Quantifying Wind Turbine-Induced Seismic Noise via Generalized Additive Modelling

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1. Introduction & Objectives

Context : Eskdalemuir (EKA, IMS/CTBT) monitors the **0.5–8 Hz** band. UK rules: no turbines <10 km and cumulative motion within 50 km must stay below **0.336 nm RMS**. Turbines can raise motion in this band.

Objectives :

- Isolate turbine-attributed uplift using matched *background* vs *operational* periods.
- Quantify how uplift varies with wind speed and direction (orientation effects).
- Assess compliance margin relative to the **0.336 nm RMS** line.
- Provide practical guidance for monitoring and siting around EKA.

2. Site & Data Overview

Site : EKA array, southern Scotland; all measurements from the same borehole **WS12** to avoid site/instrument changes.

Periods : Background: Pre-installation — No turbines present. **Operational**: Post-installation — turbines installed and generating.

Dataset types : Time series: vertical ground velocity $v(t)$ at **1 s** cadence. **Frequency**: PSD $S_x(f)$ over ≈ **0.01–10 Hz**; FDWF applied to emphasise 0.5–8 Hz.

Metadata : Wind speed (m/s), wind direction (deg/rad), turbine status (0/1); Date/Hour/Time.step for alignment.

*Aligned summarised to **10-min** windows.*

3. Methods Overview (Pre Processing + GAM Modelling)

Pre-processing :

- *PSD estimation:* from 1 s vertical velocity $v(t)$, compute PSD $S_x(f)$ *(m^2/Hz)* on a common grid (≈0.01–10 Hz; constant Δf).
- *FDWF weighting:* emphasise EKA band with $\tilde{S}_x(f) = w(f)\, S_x(f)$ (weights peak over **0.5–8 Hz**).
- *Scalar energy per second:*

$$E_t = \sum_f \tilde{S}_x(f)\, \Delta f \quad \text{(units: m}^2\text{)}$$

- *Response (stabilised):*

$$Y_t = \log_{10}(E_t + \varepsilon)\,, \qquad \varepsilon = 10^{-12}.$$

- *Temporal features:* `Hour` (0–23), `DateF` = Date + Hour/24.
- *Sync & summarise:* time-align seismic, wind, and turbine-status streams; fit on **10-min** aggregates.

Why GAM? Handles **non-linear** wind effects, **cyclic** direction, and **day** random effects while staying interpretable.

GAM (Final model) : Gaussian response on Y_t (Identity link) with nonlinear, cyclic, and random-effect terms:

$$Y_t = \beta_0 + \beta_1 \,\text{Operational}_t + s_1(\text{Wind.speed}_t) + s_2(\text{Wind.speed}_t)\cdot\text{Operational}_t + s_3^{\text{cc}}(\text{Wind.dir}_t) + b_{\text{Date}(t)} + \varepsilon_t\,,$$

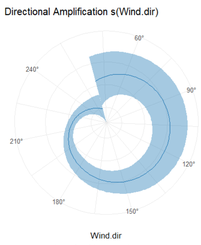
$\varepsilon_t \sim \mathcal{N}(0, \sigma^2)$; $b_{\text{Date}(t)}$ is a day-level random intercept ($b_d \sim \mathcal{N}(0, \sigma_b^2)$).

Model selection: Compared nested GAMs — Operational → + s(Wind.speed) → + s(dir)`"cc"` → + s(DateF)`"re"` → + s(ws):by op; final chosen by AIC ↓ + diagnostics.

- *Terms:* **Operational** shift; s_1 = thin-plate smooth of wind speed; s_2 = conditional speed smooth (on/off); s_3^{cc} = *cyclic* direction smooth; b_{Date} = `bs="re"` (day RE).
- *Penalty & estimation (REML):* maximise $\ell(\theta) - \sum_j \lambda_j \int [s_j''(x)]^2\, dx$; conservative k per covariate.
- *Implementation:* `mgcv::gam`; circular knots for direction (`bs="cc"`); random-effect spline for day (`bs="re"`).
- *Checks:* AIC, QQ, residual–fitted, ACF ⇒ assumptions reasonable; mild serial correlation monitored.

