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Re: Peer review of report produced by HMSC Inc and Drs. Limberger and Rümpker

CWP Energy has asked me to provide an independent assessment of the work carried out by Hasting Micro-Seismic Consulting (HMSC) and a separate report by Drs. Limberger and Rümpker. Both reports investigate seismic noise associated with wind turbines (WTs) and evaluate whether the proposed upgrade to the Eskdalemuir Seismic Array (station code EKA) could mitigate these effects of nearby WTs. This is relevant as CWP Energy intends to develop a new onshore wind farm in the vicinity of EKA. In addition to these reports, I also draw on relevant information available in the public domain.

My Background

For context, I hold the Chair of Geophysics and am a former Head of the Department of Earth Sciences at the University of Oxford. I am also the founding director of Oxford EARTH, a strategic initiative uniting nine departments across the University to advance equitable and sustainable access to natural resources.

Before joining Oxford, I served as the BGS Professor of Geophysics at the University of Bristol, where I founded the Bristol University Microseismicity Projects (BUMPS), an industry-sponsored consortium studying natural and anthropogenic seismicity. I hold a PhD from Queen's University, Canada, and completed a postdoctoral fellowship at the Scripps Institution of Oceanography in the United States. My academic career has also included faculty posts at the Universities of Toronto and Leeds.

I previously served as President of the British Geophysical Association and as Vice-President (Geophysics) of the Royal Astronomical Society. My contributions to geophysics have been widely recognised: I was elected a Fellow of the American Geophysical Union (2011), the Royal Society of London (2019), and the Royal Society of Canada (2022). In 2024, I received the Gold Medal of the Royal Astronomical Society. I have supervised nearly 50 PhD students and 30 postdoctoral researchers and have published more than 300 papers in leading scientific journals.

Regarding the topic of these reports, I have more than 20 years of experience in microseismic monitoring and I have worked seismic array analyses in a wide range of settings (e.g., imaging the lowermost mantle; icequakes; induced seismicity; etc.). I have advised regulators and operators on induced seismicity associated with oil and gas production, including shale gas stimulation in northwest England. I have also worked on seismicity related to CO_2 storage and geothermal energy and collaborated with the BGS on landslide monitoring using geophysical methods. As a consultant, I have advised nearly 20 companies on microseismic monitoring.

Statement of Independence

I am independent of all parties involved. I have no connection to HMSC. In the early 1990s, I was a PhD student at Queen's University, Canada, under the same supervisor as Prof. Georg Rümpker, and I have co-authored eight papers with him, the last in 2013. I know Drs. David Bowers and Neil Selby professionally, and one of my former PhD students, Dr. Stuart Nippress, now works at AWE Blacknest.

Independent Review

The first seismic station at Eskdalemuir was established in 1908 alongside a geomagnetic observatory. The site was selected for its remoteness and low levels of seismic and geomagnetic noise. In 1962, the British Geological Survey (BGS) established EKA, one of the world's earliest seismic arrays. It is now operated by AWE Blacknest (MoD) and is extensively used for nuclear test monitoring. EKA plays a central role in the International Monitoring System (IMS), which supports verification of the Comprehensive Test Ban Treaty (CTBT). As of this writing, of 196 states, 187 have signed and 178 have ratified the treaty.

CWP Energy proposes developing an onshore wind farm within 50 km of EKA. The Scoop Hill site, located in Dumfries and Galloway approximately 5 km southeast of Moffat, is planned to include 60 commercial-scale turbines. Concerns about interference from onshore WTs are longstanding. A comprehensive study by the University of Keele (Styles et al., 2005) established characteristic vibration modes and frequencies generated by turbines. That study suggested some development would not interfere with IMS requirements, although it lacked specific detail.

