Xi Engineering Consultants

Standardised Measurement of Baseline Seismic Noise

Instrument Deployment & Analysis Process

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Xi Engineering Consultants, CodeBase, Argyle House, 3 Lady Lawson Street, Edinburgh, EH3 9DR, United Kingdom.
T: +44 (0)131 290 2250, xiengineering.com, Company no. SC386913

Document Summary

This document defines the standard methodology for deploying seismic instrumentation and conducting seismic vibration measurements associated with wind turbine generators. It has been developed by Xi Engineering Consultants to support compliance with the Ministry of Defence (MoD) requirements for wind farm development within the Eskdalemuir Consultation Zone (ECZ).

This document forms a broader suite of technical standards developed to support seismic assessment within the ECZ. Specifically, this document defines the standardised methodology for conducting baseline seismic vibration measurements prior to the installation of wind turbine generators.

The procedures described are designed to quantify background seismic noise levels in the absence of turbine activity. These baseline measurements serve as a critical reference for distinguishing natural or environmental seismic contributions from those induced by wind turbine operation. As such, they enable the accurate characterisation and subtraction of background noise (e.g. from wind turbines in a neighbouring windfarm, and/or anthropogenic sources) during the assessment of operational wind farm seismic impacts.

This document is intended for use by technical teams responsible for planning, executing, and analysing seismic measurement campaigns at proposed wind farm sites. For the corresponding procedures relating to the standardised measurement of seismic emissions from active wind turbines, refer to *Standardised Measurement of Operational Wind Turbine Seismic Noise*.

Contents

1. Introduction

This document defines the standardised process for the deployment of seismic instruments and the collection of seismic vibration data associated with wind turbine operations within the Eskdalemuir Consultation Zone (ECZ). These procedures have been developed to support the Ministry of Defence (MoD) seismic budget assessment process by ensuring consistency, traceability, and technical robustness in the measurement of wind turbine-induced seismic vibrations that have the potential to impact the detection capabilities of the Eskdalemuir Seismic Array (EKA).

This report outlines the instrumentation, site selection criteria, deployment methodology, and data handling protocols required to produce reliable and repeatable measurements of background seismic noise, defined as ground vibration levels in the absence of wind turbine operation. These baseline measurements are essential for assessing turbine-induced seismic contributions, enabling the separation of operational signals from ambient environmental noise that may include seismic vibration signals from turbines on a neighbouring wind farm.

This document specifically supports the pre-installation measurement phase, forming the reference dataset against which future operational measurements shall be compared.

2. Objectives

The objectives of this document are to:

- Define a clear and consistent methodology for conducting seismic vibration measurements at proposed wind turbine sites within the Eskdalemuir region.
- Ensure that all relevant environmental, operational, and technical variables are appropriately considered and documented.
- Enable the calculation of background seismic vibration levels
- Support the accurate characterisation of seismic vibration levels across a range of wind speeds and environmental conditions, with specific focus on wind speeds centred around 12 m/s at a reference height of 80 m.
- Facilitate traceable and reproducible deployment and analysis.

These objectives collectively support fair, transparent, and technically robust assessments of wind turbine developments within the ECZ.

3. Definitions and abbreviations

Background Seismic Vibration Levels – The measured ground vibration at a site prior to the erection of any wind turbines. This forms the reference baseline against which turbine-induced vibration is compared. Corrections may be needed to account for interference from existing turbines.

Candidate Wind Turbine – A wind turbine selected for seismic measurement that is representative of the proposed turbine model to be installed within the Eskdalemuir Consultation Zone.

Eskdalemuir Seismic Array (EKA) – The seismic monitoring facility operated by the Ministry of Defence (MoD), located at the centre of the Eskdalemuir consultation zone. The Seismic array monitors ground vibrations and is sensitive to low-frequency signals generated by wind turbines.

Eskdalemuir Consultation Zone (ECZ) – A 50 km radius zone surrounding the EKA, within which all wind farm developments must be assessed and approved by the MoD to ensure compliance with seismic noise budget constraints.

Eskdalemuir Exclusion Zone – Originally set at 10km in 2005 but is expected to be a 15km radius around the EKA in which wind turbine developments are prohibited.

Eskdalemuir Seismic Threshold – The cumulative ground vibration limit from wind turbines operating in the ECZ is 0.336 nm.

Frequency Domain – A representation of ground wave data in terms of frequency components, obtained through mathematical transformation (e.g., Fourier Transform) of time series recordings.

Interquartile Mean (IQM) – A statistical measure of central tendency calculated as the mean of the data values between the first and third quartiles (i.e., the middle 50% of the dataset). It is used to reduce the influence of outliers and provide a robust average, particularly in the analysis of variable or noisy seismic data.

Light Detection and Ranging (LIDAR) – A remote sensing technology that uses laser pulses to measure wind speed and direction at multiple heights.

Ministry of Defence (MoD) – The UK government department that is the statutory consultee for proposed wind farm developments within the ECZ, based on their seismic impact.

Normalised Candidate Wind Turbine Seismic Vibration Levels – The measured vibration contribution of a candidate turbine, normalised to a standard reference distance and site conditions, to allow comparison with other turbines or background levels.

Operational Wind Farm Seismic Vibration Budget Contribution – The seismic impact of a wind farm site once turbines are operational, as quantified against the MoD's vibration budget criteria.

P-wave (Primary Wave) - A type of seismic body wave that travels through the ground by compressing and expanding material in the direction of propagation. P-waves are the fastest seismic waves and arrive first at a measurement point. They transmit through solids, liquids, and gases.

Proposed Turbine – The specific wind turbine make and model that is intended to be installed at a site within the ECZ and assessed for compliance.

Power Spectral Density (PSD) – A quantitative measure of the distribution of power in ground wave signals as a function of frequency, typically expressed in units of power per frequency (e.g., m^2/Hz). PSD is used to characterise the power content of ground motion across frequencies for seismic site analysis.

Q factor (Quality factor) - A dimensionless parameter describing the attenuation of seismic waves as they propagate. Higher Q indicates lower energy loss and less damping during wave propagation through the ground.

Rayleigh Wave - A surface wave combining vertical and horizontal ground motion which for a fundamental mode is a particle motion with a retrograde elliptical path. It travels slightly slower than the shear wave speed and often dominates surface seismic measurements.

S-wave (Secondary Wave) - A type of seismic body wave that moves material perpendicular to the direction of wave propagation, causing a shearing motion. S-waves travel more slowly than P-waves and only propagate through solids. They often follow P-waves in recorded seismic data and can contribute to observed vibration levels.

Supervisory Control and Data Acquisition (SCADA) – A system for monitoring and logging turbine operational data such as power output, rotor speed, and yaw position.

Seismic Budget – The cumulative allowable seismic vibration contribution from all wind turbines in the Eskdalemuir Consultation Zone. See Eskdalemuir Seismic Threshold.

Seismic Impact Limit (SIL) - The maximum permitted seismic vibration contribution, normalised by the square root of rated electrical power for each wind turbine at a wind farm within the Eskdalemuir Consultation Zone (ECZ).

Seismic Pit – A prepared installation location for a seismometer, typically lined and insulated to improve vibration coupling and reduce environmental interference.

Seismic Signature – The displacement power spectral density (PSD) characterising the vertical ground motion generated by a single target wind turbine, normalised to a reference distance of 1 km on the representative geology of the ECZ. This signature serves as a standard reference for assessing seismic impacts within the consultation zone.

Seismometer – A sensitive instrument used to measure ground vibration. Sometimes referred to as a geophone, though typically seismometers offer broader frequency response and higher sensitivity suitable for seismic monitoring applications.

Target Wind Turbine – The turbine within a wind farm that has been selected as the focus for seismic measurement. Often chosen based on proximity to instrumentation or representativeness of site conditions.

Time Series Data – A sequential set of data points representing recorded ground motion or other seismic parameters as a function of time acquired during a seismic survey.

Vibration Budget – The allowable cumulative seismic vibration level set by the MoD for a given wind farm site within the ECZ.

Wind Farm – A group of wind turbines located in the same area and operated collectively to generate electricity from wind energy. In this context, the wind farm is the target site of the seismic survey.

Wind Turbine Generator (WTG) – A standard abbreviation for wind turbines used throughout this document.

4. Scope

This document presents measurement procedures that enable the baseline seismic vibration levels of a proposed wind turbine farm site to be characterised. This involves measurement methods appropriate to seismic assessment at:

- Proposed wind farm sites within the Eskdalemuir Consultation Zone

The procedures described are intended to facilitate the characterisation of wind turbine-induced seismic vibration as a function of wind speed, enabling a normalised vibration contribution to be established for a proposed wind farm site.

Standardisation of measurement procedures also facilitates comparisons between different wind turbines. The procedures present methodologies that will enable the seismic vibration emissions of a wind farm to be characterised consistently and accurately. These procedures include the following:

- Location of seismic measurement positions
- Minimum requirements for the acquisition of seismic vibration, and meteorological data
- Definition of specific seismic vibration parameters and associated descriptors which are used for making seismic vibration contribution assessments.
- Analysis of the data obtained and the content for reporting seismic vibration levels

4.1. Applicability to wind turbine designs

The methodology described in this document is intended for application to proposed wind farm sites that will be composed of wind turbine generators of standard design, specifically those with the following characteristics:

- Horizontal rotational axis
- Concrete gravity foundation
- Three-bladed upwind rotor configuration

Wind turbine types with alternative designs (e.g., two-bladed turbines, downwind configurations, non-standard tower designs, or alternative foundation types) may require additional justification, supporting measurements, or alternative assessment methods to demonstrate their seismic suitability.

5. Outline of method

This procedure defines a standardised approach for the deployment of seismic instrumentation, the collection of ground vibration data, and subsequent analysis to assess wind turbine-induced seismic emissions. The method is applicable to proposed wind farm sites within the ECZ.

Measurements shall be carried out using seismometers positioned with respect to a proposed turbine location. The instrumentation shall be installed following the guidance set out in Section 7 Seismic vibration measurements and procedures, with particular attention paid to ground coupling and location selection to minimise extraneous environmental noise.

Simultaneous wind speed data shall be recorded during the measurement period using LIDAR, met masts, or equivalent. All wind speed measurements shall be either recorded at or normalised to an 80 m height above ground and recorded in 10-minute average bins. Where available, wind direction data may also be logged to support further analysis.

Baseline measurement campaigns shall be designed to run for a minimum of 3 months and until at least a minimum of forty 10-minute data bins at a wind speed centred on 12 m/s (between 11.5 and 12.5 m/s) are collected (Appendix C – Minimum number of samples in the 12 m/s bin).

All relevant positional, timing and associated metadata shall be recorded using Global Navigation Satellite System (GNSS) equipment operating with a horizontal accuracy of ≤2 m. Instrument locations, proposed turbine positions, and wind measurement systems must be documented to support traceability and subsequent analysis.

Once data are acquired, seismic vibration time series shall be validated, binned by wind speed, and analysed using spectral techniques to determine seismic vibration metrics which in turn are reported as:

- Background seismic vibration levels

Results shall be presented in accordance with the analysis and reporting procedures described in Section 10 Data processing and analysis.

6. Instrumentation

The following equipment shall be used to perform the seismic vibration measurements at a quality suitable for accurate evaluation. Instrumentation must be compliant with the technical specifications defined in this section.

6.1. Seismometers

Seismic vibration shall be recorded using seismometers. The instruments used shall meet or exceed the specifications as set out in Table 1.

Assessment relies only upon seismic vibration in the vertical direction, therefore instrumentation is required to record in at least the vertical axis. Optional recording of the horizontal components is permissible and may assist in more detailed interpretation of seismic signals.

Seismometers shall record vertical-axis ground vibration at a suitable sampling rate to measure the frequency range of interest taking account the Nyquist frequency (e.g. 100Hz to ensure adequate frequency resolution). Time synchronisation shall be achieved via GPS, radio clock, or another traceable and stable source. Accurate time logging is essential for correlation with wind conditions and turbine operational data.

Table 1 - Recommended seismic instrumentation specifications

Parameter	Value
Velocity output	30 s (0.03 Hz) to 100 Hz standard
Output sensitivity	2400 V/ms^{-1} (2*1200 V/ms^{-1}) differential output
Peak full-scale output voltage	Differential: ±20 V (40 V peak-to-peak) Single-ended (e.g. mass positions): ±10 V (20 V peak-to-peak)
Self noise	–172 dB (Relative to 1 $[m/s^{-1}]^2 Hz^{-1}$)

6.2. Seismometer installation guidance

For robust and accurate measurements, care should be taken during the installation of the seismometers. The specific installation method will depend on the instrumentation used, manufacturer guidance, and the terrain at the sensor location. In general, attention should be given to ensuring good coupling between the instrument and the ground, with effective transmissibility of vibration. This may require digging to bedrock or another firm layer and preparing a stable foundation in accordance with the manufacturer’s instructions.

As seismic instrumentation is typically highly sensitive, steps should be taken to minimise disturbance from thermal fluctuations and air movement, such as insulating the instrument from drafts and temperature swings. It is essential to ensure continuous power supply throughout the measurement period to avoid data loss or corruption.

Appropriate site access and security should be arranged in advance, including obtaining permission from the landowner or relevant authority. A site-specific risk assessment should be conducted to identify potential hazards such as live electrical cables, buried infrastructure, or environmental risks.