4. Results & Compliance

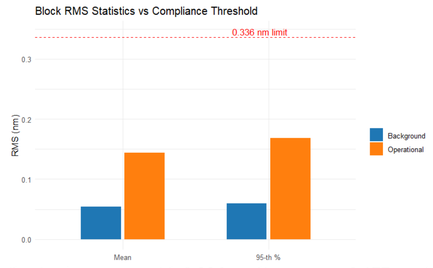
Operational turbine activity produces a clear uplift in seismic energy within the 0.5–8 Hz band, strongest for south-westerly winds (130–150°). Despite this increase, all RMS displacements remain well below the 0.336 nm limit (peak 0.177 nm), indicating no compliance risk.



Model-predicted energy vs wind direction: Operational (orange) exceeds Background (blue), peaking near 130–150° (SW).

Results : Lowest-AIC GAM shows a clear directional signature: energy peaks for **SW winds (130–150°)** and is **higher when ON** at all directions. **Wind speed** is negligible when **OFF**, but under **ON** adds a **mild, saturating** uplift. Day-level random effects capture small baseline shifts. On the energy scale ($\sim 10^{-24}$ m^2), **Operational ≈ 20% above Background**. Diagnostics (QQ/ACF) indicate good calibration and weak serial correlation after 10-min aggregation.

Compliance: RMS summaries confirm uplift yet sustained compliance. **Background** 0.054 (mean) / 0.060 (95th) / 0.060 (max) nm; **Operational** 0.144 / 0.169 / 0.177 nm. All values lie below the **0.336 nm** limit; the peak (0.177 nm) is ∼**53%** of the threshold, leaving a margin of ≈ 0.159 nm. ECDF/summary plots show a rightward shift when ON, but the entire distribution remains within bounds—means and 95th percentiles are comfortably sub-threshold—indicating no compliance risk under observed conditions.



RMS distribution/summary with 0.336 nm line; max ≈0.177 nm (compliant).

5. Limitations

- **Single site/pit:** findings are specific to **WS12**; array-wide generalisation is limited.
- **Coarse ops metadata:** status only (0/1); no per-turbine load or spatial telemetry → no turbine-level attribution.
- **Temporal dependence:** mild residual autocorrelation remains after 10-min aggregation; CIs may be optimistic (consider GAMM/AR).
- **Spectral compression:** energy metric + FDWF collapses spectrum; conclusions depend on the 0.5–8 Hz band and chosen weights.

6. Future Research

To advance this work and inform sustainable turbine development, future research should consider:

- Cumulative impact modelling to assess seismic implications of higher turbine density.
- Spatiotemporal GAMs or Gaussian processes to address spatial interference and terrain variation.
- Bayesian GAMs to quantify uncertainty in uplift estimates.
- Integration with turbine telemetry for finer-grained attribution of seismic signatures.
- Multi-station validation to test generalisability and support regional infrastructure planning.

7. Key Takeaways

Turbine operation raises energy in **0.5–8 Hz** (strongest for **SW** winds), ∼**20%** uplift. **RMS** stays below **0.336 nm** (peak ≈0.177 nm); FDWF+GAM isolates direction/speed effects for monitoring and planning.

8. Conclusion

Using an FDWF-weighted energy metric and a GAM (interaction, cyclic direction, day RE), we detect turbine-driven uplift in the **0.5–8 Hz** band at EKA–WS12. The effect is modest (energy $\sim 10^{-24}$ m^2) and **RMS** during operation peaks at **0.177 nm** (∼53% of the **0.336 nm** limit). No current compliance risk; continued monitoring for cumulative impacts is advised.

9. Scan QR Code for Report

Scan to Access:

- Full Report (PDF)
- Rmd Code (GAM pipeline)
- Knitted Pdf (Diagnostics)

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