Seismology is relevant to WT projects for two reasons. First, turbine foundations must be engineered to withstand regional seismicity, although this is generally not a major concern in the UK (despite occasional felt earthquakes such as the recent ML 3.3 Silverdale event on 3 December 2025). Second, seismic noise generated by WTs may interfere with seismic monitoring, which is a concern for AWE and the CTBTO. Polarisation analyses show that WTs primarily generate surface waves (Westwood & Styles, 2017). Depending on turbine size and design, several vibrational modes may occur - including blade, torsional, tower, and foundation modes - resulting in characteristic seismic peaks. Local topography can influence seismic noise (Zieger, 2019), and mitigation methods exist, such as air-filled trenches that reduce noise in the 1–10 Hz range (Abreu et al., 2022).

CWP commissioned HMSC to investigate whether deep borehole sensors could reduce seismic noise at EKA. A GaiaCode Alpha three-component broadband sensor was deployed in a 200 m borehole. Noise in the 2–8 Hz range - critical for detecting nuclear tests - was substantially reduced. Despite imperfect coupling (the sensor was not cemented), noise reductions reached up to 25 dB in strong winds and 10 dB in light winds. These results suggest borehole sensors could detect signals at ~18% of the amplitude required by surface sensors, significantly improving detection thresholds.

A key difference between surface and borehole sensors is that borehole sensors will have a much higher signal-to-noise (SNR) ratio. Another difference lies in how the seismic wavefield interacts with the near-surface environment. Low-velocity sediments and free-surface effects can modify the recorded waveforms. These influences can be easily modelled and their impact quantified using both real and synthetic data. There is some concern that the waveforms from surface versus borehole sensors could be different, but it is worth noting the current surface array is not being removed so comparisons will legacy data will be still possible, especially as the Limberger and Rümpker study suggests negligible effects from the WTs. An interesting possible topic for future research could study these waveform differences.

In a separate study, Limberger and Rümpker analysed the decay of WT-generated seismic energy with distance. Using a linear array of Güralp 6TD instruments deployed at increasing distances from a turbine, they examined attenuation over frequencies and wind conditions. Their results indicate that WT-induced noise is strongly localised and barely detectable at 5.4 km but not at 8.4 km. While 6TDs are narrower-band than GaiaCode Alpha seismic instruments, they are comparable in the 2–8 Hz range. The analyses presented in this report are robust but I would caution that these conclusions are very site specific. However, the near-surface conditions, tomography, etc. that will affect the results or L&R are very similar to the those around the proposed WTs.

HMSC Response to MoD Concerns – My Assessment

1. P-wave distortion

HMSC concludes this is not an issue. It's not a question of one of the waveforms (either downhole or surface) being "distorted" - both types of sensor deployment record the waveforms accurately. Nevertheless, the free-surface effect and near-surface attenuation will create differences in the waveforms between the downhole and surface stations, but the downhole data would be clearer due to a higher SNR. Nevertheless, as part of the integration and corroboration process a more quantitative evaluation – e.g., comparing phase and amplitude differences (e.g., Kristeková et al., 2009) – would help, perhaps as a future research project.

2. Impact of borehole installations on SNR

I would expect borehole installations to offer significantly improved SNR. It is unclear why regional events would show weaker borehole amplitudes – I presume that this is due to the free-surface effect and focussing due to the low-velocities near surface. Again, this could be easily modelled. Although not necessary, comparisons with the UK-GEOS borehole stations near Glasgow (operated by BGS) may provide additional insight.

3. Influence of wind noise

Although some disagreement exists regarding the contribution of trees, the borehole sensor clearly reduces wind-related seismic noise and the power spectral density (PSD) comparisons are convincing.

4. Impact of forestry activity
The borehole sensor also performs better in mitigating noise from forestry operations.

5. WT-noise decay and the Limberger and Rümpker report
Their estimate that signals become undetectable beyond 5.2 km is plausible but should not be treated as universally applicable. Attenuation varies by frequency (hence turbine type), geology, and site conditions. Other studies report detectability at greater distances, but the Limberger and Rümpker report is calibrated in the region of the EKA array, and is more relevant as it deals with similar geologic site conditions.