6.3. Wind speed and conditions

To ensure accurate correlation between seismic vibration and wind turbine operation, wind speed data shall be recorded concurrently with seismic measurements. Wind speed shall be measured at, or normalised to, 80 m hub height and typically binned in 10-minute averages. These data shall be time-synchronised with the seismic recording intervals. The wind speed binning interval shall be selected to support the temporal resolution required for effective seismic data analysis (e.g., resolving frequencies down to 0.5 Hz using spectral methods).

The wind speed instrumentation and associated signal processing systems shall have a maximum deviation from calibration of ±0.2 m/s within the measurement range of 4 m/s to 16 m/s. The system shall be capable of calculating and recording average wind speeds, time-synchronised with the seismic data intervals.

Wind direction should also be recorded where available, to further inform operational state analysis.

Care shall be taken when installing meteorological masts or equipment near seismometers, as these may introduce localised vibration and degrade seismic data quality.

6.4. Positioning and distance

GNSS equipment shall be used to record the coordinates of all seismic instrument locations and, if necessary, the associated wind turbines. The GNSS system may use any combination of satellite constellations (e.g. GPS, Galileo, BeiDou, GLONASS) and shall achieve a horizontal positional accuracy of ≤2 metres under typical field conditions.

Accurate positional records shall be maintained to support future re-measurement, regulatory review, and assessment of environmental noise influences near the instrument locations.

GNSS positioning may be supplemented by optical or laser range-finding equipment to achieve sub-metre (<1 m) accuracy when determining distances from instruments to wind turbines. Where distances are measured to the tower wall, the radius shall be subtracted to estimate the distance to the turbine’s central axis.

7. Seismic vibration measurements and procedures

7.1. Instrumentation site selection

Seismometer instrumentation shall be positioned with consideration given to the proposed wind farm layout and the future locations of wind turbines.

Key considerations for instrument placement include the following:

Distance to target proposed wind turbine – The optimum horizontal distance from the instrument to the central axis of the target wind turbine is between 100 m and 600 m. Closer distances within this range are preferred to improve the signal-to-noise ratio. (Appendix A – Instrument distance to nearest turbine)

Number of instruments – While seismic analysis can be performed using a single instrument, it is recommended that at least four seismometers be deployed. This provides redundancy and improves measurement reliability.

Instrument arrangement – Where layout permits, the arrangement of multiple instruments should support comparative analysis. A linear configuration, with one instrument positioned perpendicular (i.e. at 90°) to the main axis, can be beneficial for more detailed analysis. Further guidance on directional considerations for sensor placement is provided in Appendix B – Directional Dependence: Modelling and Historical Data. Appendix C (Minimum Number of Samples in the 12 m/s Bin) indicates that directional dependence is minimal and does not significantly affect measurement quality. However, where possible, preference may be given to downwind placement relative to the prevailing wind direction. An example configuration is shown in Figure 1 of Appendix C.

Position within wind farm – Seismometers shall be positioned to ensure that vibration signals are dominated by the target wind turbine. Placement between turbines, or in locations where multiple turbines contribute similar seismic levels, shall be avoided. Instrument placement near the edge of the wind farm should be used to isolate the target turbine's contribution.

Instrument foundation – A stable and well-coupled foundation is critical for accurate measurements. Installation shall follow manufacturer guidance. Additional considerations are detailed in Section 7.2.

Local noise considerations – Seismometers are highly sensitive to local environmental noise. Instrument placement shall avoid, or account for, potential vibration sources, including:

- Watercourses (e.g. rivers, streams, drainage)
- Ridges and summits

- Significant topographic depressions (e.g. deep gullies, ravines) located between the sensor and the target wind turbine
- Roads and vehicle tracks
- Buildings, structures, or met masts
- Local operations, (e.g. farming and forestry)
- Livestock or wildlife activity
- Isolated trees
- Forestry activity
- Fencing

Additional consideration shall be given to any off-grid power sources used to operate the sensors. For example, micro-wind turbines are not suitable due to vibration that they produce. Similarly, structures supporting solar panels may vibrate under wind loading and contribute to the measured seismic signal. Where off-grid systems are required, they shall be installed with care to consider and minimise vibration contribution to the seismic instrument.

Trnkoczy (2012) provides general recommendations on suitable separation distances from seismic noise sources.

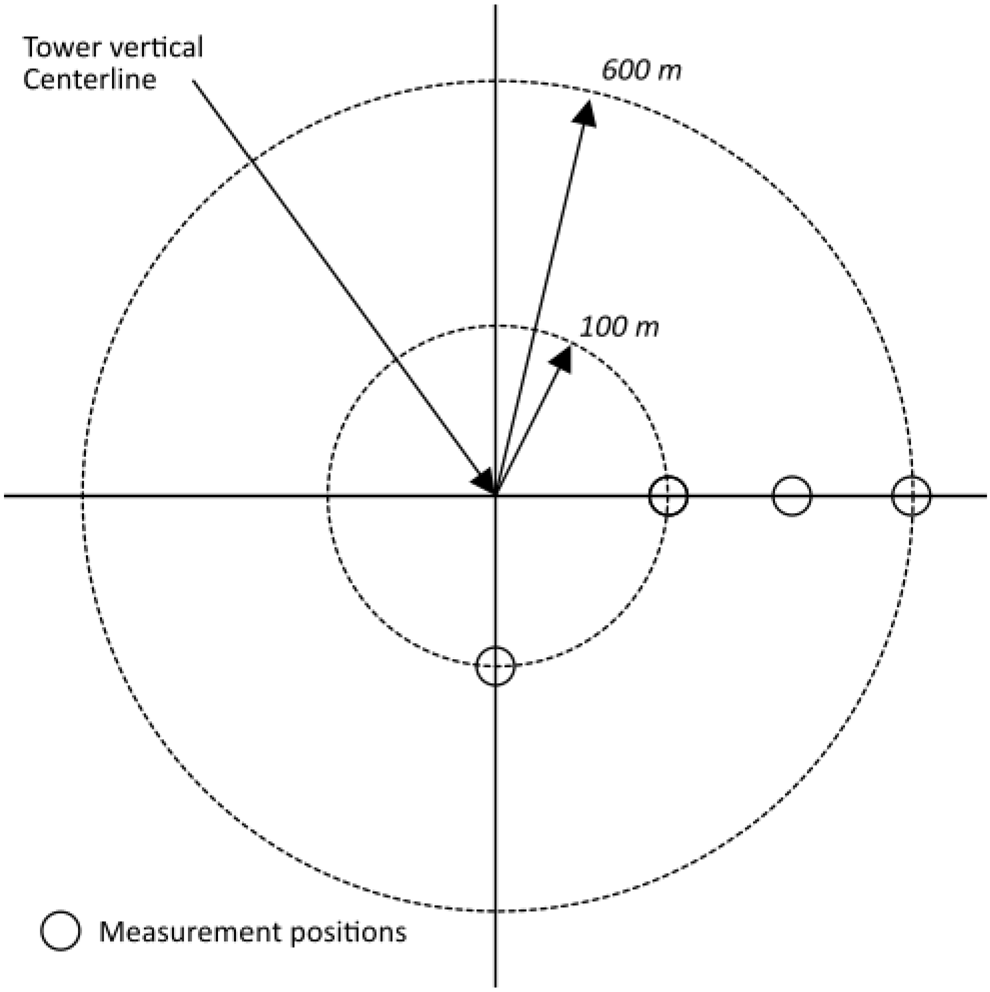

Figure 1 – Example sensor pattern for multiple instrument installation around target proposed wind turbine (plan view)

7.1.1. Influence of background seismic noise

Seismic vibration measurement locations shall be selected and prepared to minimise environmental noise thereby enhancing sensitivity to the target wind turbine. Contrary to common assumption, elevated background seismic noise does not obscure turbine-induced signals; rather, it is included in the final vibration assessment. The calculation method is conservative by design, incorporating background levels into the normalised vibration result. While this ensures the assessment errs on the side of caution, best practice remains to maximise the signal-to-noise ratio by minimising background noise wherever possible. This improves the fidelity of the results and enhances the ability to isolate turbine-related signals.

7.2. Instrument ground connection

Seismometers shall typically be buried in the ground to achieve adequate connectivity for recording seismic vibration. It is possible to achieve adequate seismic connectivity through direct burial of the sensor whereby a hole is dug the instrument placed inside and the hole backfilled. However, a seismic pit is recommended for a more reliable and accessible installation. This also allows access to the sensor if required. To prepare a seismic pit a shallow hole should be dug to a depth of around 70 cm or until bedrock or a solid surface is reached. The hole may then be lined. A foundation surface, typically of a marble, granite or concrete plinth shall then be prepared. The instrument shall then be placed with appropriate thermal insulation before the pit is covered. Depending on the ground conditions a drain may be required to prevent water ingress.

Seismometer installation shall avoid areas of peat, bog, or deep unconsolidated soil, as these substrates result in poor seismic coupling and elevated vibration amplitudes across the frequency range of interest, particularly at higher wind speeds.

7.3. Seismic measurements

7.3.1. General

The seismic measurements shall include the following data to be recorded:

- Vertical-axis ground vibration time series, sampled at an appropriate rate of samples per second (sps) to measure the frequency range of interest (e.g. 100Hz).
- Time series data sufficient for spectral analysis of vertical-axis vibration.

Recording of horizontal vibration components is optional but may be included to support further analysis or mitigation design.

The measurement campaign shall collect data for a minimum of 3 months and until a minimum of forty (40) 10-minute data bins have been gathered at a mean wind speed centred at 12 m/s, measured at the normalised hub height of 80 m (see Appendix C – Minimum number of samples in the 12 m/s bin). Additional data may be recorded to improve robustness and account for variability in operating conditions.

8. Non-seismic measurements

8.1. Wind speed measurement

Wind speed and direction shall be recorded during seismic vibration measurement. The method is not limited to a specific measurement technology; however, any limitations or uncertainties associated with the selected technique shall be identified and addressed during analysis.

Calculations of seismic contribution depend on wind speeds evaluated at a normalised height of 80 m above ground level. Therefore, the chosen measurement method shall also account for any height-related uncertainty or correction factors introduced by the instrumentation.

Acceptable wind measurement technologies include, but are not limited to:

- Light Detection and Ranging (LIDAR) – Remote sensing system using laser pulses to measure wind speed and direction at multiple heights.
- Sonic Detection and Ranging (SODAR) – Acoustic remote sensing system that uses sound waves to determine wind profiles. Typically deployed on the ground and sensitive to ambient noise conditions.
- Permanent site meteorological mast(s) – Fixed meteorological masts equipped with calibrated anemometers and wind vanes, positioned to capture long-term hub-height wind data.
- Temporary meteorological mast – Portable mast installations used for short-term measurements, typically during site development or campaign-based assessments.

Where multiple wind speed sources are available, the data may be combined and averaged using the method defined in Section **Error! Reference source not found.**.

Wind speed data shall be used to bin seismic measurements by wind speed at the normalised 80 m height. Binning shall be performed in 1 m/s intervals, centred on integer wind speeds (e.g. 11.5–12.5 m/s for the 12 m/s bin). A minimum of forty (40) 10-minute measurements at a wind speed of 12 m/s are required over a period of at least 3 months.

8.1.1. Wind measurement position

Where mobile or temporary wind measurement systems are deployed, there is no fixed requirement for measurement location; however, the following considerations shall be taken into account:

- The measurement system shall be located within or in close proximity to the wind farm or the target wind turbine.

- To minimise uncertainty, the measurement position shall be as close as reasonably practicable to the target wind turbine whilst avoiding local and wake effects.
- The prevailing wind direction shall be considered to avoid placing the measurement system in turbine wakes.
- Locations influenced by local topography, vegetation, or structures (e.g. trees, buildings) shall be avoided.
- Where temporary measurement is intended to support both background and operational phase assessments, the measurement method and position shall remain consistent. Planning of background measurements shall account for the final turbine layout to minimise the risk of wake effects during future operational phase measurements.

To support accurate comparison between background and operational seismic measurements, it is strongly recommended that the same wind measurement method and position be used across both phases. Where a change in measurement system is unavoidable, the potential impact on wind speed characterisation shall be assessed. If practicable, an overlap period using both systems should be conducted to evaluate any bias or offset.

8.2. Positional data

Accurate positional data shall be recorded for all relevant components and features of the wind farm. This includes, but is not limited to:

- Proposed wind turbines
- Seismic measurement locations
- Anemometers and meteorological masts

GNSS technologies such as GPS, Galileo, BeiDou, GLONASS may be used to obtain positional data, provided the system achieves a horizontal positional accuracy of ≤2 metres under field conditions.

Measured distances between key features shall be recorded to support data traceability, future re-measurements, and seismic contribution analysis. In particular, the horizontal distance from each seismic instrument to the nearest proposed wind turbine(s) shall be calculated and documented.

In areas with steep or complex terrain, consideration should be given to the true three-dimensional (vector) distance, as elevation differences may introduce a significant deviation from horizontal measurements.

8.3. Supporting measurement data

Additional measurements may support more detailed analysis, improve understanding of vibration sources, and inform the development of mitigation strategies. Such measurements may be used to characterise seasonal wind effects, directional influences due to rotor orientation, or vibration transmission at the source (i.e. the wind turbine structure itself).

8.3.1. Wind direction

Many wind speed measurement systems also record wind direction. Wind direction may be recorded in 10-minute average bins, aligned with wind speed and seismic data.

Where directional analysis is required, the number of wind speed bins within each direction bin shall be considered to ensure statistical robustness. In such cases, the overall measurement duration may need to be extended to obtain sufficient data across wind directions.

