment depths and at the highest windspeeds. This is excellent evidence that the deployment of seismometers in boreholes reduces the levels of the seismic noise recorded as compared to instruments installed at or near the surface of the earth (Withers et al., 1996; Zeiger and Ritter, 2018; Limberger et al. 2023) . In general, seismic noise in the frequency band from 1 to 15 Hz is primarily due to wind or anthropogenic sources.

HMSC further recommends replacing or augmenting at least 10 of the EKA array stations with seismometers deployed in boreholes of various depths, which is strongly encouraged by the CTBTO to reduce the impacts of increasing seismic noise from anthropogenic sources on monitoring. Adding 10 borehole seismic stations to EKA would fulfill two goals. It would comply with the CTBTO 2024 report recommendation of the minimum number of borehole stations to be included in a seismic monitoring array. And, it would ensure a reduced amplitude of seismic noise in the frequency band between 1 and 15 Hz, even if WT were closer to EKA than at the present time. The mix of instrumentation and depths in the HMSC proposal includes 3C broadband seismometers at 4 sites, and that the boreholes near the ends of the array arms be drilled to greater depths. Adopting these suggestions would provide valuable improvements in capabilities over the current CTBTO recommendations, as they will allow a better characterization of the wavefield, ensure higher signal-to-noise ratios at those stations, and contribute to longer term high performance of the EKA array. Although HMSC recommends that the seismometers be cemented into the boreholes to maximize the coupling of the seismometer, this is not always beneficial in my experience. If the instruments are cemented into the borehole, both the instrument and the borehole are “lost” in case of failure of some element of the system or the need for upgrade. In the 1-15 Hz frequency band, sanding in the seismometer at the bottom of the borehole or the use of an appropriate hole lock will allow the instrument to be retrieved and the borehole to be reused.

Conclusions

Overall the observations and recommendations of Limberger and Rumpker (2025) and of HMSC (2025) are consistent with seismological observations made over the past 50 years in the analysis of broadband, high dynamic range, digital seismic data from borehole and surface stations. As anthropogenic sources of seismic noise increasingly encroach on seismic stations, installation methods for seismometers must improve to retain the excellent signal-to-noise ratios that have enabled new scientific insights as well as monitoring for explosions, be they large or small. Recommendations also exist for reducing the generation of seismic noise by wind turbines (Ritter, 2022). The recommendations from HMSC to upgrade the EKA array with seismic instruments installed in boreholes are a realistic means to ensure that high signal-to-noise data of high quality, will be available from the array for many years to come.



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Seidl, D., M. Hellweg, P. Okubo and H. Rademacher (1996): A Preliminary Survey of the Broadband Seismic Wavefield at Puu Oo, the Active Vent of Kilauea Volcano, Hawaii, *Annali di Geofisica*, **39**, p. 283-299. Withers, M., R. Aster, C. Young, and E. Chael (1996). High-frequency analysis of seismic background noise as a function of wind speed and shallow depth. *Bull. Seismol. Soc. Am.* 86 1507–1515.

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<i>TRAINING INSTITUTION</i>	<i>DEGREE</i>	<i>YEAR</i>
University of California, San Diego	B.A., Physics, German Lit.	6/1973
Universität Göttingen, Germany	Diplom – Physics	4/1976
Mills College, Oakland, CA, USA	Teaching Credential	6/1989
	Physical Sciences, Math	
Universität Stuttgart, Germany	Dr. rer. nat – Geophysics	2/2000

PROFESSIONAL EXPERIENCE

6/2021 – present. Geophysical consulting (Orinda, CA, USA). Geophysical consultant for geophysical instrumentation, earthquake monitoring, and projects such as updating earthquake catalogs and studying current and historical earthquakes.

6/2001 – 6/2021. Berkeley Seismological Laboratory (BSL), UC Berkeley (CA, USA). Researcher and Operations Manager. Realtime earthquake reporting, earthquake early warning, seismic network management and operations, data center management, seismic and geodetic instrumentation oversight, including operation of AS109, a CTBTO auxiliary seismic station.

11/1995 – 5/2001. Geophysical consulting (Orinda, CA, USA). Geophysical consultant for geophysical instrumentation and monitoring.

1/1996 – 2/2000. Universität Stuttgart (Germany). Doctoral thesis. Volcano seismology.

3/1990 – 10/1995. US Geological Survey, Branch of Seismology (Menlo Park, CA, USA). Geophysicist. Local earthquake, coda and strong motion studies.

7/1986 – 2/1990. Geophysical consulting (Orinda, CA, USA). Geophysical consultant for geophysical instrumentation and monitoring.

4/1978 – 6/1986. Seismologisches Zentralobservatorium Gräfenberg (SZGRF, Erlangen, Germany) & Bundesanstalt für Geowissenschaften und Rohstoffe (Hannover, Germany). Computer Programming & seismic observatory network operations.

SYNERGIES

Commissioner, California Seismic Safety Commission (2011-2017)

Secretary, Seismological Society of America (2016-2021)

President Elect/President/Past President, Seismological Society of America (2021-2024)

Panelist, Science and Technology Conference of the Comprehensive Test Ban Treaty Organization (2023)