6. Relevance of the 0.336 nm threshold
This threshold appears outdated, and current array noise often exceeds it. It would seem that cultural noise has risen in the area over the past few decades. Borehole sensors consistently show far lower noise - typically 5–30% of the array average, depending on wind and frequency.

7. Effectiveness of borehole seismometers
Borehole installations will unequivocally help mitigate seismic noise (e.g., forestry activity). What remains to be determined is the optimal borehole depth, which involves a cost–benefit trade-off. Furthermore, a borehole array will have increased sensitivity to other topics of forensic seismology (e.g., events like the Kursk submarine disaster or vandalism of the Nord Stream pipeline).

8. Is the current array fit for purpose?
The current array meets its purpose but is increasingly affected by cultural noise. A proposed upgrade of 10 borehole instruments would substantially improve EKA's detection capability. CWP has obtained quotes for Güralp 3T borehole sensors, which meet all relevant requirements. However, there is a great deal of legacy data from EKA, which would need to be contextualised with the new data as part of an integration and corroboration process.

Recommendations

- All new instruments should have uniform response characteristics, be broadband, and be three-component. British-made Güralp 3Ts and GaiaCode Alphas meet these criteria.
- Borehole sensors must be properly coupled, ideally cemented, and cabling should be installed to minimise noise transmission.
- A robust maintenance plan is essential. Locating electronics at the surface is advisable. Redundant sensors could be installed where feasible.
- The surface and borehole arrays should operate concurrently for a pre-arranged period of time to allow calibration and ensure continuity with legacy data.
- Once turbines are installed, a detailed study of their seismic signatures and distance-dependent attenuation should be undertaken.

- The proposed changes will generate extra work for AWE seismologists, and appropriate resources should be allocated. But the new array will be a world-class facility, which will have a diverse set of academic applications.

Final Comments

I am not a specialist in nuclear test-ban monitoring, but my understanding is that neither the CTBTO nor the IMS Operational Manual specifies minimum distances for WT siting. The key requirement is simply that an IMS station must maintain certified noise performance - especially in the 2–8 Hz band critical for nuclear-test detection. The CTBTO recognises that anthropogenic noise may increase over time and allows arrays to be reconfigured accordingly. It is worth noting that borehole installations are recommended in modern IMS stations.

In my view, deploying broadband seismometers in boreholes of 100 m depth or greater would improve EKA's performance and, with appropriate care, enable the development of a nearby onshore wind farm. The UK has long been a leader in nuclear test-ban monitoring and is also a world leader in wind-energy deployment. With thoughtful design and implementation, the proposed modifications would support both objectives.

References

Abreu, R., Peter, D., and Thomas, Ch., (2022) Reduction of wind-turbine-generated seismic noise with structural measures, Wind Energy Science, 7, 1227–1239. doi:10.5194/wes-7-1227-2022.

Kristeková, M., Kristek, J. and Moczo, P. (2009) Time-frequency misfit and goodness-of-fit criteria for quantitative comparison of time signals, Geophysical Journal International, 178: 813-825. https://doi.org/10.1111/j.1365-246X.2009.04177.x

Styles, P., Stimpson, I., Toon, S., England, R., and Wright, M. (2005) Microseismic and infrasound monitoring of low frequency noise and vibrations from windfarms, Recommendations on the Siting of Windfarms in the Vicinity of Eskdalemuir, Scotland, Report to MOD/FTI/BWEA, 125 pp., https://docs.wind-watch.org/AEG-Eskdalemuir.pdf.

Westwood, R. F. and Styles, P. (2017) Assessing the seismic wavefield of a wind turbine using polarization analysis, Wind Energy Science, 20, 1841–1850. doi: 10.1002/we.2124.

Zieger, T. (2019) Experimental quantification of seismic signals induced by wind turbines, PhD thesis, Karlsruher Institut für Technologie, doi.org/10.5445/IR/1000096453, 2019.

Sincerely,

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