8.4. Measurement instrumentation requirements overview

Table 2 - Measurement instrumentation requirement overview

Measurement Item	Required	Purpose	Typical Source / Logging Method
Vertical-axis ground vibration	Yes	Primary seismic data	Seismometer (appropriate sps sampling rate e.g. 100Hz)
Wind speed (10 min averages)	Yes	Wind binning, normalised to 80 m	LIDAR, met mast
Instrument location (GPS)	Yes	Traceability and distance calculations	GPS or GNSS logger
Proposed Turbine location	Yes	Source identification and distance calculations	Site layout plan or GPS
Distance to nearest proposed turbine(s)	Yes	Input to normalisation and comparative analysis	Calculated from positional data
Wind direction (10 min averages)	Optional	Directional binning, wake effects analysis	LIDAR, met mast
Anemometer/mast location	Optional	Support traceability and wind normalisation	GPS or site records

9. Weather considerations

Seismic vibration measurement is generally unaffected by weather conditions other than wind. Parameters such as rain, precipitation, temperature, and humidity are not expected to materially influence measurement results and can typically be excluded from consideration, except where they affect practical aspects of field deployment.

Where used, adequate drainage of seismic measurement pits should be ensured to prevent instrument immersion or long-term water ingress.

Extreme weather conditions, such as heavy snow or ground-freezing temperatures, may have some influence on measurement quality. While empirical evidence is limited, frozen ground has been observed to provide improved coupling in comparison to saturated or boggy soils. The potential influence of ground condition changes on seismic coupling should be considered during deployment and analysis, particularly in cold climates.

10. Data processing and analysis

This section details how a baseline seismic spectrum (PSD) for the proposed wind farm location is derived from data collected during the seismic survey. The requirements for post-processing are:

- Seismic data collected in accordance with the methodology described in this document.
- Wind speed data covering the entire survey period.
- Grid references of the positions of all proposed wind turbines.
- Grid references of all instruments.

All data must be processed using standard units. A validated computational tool or programming environment (e.g., MATLAB, Python) shall be employed for performing numerical analysis and data processing in accordance with the applicable technical requirements.

10.1. Seismic data conversion to frequency domain

This section details how time series data shall be converted to power spectral density (PSD) in the frequency domain.

1. The vertical motion of the seismometer shall be calibrated using traceable reference standards and validated computational tools.
2. Any linear trends and or instrument response present in time series data shall be identified and removed prior to analysis to ensure the validity of subsequent interpretations and results.
3. Time series velocity measurements shall be divided into individual samples, 10-minutes in length. The time window of each sample shall correspond temporally with 10-minute average wind speed (see section 10.2). The dataset must contain at least forty (40) 10-minute samples with an average wind speed between 11.5 and 12.5 m/s at a reference height of 80 m above ground level (i.e., the 12 m/s wind speed bin) collected over a period of at least 3 months. (Appendix C – Minimum number of samples in the 12 m/s bin).
4. Each 10-minute sample of time series velocity data shall be converted to a Power Spectral Density (PSD) estimate using a spectral analysis method suitable for reducing variance and minimising spectral leakage. Welch's method is a well-established approach and may be used as follows: divide the data into multiple overlapping segments (e.g., 28 segments with 50% overlap), apply a Hann window to each segment, and average the resulting periodograms to produce a stable PSD estimate. The key objective is to improve the accuracy and consistency of the frequency-domain representation, particularly in the 0.5–8 Hz range of interest. The output shall be equal-length vectors of frequency (Hz) and velocity PSD ($(m/s)^2$/Hz).

Alternative approaches may be employed if they achieve equivalent or better resolution and stability.

5. The velocity PSD shall be converted to displacement PSD by dividing each spectral component by $(2\pi f)^2$, where f is the frequency in hertz, to obtain an accurate frequency-domain representation of displacement.

After completing these steps, a set of displacement PSD functions and their corresponding frequency vectors shall be obtained. The number of PSD and frequency datasets must match the number of 10-minute time series segments processed. This ensures consistency in the spectral analysis and allows for accurate comparison and statistical evaluation across all segments.

10.2. Derivation of wind speed

The average wind speed shall be calculated over the same 10-minute intervals used for the computation of the displacement PSD functions. Wind speed measurements shall be referenced to a height of 80 meters above ground level to ensure consistency with the seismic response data. This temporal and spatial alignment is essential for accurate correlation between loading and seismic response. Acceptable sources of wind speed data are provided in section 8.1.

Wind speed data obtained from LIDAR, SODAR, anemometers (or a combination of all) shall be processed using source-specific methodologies, as follows:

10.2.1. LIDAR and SODAR

Data shall be filtered for quality using signal-to-noise ratio thresholds and range gate consistency checks. Measurements shall be averaged over the vertical range centred at 80 m with appropriate weighting to account for beam geometry.

10.2.2. Anemometer

Raw data shall be quality-controlled for instrument malfunction, spikes, and flatlining. Averages shall be computed directly from 1 Hz or higher sampling rates. If the anemometer is located at a height other than 80 m, wind speeds shall be adjusted to the reference height using the logarithmic wind profile law.

$$v_{ref} = v_{measured} * \frac{ln\left({}^{Z_{ref}}/_{Z_r}\right)}{ln\left({}^{Z_{measured}}/_{Z_r}\right)} \tag{1}$$

v_{ref} in equation (1) is the wind speed at the 80m reference height, $v_{measured}$ is the wind speed measured anemometer, Z measured is the height of the anemometer above ground level and z_r is the surface roughness length. An appropriate surface roughness length shall be used if known. If not known, a default roughness length of 0.05 m shall be assumed in accordance with good practice guidance provided in ETSU-R-97.

10.3. Binning of seismic data by wind speed

Following the computation of average wind speeds and displacement PSD functions over 10-minute intervals, the resulting PSDs shall be grouped into wind speed bins for statistical analysis. Binning shall be performed using wind speed intervals of 1 m/s width, with bins centred on integer values (e.g., 11.5 m/s to 12.5 m/s centred at 12 m/s). Each PSD shall be assigned to the corresponding bin based on its associated 10-minute average wind speed. This binning procedure facilitates the aggregation and comparison of spectral response characteristics as a function of wind speed, enabling robust trend analysis and uncertainty assessment.

10.4. Inspection of background seismic spectrum

For each wind speed bin, the normalised displacement PSD functions shall be aggregated, and the interquartile mean shall be computed at each frequency. The interquartile mean is defined as the arithmetic mean of the PSD values falling within the 25th to 75th percentile range at each frequency point, thereby excluding the lowest and highest quartiles. This statistical approach reduces the influence of outliers and provides a robust estimate of the typical spectral response within each wind speed bin. The seismic signature shall be defined as the interquartile mean of the displacement PSDs within the 12 m/s wind speed bin. Given that a minimum of four instruments should be used, the seismic signature shall be selected from the instrument exhibiting the lowest noise floor within that bin to ensure optimal signal fidelity. As a best practice, the interquartile mean PSD for each wind speed bin may be plotted as a function of frequency on a single graph to facilitate visual comparison of seismic response across wind speeds.

11. Limitations

- Geological Variability: Results obtained from seismic surveys are highly sensitive to local subsurface conditions.
- Distance Assumptions: The seismic signature defined at a reference distance of 1 km assumes uniform propagation characteristics that may not hold at shorter or significantly longer ranges, particularly in the presence of topographical or structural variations.
- Frequency Range Resolution: Power spectral density (PSD) analyses are limited by the resolution and dynamic range of the instruments and processing methods.
- Instrumental and Environmental Noise: External noise sources, including anthropogenic and environmental factors, may influence time series data and should be appropriately accounted for or filtered during analysis.
- Normalisation Accuracy: The process of normalising seismic data from outside the consultation zone relies on the accuracy of geological models and assumed transfer functions, which may introduce uncertainty if input parameters are not well constrained.

12. Summary of normative requirements

This section summarises all normative ('shall') requirements from the document. These mandatory actions ensure consistency, traceability, and technical rigour in measuring and analysing seismic emissions from wind turbines within the ECZ. Each item is listed with its source section for easy reference.

Table 3 – Normative requirements required to perform baseline seismic vibration measurement and analysis.

Section(s)	Requirement
5, 6, 7	Seismic measurements shall be carried out using seismometers positioned with respect to the proposed turbine location, ensuring strong ground coupling and installed per Section 7 and manufacturer guidance.
5, 6, 8	Simultaneous wind speed data shall be recorded during the measurement period using LIDAR, met masts, or equivalent; normalised to 80 m height; binned in 10-minute intervals.
5, 7	Baseline campaigns shall run for a minimum of 3 months and collect at least 40 10-minute data bins centred at 12 m/s.
5, 6, 8	All relevant positional and metadata shall be recorded using GNSS with ≤2 m horizontal accuracy. Coordinates of instruments, turbines, and masts shall be documented.
6, 10	Seismometers shall record vertical-axis vibration at a sample rate suitable to detect the frequency range 0.5 – 8Hz with time reference accurate to ±1 s, and be synchronised via GPS, radio clock, or traceable source.
6	Seismic vibration instruments shall meet or exceed the specifications in Table 1.
6, 7	Instrument foundations shall be stable, insulated from thermal/draft interference, and constructed using appropriate plinth materials. Peat or soft soils shall be avoided.
6	Wind speed instrumentation shall have calibration deviation ≤±0.2 m/s (4–16 m/s range) and shall log time-synchronised 10-minute averages.
6, 8	Laser or optical range-finding may be used to enhance distance accuracy. Horizontal distances to turbines shall be calculated.
7	Seismometers shall be placed to isolate signal from target turbine, preferably near the farm edge, and avoid environmental noise sources and wake zones.
7	Off-grid power sources (e.g., solar) shall be installed with care to minimise vibration.
7.3	Seismic datasets shall include 10-minute vertical-axis time series recordings sampled at ≥100 Hz.
8	Wind speed and direction shall be recorded; method limitations shall be identified and addressed.
8	Wind speed binning shall use 1 m/s intervals centred on integers.
8	Consistency in wind measurement method and location across background and operational phases is strongly recommended; changes shall be assessed.
10	All data must be processed using SI units with validated tools (e.g., MATLAB, Python).
10	Seismometer output shall be calibrated using traceable standards.
10	Time-series data shall have linear trends and instrument response removed.
10	Data shall be segmented into 10-minute samples, matched to wind speed bins, using Welch’s method (28 segments, 50% overlap, Hann window).
10	Velocity PSD shall be converted to displacement PSD.
10	Anemometer data at non-80 m heights shall be corrected using the logarithmic profile law; default roughness length of 0.05 m shall be used if unknown.
10	Seismic signature shall be based on interquartile mean of displacement PSDs at 12 m/s bin, from the sensor with the lowest noise floor.

13. References

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14. Appendix A – Instrument distance to nearest turbine

14.1. Purpose and summary

This appendix presents analysis to determine, from historical seismic measurement data, the maximum distance between an instrument and the nearest turbine while maintaining an acceptable (10 dB) signal-to-background noise ratio.

Historical measured seismic data at a 12 m/s wind speed was used for analysis from Crossdykes Wind Farm. Different normalisation distances of instrument to a single turbine were used ranging from 100 m to 1000 m and were assessed based on the frequency-distance weighting function assuming a worst-case 10 km range from the EKA.

Two different frequency ranges were used to calculate the signal-to-background noise ratios at each distance: 1.5 to 8 Hz and 2 to 8 Hz. Results of maximum instrument distances from the nearest turbine to achieve a signal-to-noise ratio of 10 dB were found to be 602 m and 628 m for frequency ranges of 1.5 to 8 Hz and 2 to 8 Hz, respectively.

A recommended maximum instrument-to-turbine distance is therefore 600 m.

14.2. Brief

Analysis is required to determine the maximum distance between an instrument and the nearest turbine, while maintaining an acceptable (10 dB) signal-to-background noise ratio. This result can advise the upper limit of instrument distance from the nearest turbine when positioning an instrument for seismic measurements in a wind farm.

14.3. Method

14.3.1. Dataset selection

Five background seismic noise measurement campaigns have been conducted previously by Xi. From these, only Crossdykes data was suitable for analysis.

14.3.2. Data analysis

Crossdykes seismic data was taken from the instrument "S1" (the same location was used for background and operational measurement campaigns).

Seismic data binned at 12 m/s was normalised to a single turbine at distances ranging from 100 m to 1000 m in 100 m increments. Signal-to-noise ratio (SNR) was calculated for each distance by integrating the background and operational PSDs and taking the ratio in dB.

In seismic signal processing, 10 dB commonly adopted as an acceptable SNR threshold and was therefore used in this analysis.

Background and operational data were weighted using the frequency-distance weighting function, assuming a worst-case propagation distance of 10 km from the Eskdalemuir Array. Integration of background and operational data was done using two different frequency ranges:

- 1.5 to 8 Hz (the point where background and operational PSD spectra start to diverge to the end of the region of interest for Eskdalemuir seismic analysis)
- 2 to 8 Hz (a point where background and operational PSD spectra have already diverged to the end of the region of interest for Eskdalemuir seismic analysis)

Plots were then generated comparing SNR dB against normalised distance. A best-fit line was applied to determine the distance at which a SNR of 10 dB is achieved.

14.4. Results

Figure 2 shows the normalised displacement PSDs for a wind speed of 12 m/s recorded at Crossdykes with different normalisation distances and compares these to the background noise. The frequency-distance weighting was based on a worst-case distance of 10 km from the Eskdalemuir Array:

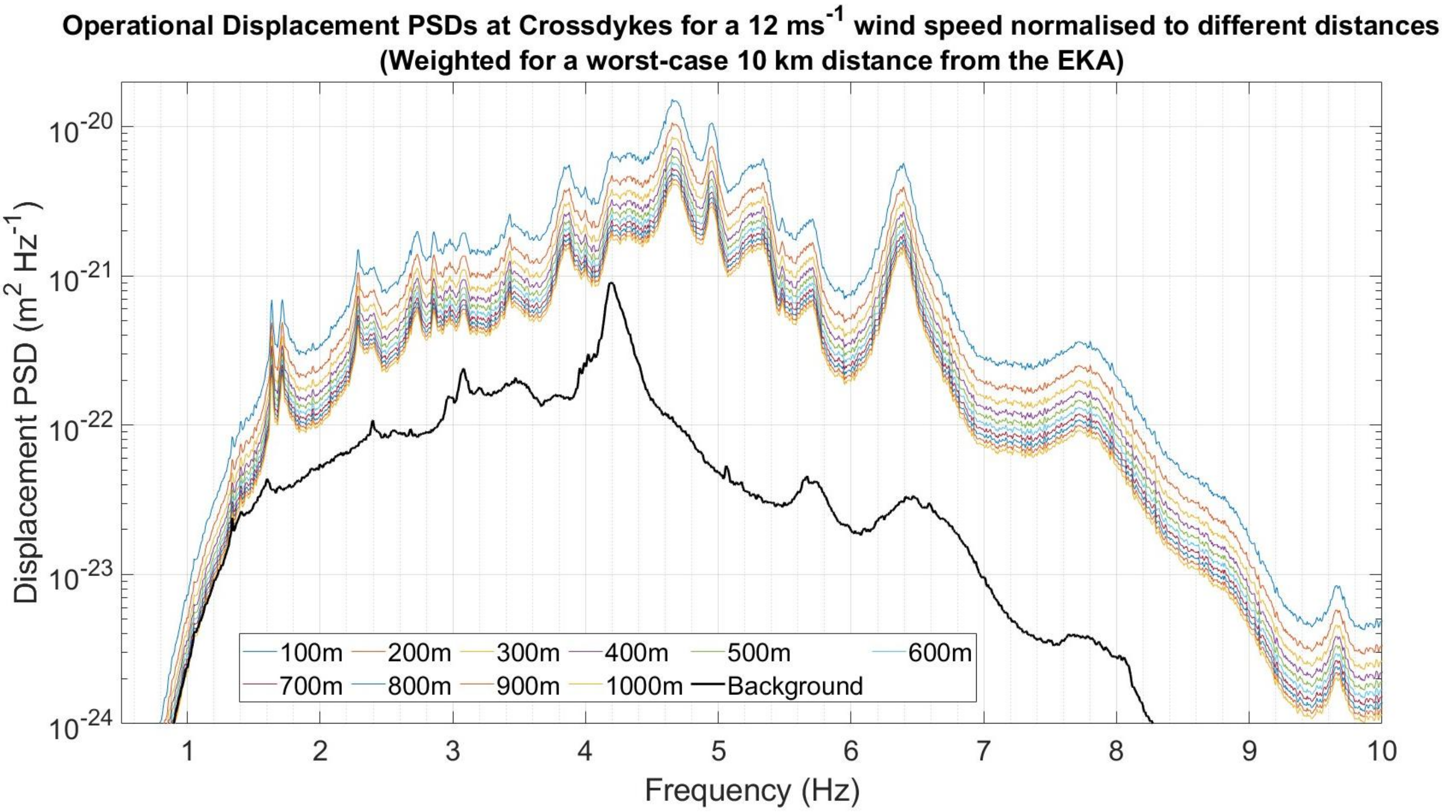

Figure 2 – Displacement PSDs normalised to different distances at Crossdykes for a wind speed of 12 m/s compared to background noise. Frequency-distance weighting function was applied using a worst-case 10 km range from the Eskdalemuir Array.

Figure 3 and Figure 4 show the signal-to-noise ratios in dB versus normalisation distance for the two different frequency ranges (1.5 to 8 Hz and 2 to 8 Hz), respectively:

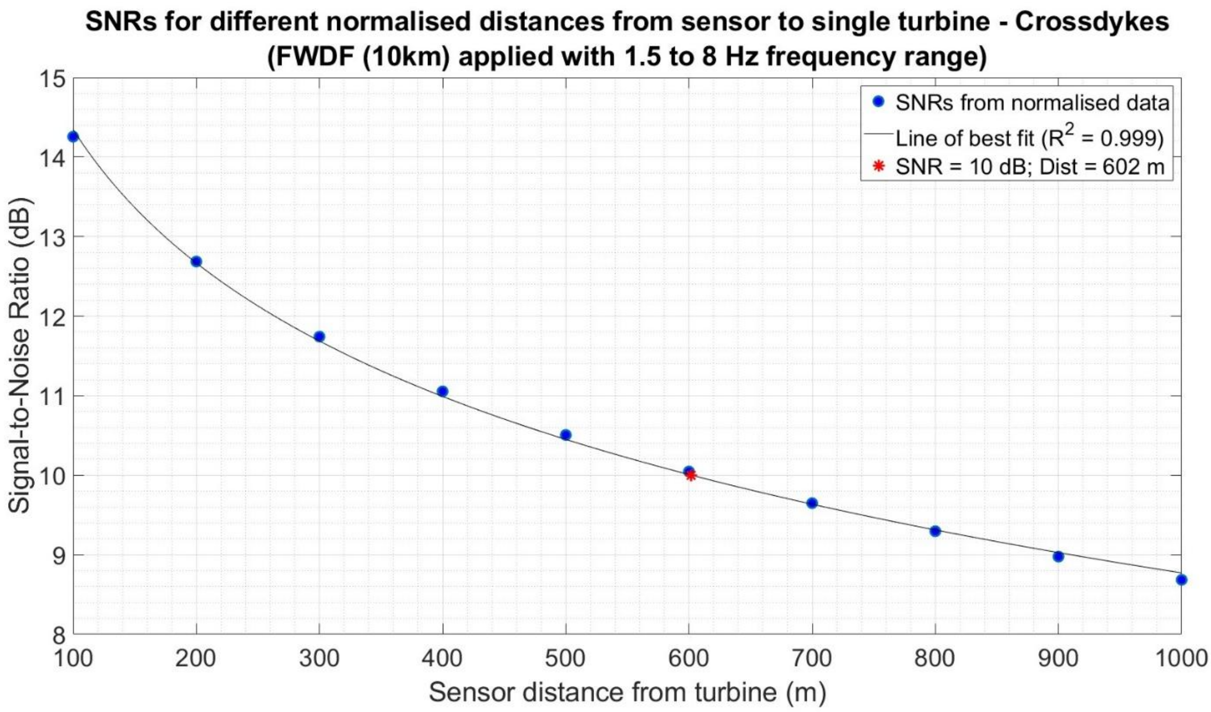

Figure 3 – SNR for different normalisation distances using the frequency range 1.5 to 8 Hz.

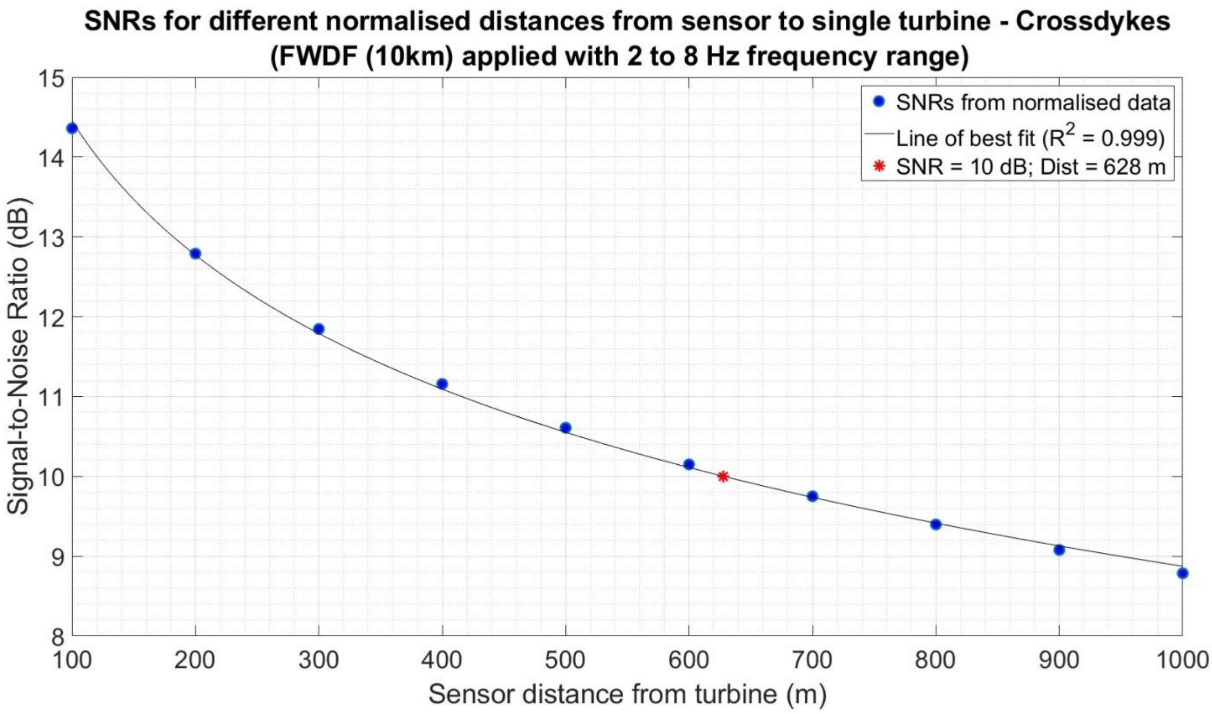

Figure 4 – SNR for different normalisation distances using the frequency range 2 to 8 Hz.

14.5. Discussion and conclusion

The only usable dataset from historical seismic measurements was from Crossdykes as this was the only measurement campaign to have sufficiently high-quality background and operational seismic vibration data.

Different instrument-to-turbine normalisation distances were used ranging from 100 m to 1000 m at a wind speed of 12 m/s.

Data were weighted based on the frequency-distance weighting function using a worst-case 10 km range from the Eskdalemuir Array.

Two different frequency ranges were used to calculate the signal-to-background noise ratios at each distance: 1.5 to 8 Hz and 2 to 8 Hz.

Results of maximum instrument distances from the nearest turbine to achieve a signal-to-noise ratio of 10 dB were found to be 602 m and 628 m for frequency ranges of 1.5 to 8 Hz and 2 to 8 Hz, respectively.

Subject to local noise conditions, a guideline instrument-to-turbine distance in the range of 100 m to 600 m is recommended.

15. Appendix B – Directional dependence: modelling and historical data

15.1. Purpose and summary

The purpose of this Appendix is to present an investigation into the potential impact of directional effects on seismic activity caused by wind turbines, and the implications for instrument placement during field measurement campaigns.

A finite element model of a wind turbine foundation and surrounding ground was produced. The model took the results of an aeroelastic model as its input.

Qualitatively, the modelling has shown a small amount of directivity in the overall displacement amplitude between 0.5 and 8 Hz.

Historical measured data was also used to investigate the effect of wind direction on resultant seismic amplitudes recorded by instruments.

Modelled results suggest that the highest seismic amplitudes are upwind from wind turbines, whilst the measured results suggest that the highest seismic amplitudes are downwind from wind turbines. However, the variation in seismic amplitude as a function of angular position is not significant. Furthermore, wind direction typically varies significantly over the course of a measurement campaign, and ground-based instruments will therefore experience a wide range of turbine-relative angles, tending to average out directional effects. Given this averaging effect and the relatively small difference in seismic amplitude with respect to direction, the angular position of instrument placement has a negligible effect on the assessment of wind turbine seismic amplitude.

15.2. Brief

It is expected that the vibration levels at discrete frequencies produced by a wind turbine will vary as a function of azimuthal angle, even when the distance from the turbine remains constant.

The reason that this is important is that if significant directivity were observed, it would be possible to place a seismic instrument at an angle relative to the prevailing wind direction that would capture higher or lower vibration amplitudes for most of the measurement campaign.

A finite element model of a wind turbine foundation and surrounding ground has been produced, with 'instruments' positioned at varying angles and distances around the turbine to simulate vibration amplitude as a function of direction. The finite element model takes as its input the results of an aeroelastic model of a wind turbine.

The results of this model are then compared to real measured historical data captured by Xi Engineering Consultants.

15.3. Method

15.3.1. Input – aeroelastic model

An aeroelastic model was produced, which gave the forces and moments of a generic wind turbine on its foundation, at a wind speed of 12 m/s and moderate turbulence intensity.

15.3.2. Finite element model

A three-dimensional finite element was produced in COMSOL Multiphysics.

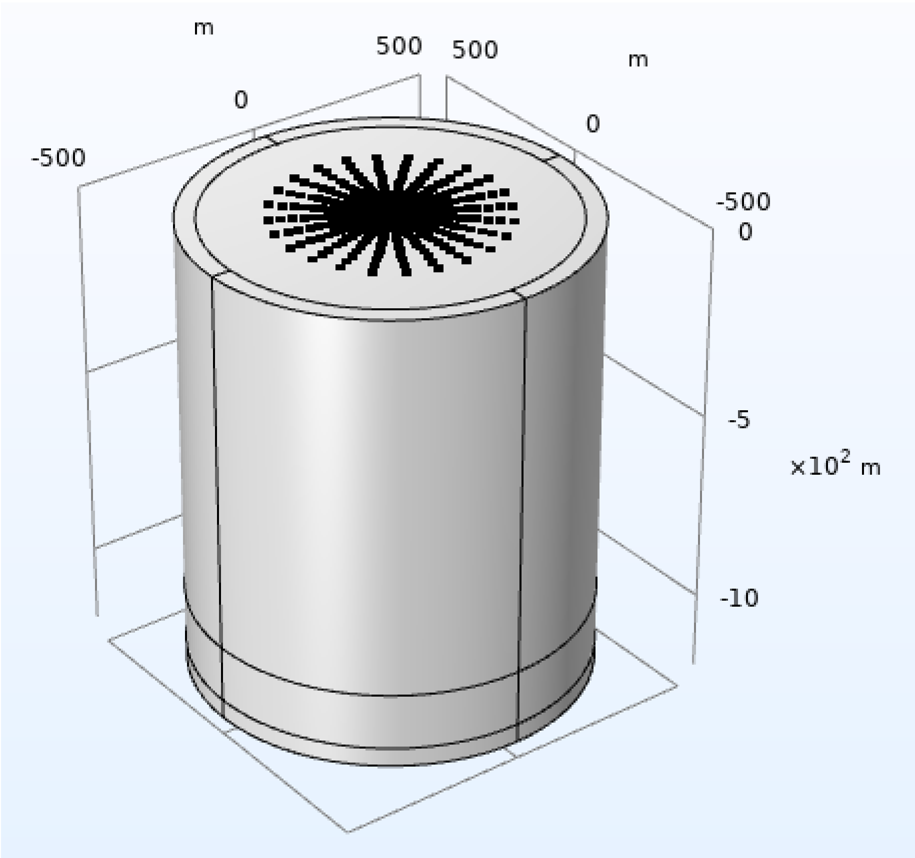

Figure 5 – Overview of model

As input, the finite element model took forces and moments from the aeroelastic model. These forces and moments were applied to a circular area representing where the wind turbine connects to the foundation (see blue circle in Figure 6). The foundation is represented by a 15 m square by 4 m deep block buried within the ground geometry. This is a simplified representation of a wind turbine's foundation, as actual foundation geometries vary.

A total of 700 'instruments' were placed in concentric circles at angles from the x direction in steps of 15°. The distances ranged from 13 m to 285 m.

The positive x direction (i.e. angle = 0°) is downwind and so 180° is upwind.

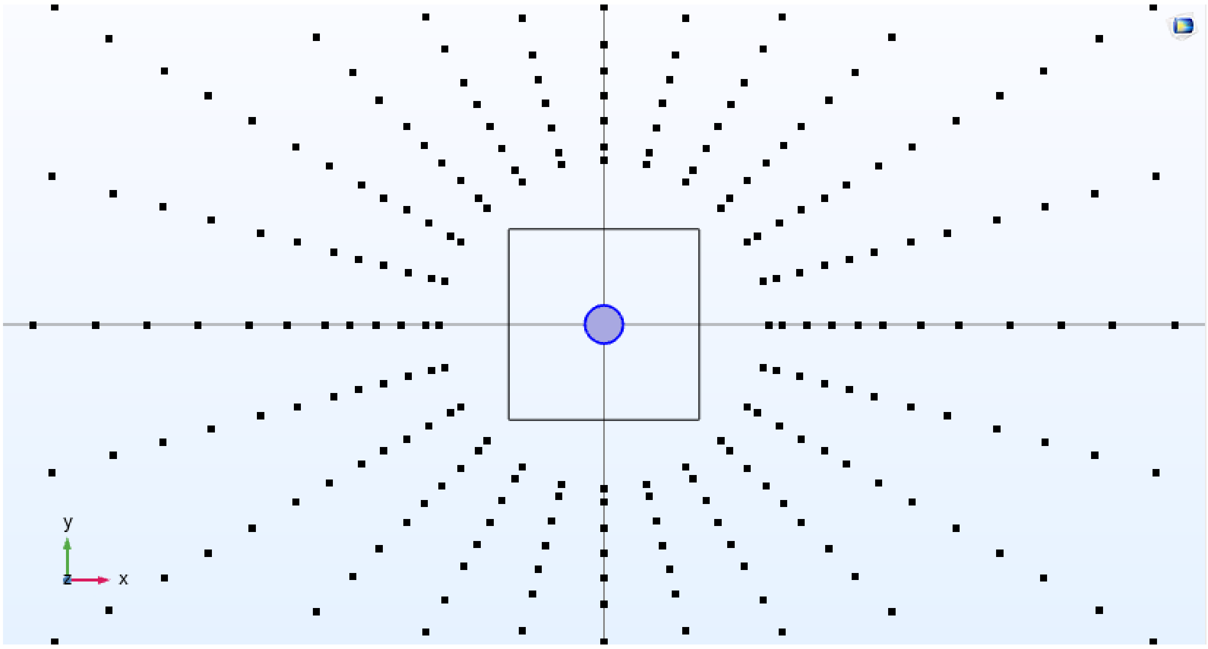

Figure 6 – Close up of xy plane of the model. Turbine base represented by blue circle. The square block is the foundation. The black dots in concentric circles represent the instruments

The model's total depth was 1200 m. A 50 m perfectly matched layer surrounds the model to prevent seismic waves from reflecting at the model boundaries and interfering with instrument readings. The first layer of ground was given different material properties to the second, which is 100m deep and begins at 1050 m below the ground, to represent the geology of the Eskdalemuir region.

The model was meshed so that there would be at least 5 mesh vertices per wavelength, up to the maximum frequency of interest, which was set as 10 Hz.

15.3.3. Output of finite element model

The output of the finite element model was a time-domain series of acceleration values from 0 seconds to 60 seconds, in steps of 0.01 seconds (total 6,001 samples), for each instrument and each direction (x, y and z).

15.3.4. Model post-processing

The time series acceleration data was subject to post-processing in MATLAB. The acceleration Power Spectral Density (PSD) estimate was calculated using Welch's method with MATLAB function ***pwelch***, using default settings (8 segments, 50% overlap).

[acceleration_psd, frequency] = pwelch(acceleration, [],[],[], sampling_frequency);

The acceleration PSD was converted to displacement PSD by division by $(2\pi f)^4$.

The result was a displacement PSD at each instrument.

15.3.5. Historical data processing and analysis

Data availability for directionality studies using historical measured seismic data was limited due to the typical length of measurement campaigns (1 – 3 months) as well as the prevailing wind direction in Scotland (south-westerly) restricting the variety of wind angles available for analysis.

From measurement campaigns conducted by Xi, three were identified as suitable for analysing directionality. Details are shown in Table 4:

Table 4 – Wind farm details for historical seismic data used for directionality analysis

Wind Farm	Date Start and End	OEM (Model)	Number of WTGs	Chosen Instrument	Directions Analysed
Glenkerie (Xi Engineering Consultants, 2023)	16/06/2021 - 07/10/2021	Vestas (V80)	11	SL3	Upwind-Downwind-Crosswind
Langhope Rig (Xi Engineering Consultants, 2023)	18/08/2021 - 21/10/2021	GE (GE1.6)	10	SL3	Downwind-Crosswind
Solwaybank (Xi Engineering Consultants, 2023)	11/05/2021 - 14/07/2021	Vestas (V100)	15	SL1	Upwind-Downwind-Crosswind

Seismic data was binned by wind speed (in 1 ms^{-1} increments) and wind direction (in the four cardinal directions) before the median of each binned dataset (per frequency) was then taken to give a single displacement PSD for each wind speed/wind direction. The PSDs were then weighted using the frequency-distance weighting function (FDWF) assuming a worst-case 10 km range from the Eskdalemuir Array. The frequency distance weighting function prescribes the attenuation of seismic noise from a noise source, over distance, relative to a reference distance of 1 km, including geometric spreading. Finally, the overall seismic amplitudes were calculated (by integrating the displacement PSD between 0.5 and 8.0 Hz) and compared for upwind, downwind, and crosswind directions.

15.4. Modelling results

The results presented here are for:

- Vertical (z-direction) displacement
- At a wind speed of 12 m/s
- At moderate turbulence intensity
- For a generic wind turbine

Figure 7 shows the Displacement PSD at various angles but at the same distance – 100 m. It is expected that this distance is great enough that any near-field effects are negligible. There is significant variation between different angles and the variation is different over the frequency spectrum.

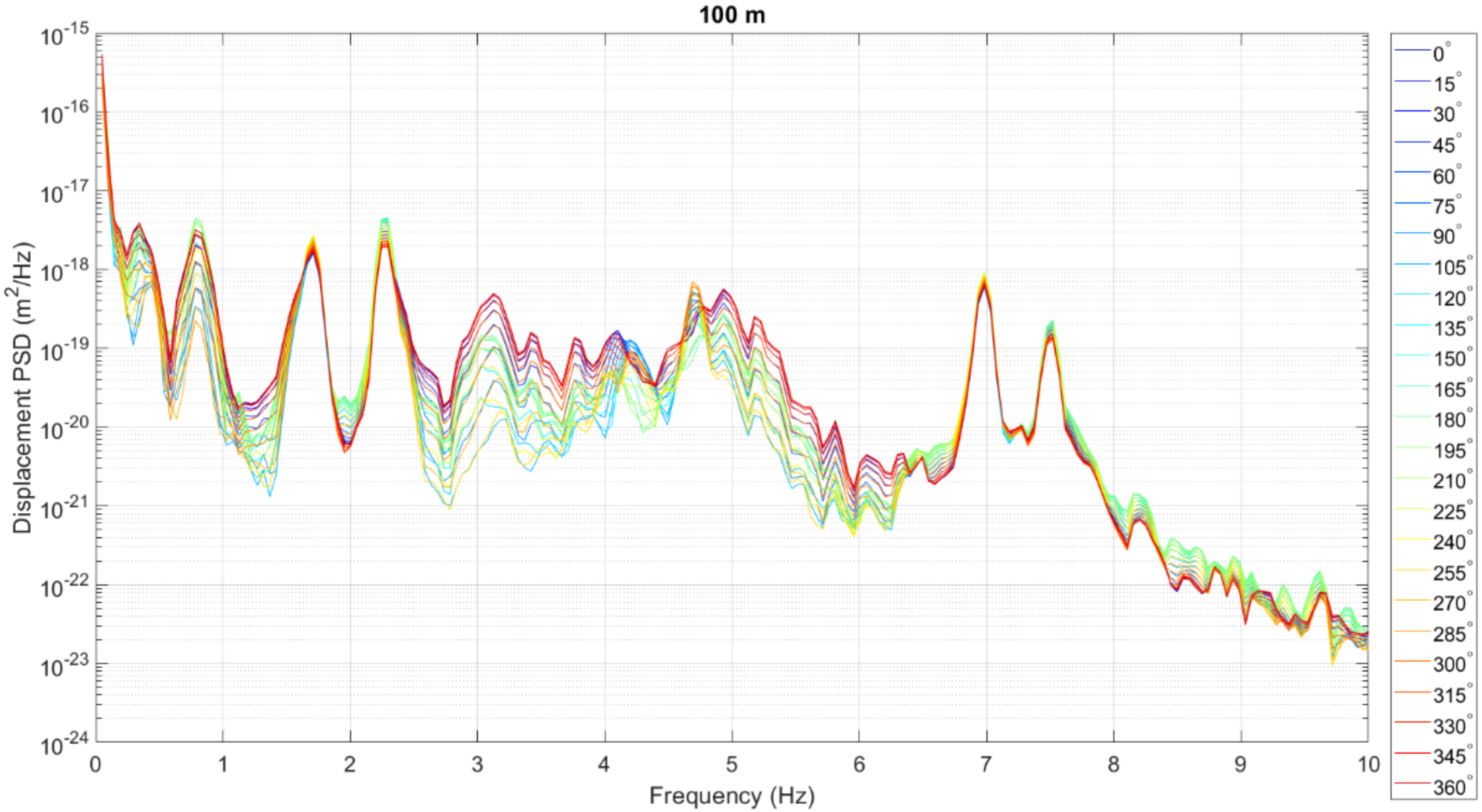

Figure 7 – Displacement PSD for instruments at 100m from the wind turbine, at all angles which were modelled

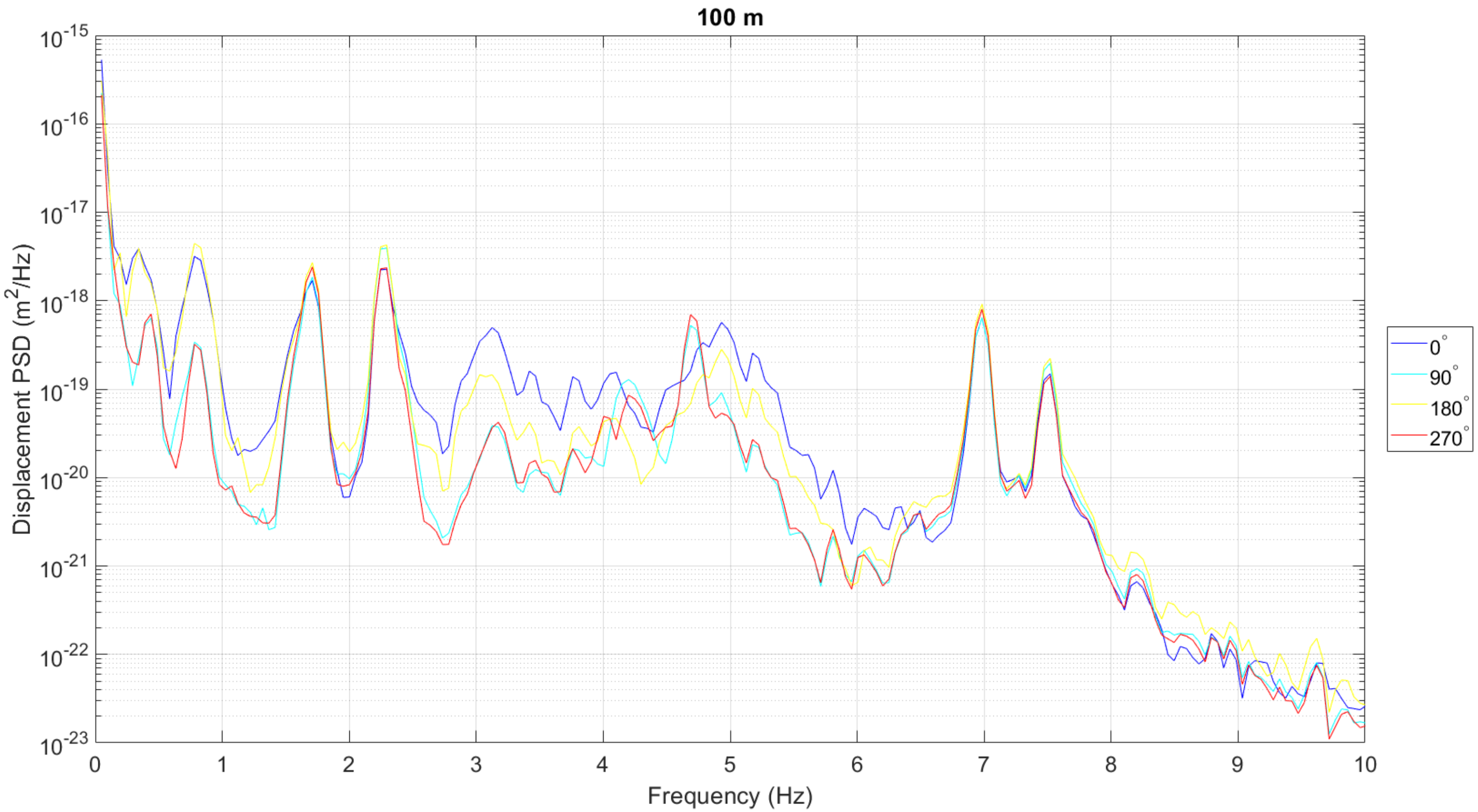

Figure 8 – Displacement PSD for instruments at 100m from the wind turbine, at different selected angles

The difference between the Displacement PSD at the angle with the highest level and the lowest, in decibels, is shown in Figure 9, for all instrument distances that were tested. The difference decreases with increasing distance from the wind turbine, i.e. less directivity is observed at greater distances.

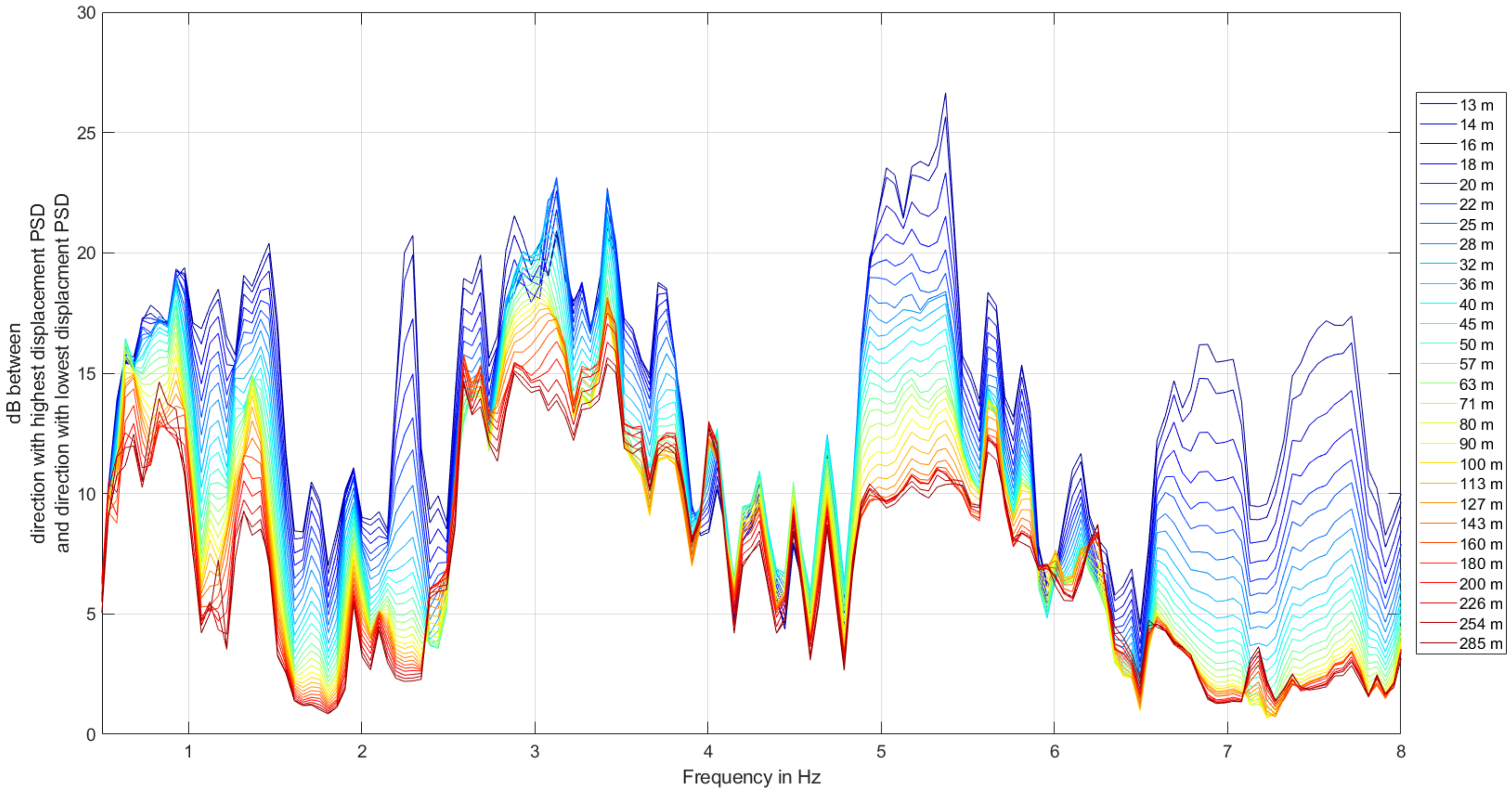

Figure 9 – Difference in Decibels between the Displacement PSD at the angle with the highest level and lowest, for each distance from the wind turbine

It has been shown that there is significant variation in Displacement PSD with angle when considering discrete frequencies. The overall displacement amplitude between the frequencies of interest for the Eskdalemuir Array (0.5 – 8 Hz) has been integrated for each instrument angle and distance. The overall displacement amplitude for distances from 13 m to 57 m at each angle are presented in Figure 10 in a polar plot. The direction with the highest amplitude is 180° (upwind), for all of these distances. Overall, there is a distinctive directivity, which is diminishes (i.e. more circular and less eccentric) as the distance to the instrument increases.

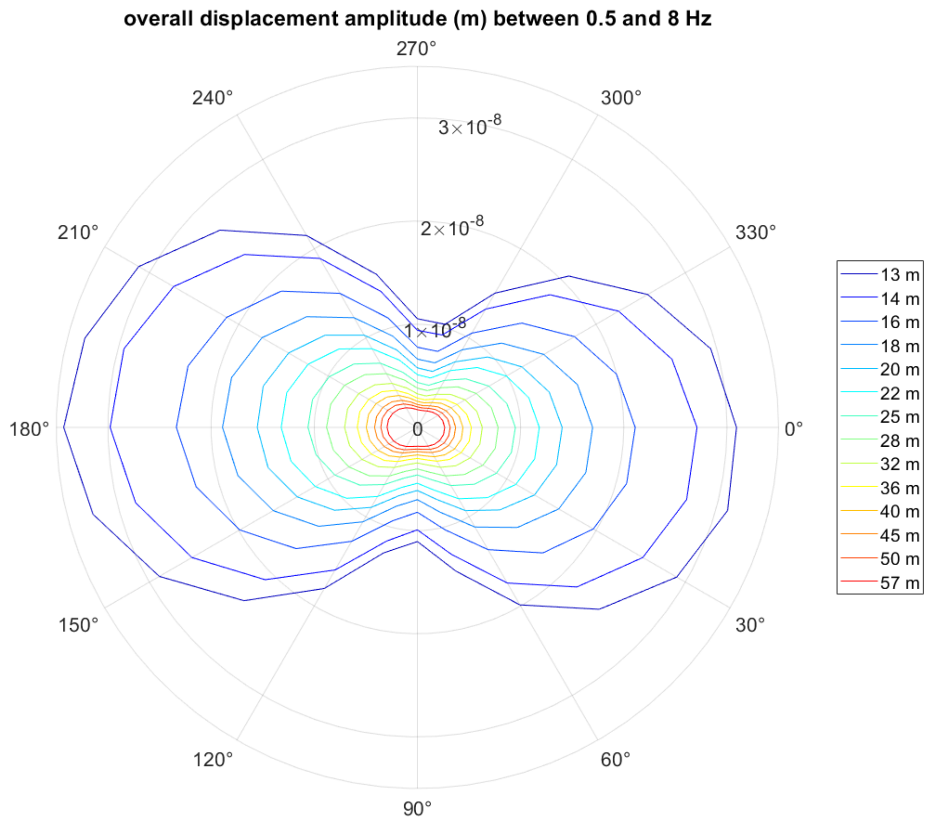

Figure 10 – Directional variation of overall amplitude sum (between 0.5 and 8 Hz) between 13 m and 57 m away from the wind turbine

The overall displacement amplitude for distances from 63 m to 285 m at each angle are presented in Figure 11 in a polar plot. At these greater distances from the wind turbine, the directivity is less pronounced. 180° (upwind) produces slightly higher displacement amplitudes than at other angles for all of these distances.

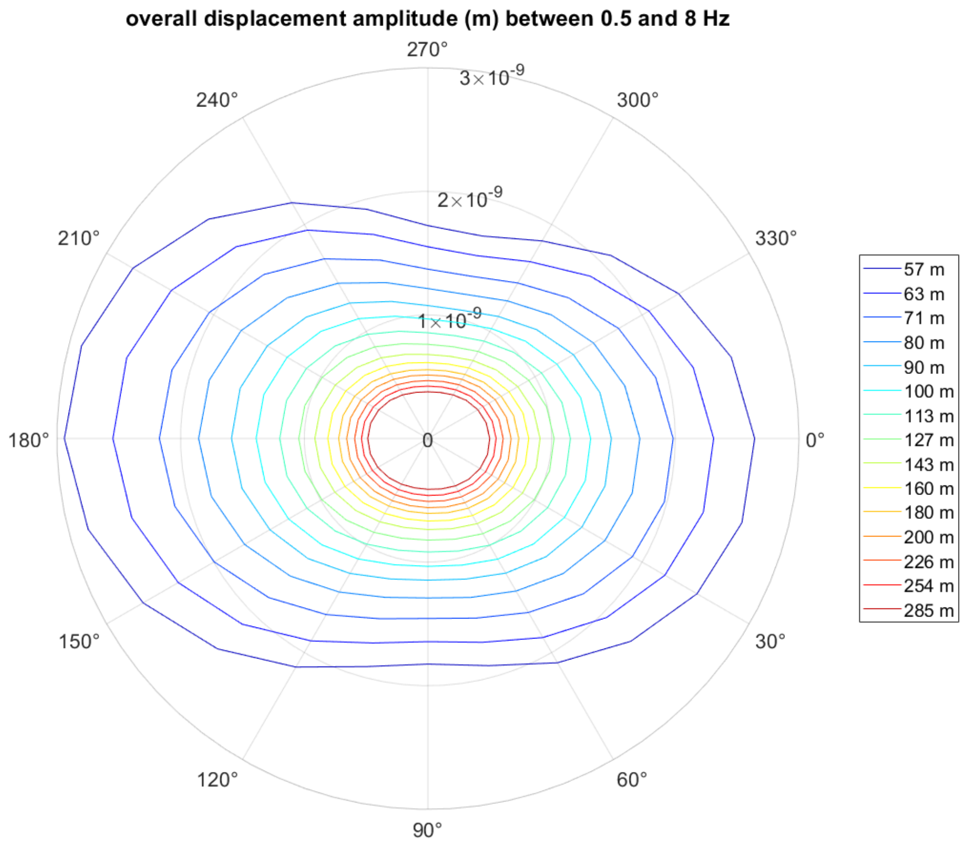

Figure 11 – Directional variation of overall amplitude sum (between 0.5 and 8 Hz) between 63 m and 285 m away from the wind turbine

15.5. Historical data results

Figure 12 shows the layout of Glenkerie Wind Farm with data from SL3 used for analysis (Xi Engineering Consultants, 2023). Due to limited data availability after wind direction binning, only the cardinal directions could be used. Downwind, upwind and crosswind directions were taken relative to the nearest turbine (i.e. T1). Figure 13 shows the result at 9 m/s, the highest wind speed with sufficient data across all three wind directions (downwind, upwind and crosswind) at Glenkerie. The seismic amplitudes show a ~15.7% difference between upwind and downwind, and a ~1.8% difference between downwind and crosswind.

Figure 12 – Layout of Glenkerie Wind Farm with labelled directions at instrument SL3.

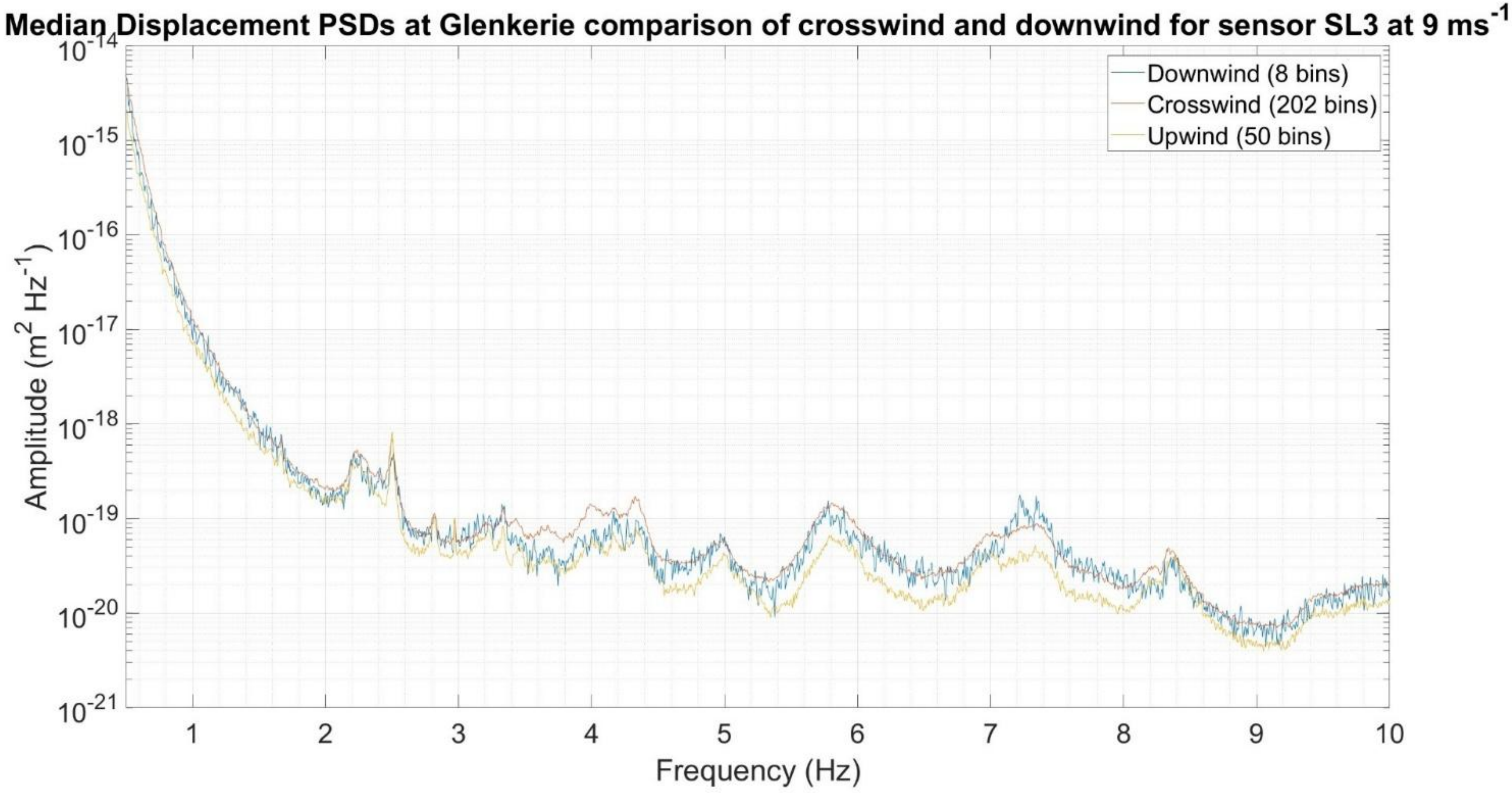

Figure 13 - Displacement PSD comparison for downwind, upwind and crosswind wind directions for a wind speed of 9 ms^{-1} at Glenkerie.

Figure 14 shows the layout of Langhope Rig Wind Farm with data from SL3 used for analysis (Xi Engineering Consultants, 2023). Due limited data availability after wind direction binning, only the cardinal directions could be used. Downwind, upwind and crosswind directions were taken relative to the nearest turbine (i.e. T9). Figure 15 shows the 12 m/s result, the highest wind speed with sufficient data at Langhope Rig for a comparison of downwind and crosswind directions. The difference between the amplitudes was found to be ~5.8%.

Figure 14 – Layout of Langhope Rig Wind Farm with labelled directions at instrument SL3.

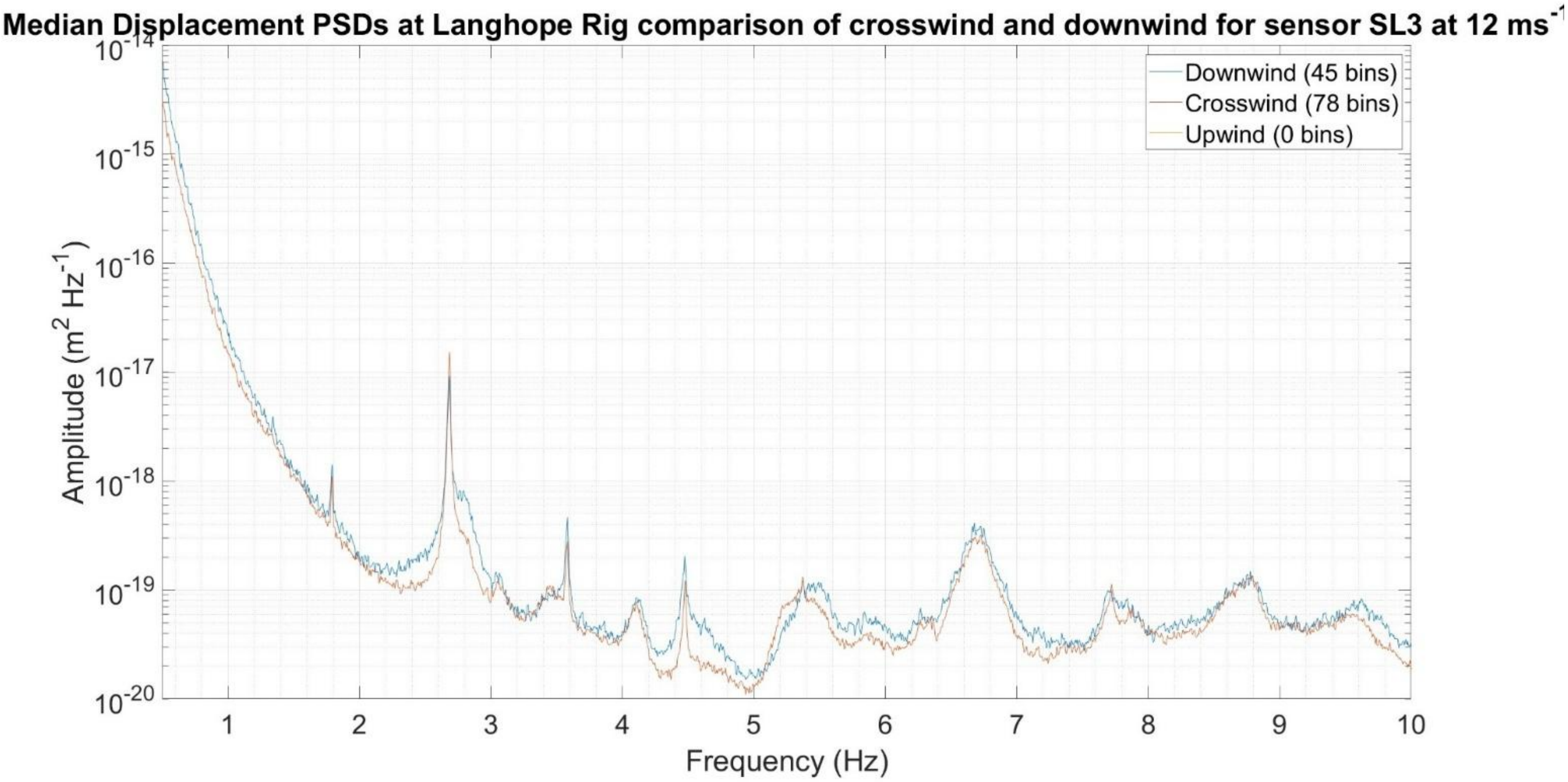

Figure 15 – Displacement PSD comparison for downwind and crosswind wind directions for a wind speed of 12 ms^{-1} at Langhope Rig.

Figure 16 shows the layout of Solwaybank Wind Farm with data from SL1 used for analysis (Xi Engineering Consultants, 2023). Due to limited data availability after binning by wind direction, only the cardinal directions could be used. Downwind, upwind and crosswind directions were taken relative to the nearest turbine (i.e. T5). Figure 17 shows the 9 m/s result, the highest wind speed with sufficient data for downwind, upwind and crosswind wind directions. The difference between the seismic amplitudes for downwind and upwind was found to be ~7.0% while downwind and crosswind was ~4.5%.

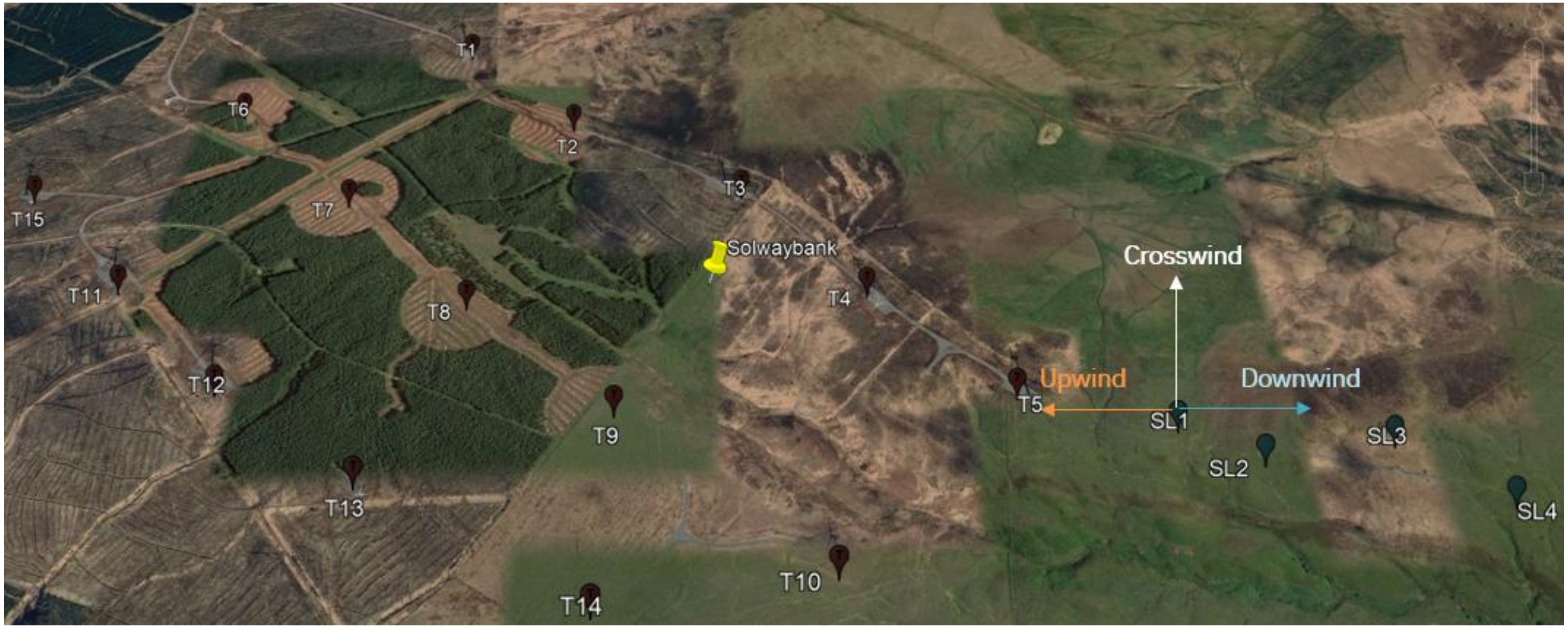

Figure 16 – Layout of Solwaybank Wind Farm with labelled directions at instrument SL1.

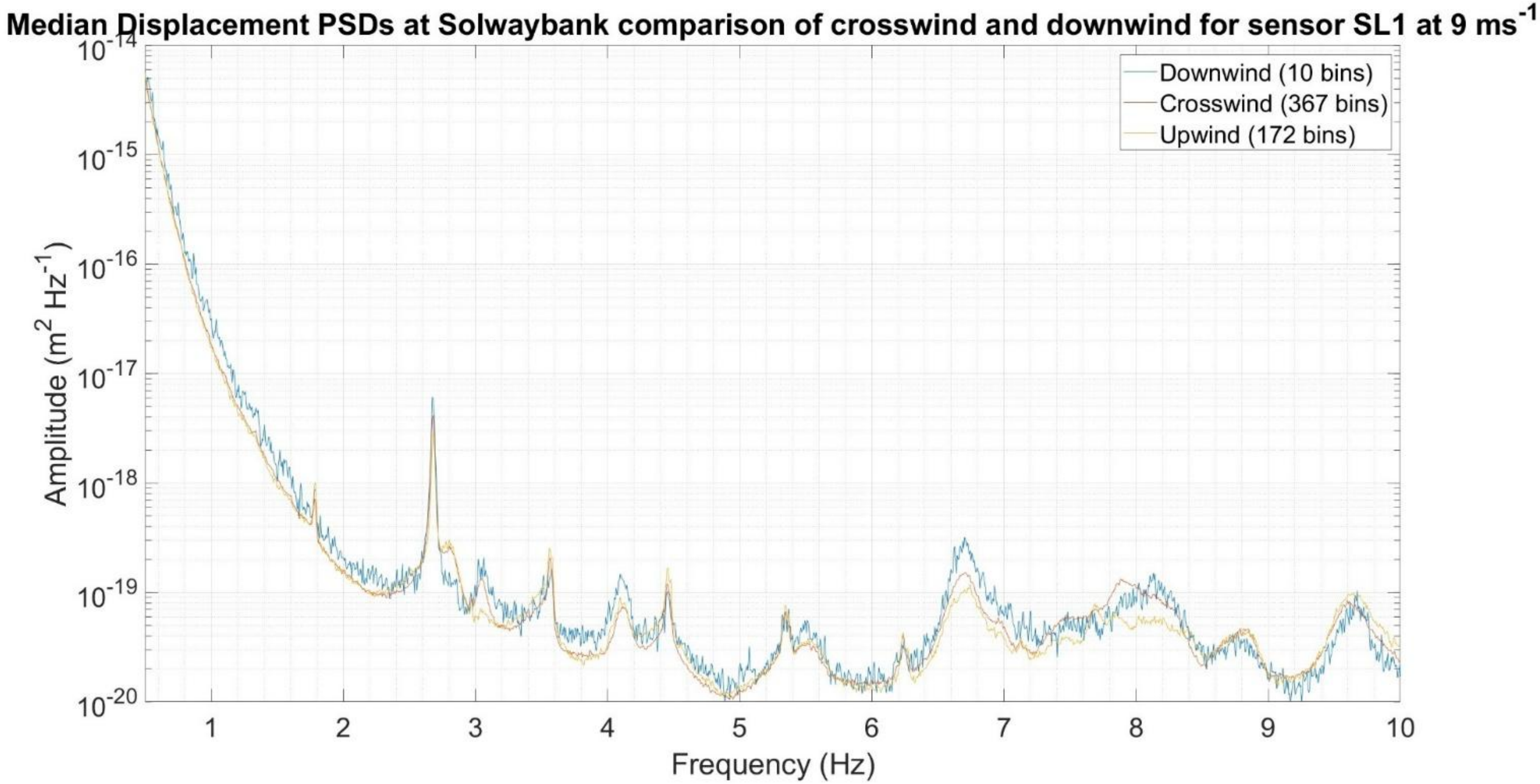

Figure 17 – Displacement PSD comparison for downwind, upwind and crosswind wind directions for a wind speed of 9 ms^{-1} at Solwaybank.

A summary of the directionality analysis conducted on historical measured data is presented in Table 5, where the percentage differences of calculated seismic amplitudes (using a worst-case 10 km from the Eskdalemuir Array) are compared between the different wind directions.

Table 5 – Summary of percentage differences between calculated amplitudes for different wind directions using historical measured seismic data.

Wind Farm	Wind Directions Analysed	Wind Speed (ms^{-1})	Amplitude Percentage Difference (%)
Glenkerie	Downwind-Upwind	7	18.10
		8	22.96
		9	15.68
	Downwind-Crosswind	7	4.98
		8	5.48
		9	1.76
Langhope Rig	Downwind-Crosswind	7	8.15
		8	2.34
		9	6.00
		10	5.18
		11	1.63
		12	5.79
Solwaybank	Downwind-Upwind	7	1.73
		8	2.34
		9	7.04
	Downwind-Crosswind	7	3.97
		8	15.02
		9	4.54

15.6. Discussion and conclusion

15.6.1. Modelling

The directivity of seismic noise produced by a wind turbine has been shown to be significant when considering the amplitude of vibration at discrete frequencies, particularly at distances close to the wind turbine (< 100 m).

When the displacement PSD is summed between 0.5 and 8 Hz (which is how seismic budget usage calculations are made), directivity is less prominent. Modelling indicates that the vibration levels are highest upwind of the wind turbine at distances from 63 m to 285 m from the turbine. Both upwind and downwind directions produce higher vibration levels than crosswind.

Field seismic measurements are predominantly made at wind farms with multiple wind turbines. The placement of instruments depends on multiple other practical demands such as landowner boundaries, access, topography and ground suitability. There is also variation in the wind direction from the prevailing wind direction.

Another consideration is that the model is based on a single generic wind turbine and the directivity is likely different for the many manufacturers and models available. Modelling has also only been undertaken to 285 m and so there is potential for directivity to change at greater distances, but it is expected that there will be less directivity the further away the instrument is from the wind turbine. The model was simplified to a turbine foundation represented by a block. Wind turbines often have circular foundations. A model has not been run with a circular foundation, but it is expected that this would result in even less directional results.

It is qualitatively summarised that considering these factors, the small amount of directivity observed and the other uncertainties inherent in wind turbine seismic measurements, it is likely insignificant to the end result where instruments are placed relative to the prevailing wind direction.

15.6.2. Historical data

Due to limited historical data in all required wind directions for analysis, differences in seismic amplitudes due to wind direction were challenging to quantify. As a result, the only wind farm that had enough data for directionality analysis up to the most critical 12 ms^{-1}, was Langhope Rig which only allowed comparison of downwind and crosswind directions. In this case it was found that the difference between downwind and crosswind data was insignificant. This was further reinforced by lower wind speed results from Glenkerie and Solwaybank.

Percentage differences between calculated seismic amplitudes from measured data taken from these wind farms were low enough to be attributed to expected error unrelated to directionality.

Similarly, for downwind-upwind analysis, the percentage differences were also found to be low (>10%) for most measurements except those from Glenkerie at 7, 8, and 9 m/s. Nevertheless, although the percentage differences are occasionally relatively high (e.g. 23% at Glenkerie), there is not enough evidence to attribute this to wind direction and other results would imply that these are outliers.

In almost all cases, the downwind results were found to be marginally higher in amplitude than the upwind or crosswind results. In line with the analysis above in the modelling discussion, this difference is likely insignificant.

15.6.3. Implication for instrument placement

Both the modelled and measured approaches showed relatively small broadband variations in seismic amplitude with respect to wind direction (ergo yaw direction of the turbine). In practice an instrument is placed in a single position for weeks or months over which period the wind direction will change significantly, and the instrument will collect data at many angular positions. The assessment of seismic amplitude using an interquartile mean approach will tend to average out any variations with directionality. The placement of an instrument with angular position will likely have a negligible effect on the assessment of seismic amplitude.

15.7. Further model details

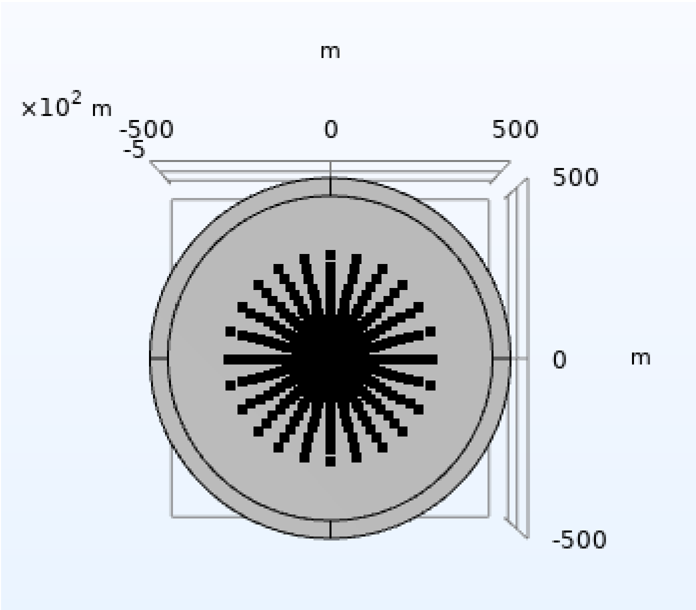

Figure 18 – xy plane of finite element model

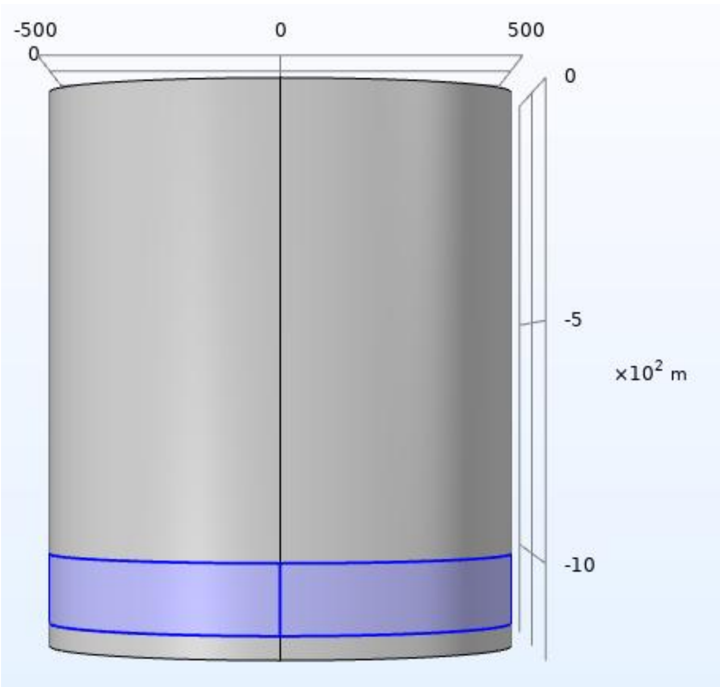

Figure 19 – xz plane of the finite element model. Blue region represents the second geological layer.

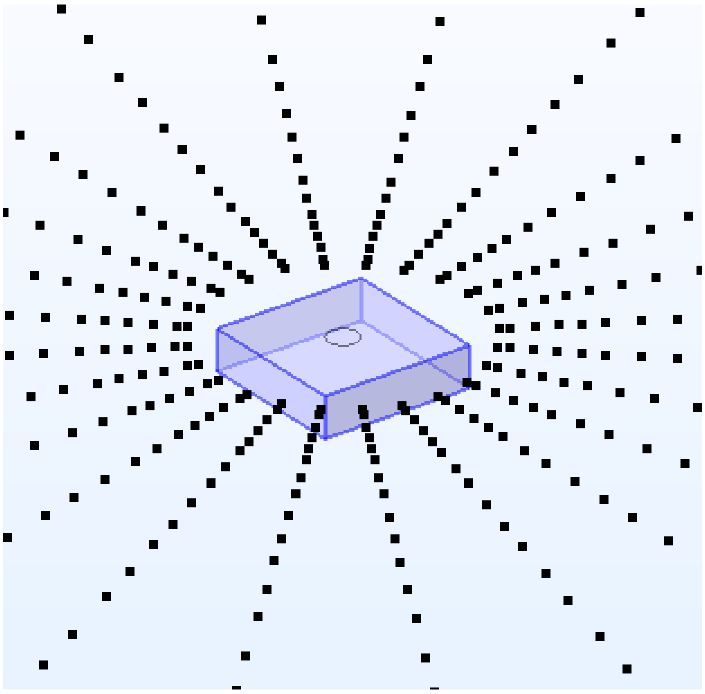

Figure 20 – Foundation block highlighted in blue

Name	Expression	Value	Description
L1_z	1000[m]	1000 m	Position of bottom of the layer
L1_vp	4.25[km/s]	4250 m/s	Pressure wave speed
L1_vs	2.45[km/s]	2450 m/s	Shear wave speed
L1_rho	2700[kg/m^3]	2700 kg/m³	Density
L1_Qp	100	100	Pressure wave quality factor
L1_Qs	50	50	Shear wave quality factor
L1_lambda	L1_vs/freq_max	245 m	
L1_meshsz	L1_lambda/5	49 m	
L1_alphaM	L1_betaK*(2*pi*targer_freq)^2	0.13823 1/s	Inferred Rayleigh Damping
L1_betaK	1/(2*L1_Qs)/(2*pi*targer_freq)	7.2343E-4 s	Inferred Rayleigh Damping

Figure 21 – Material properties of first geological layer

Name	Expression	Value	Description
L2_z	2500[m]	2500 m	Position of bottom of the layer
L2_vp	4.6[km/s]	4600 m/s	Pressure wave speed
L2_vs	2.66[km/s]	2660 m/s	Shear wave speed
L2_rho	2700[kg/m^3]	2700 kg/m³	Density
L2_Qp	200	200	Pressure wave quality factor
L2_Qs	100	100	Shear wave quality factor
L2_lambda	L2_vs/freq_max	266 m	
L2_meshsz	L2_lambda/5	53.2 m	
L2_alphaM	L2_betaK*(2*pi*targer_freq)^2	0.069115 1/s	Inferred Rayleigh Damping
L2_betaK	1/(2*L2_Qs)/(2*pi*targer_freq)	3.6172E-4 s	Inferred Rayleigh Damping

Figure 22 – Material properties of second geological layer

16. Appendix C – Minimum number of samples in the 12 m/s bin

16.1. Purpose and summary

This Appendix examines the sample size of 10-minute seismic measurement data samples at wind speeds of 12 m/s required to achieve stable and reliable results (displacement PSD IQMs and seismic amplitudes).

Four statistical methods (elbow method, relative coefficient of variation, absolute threshold coefficient of variation and asymptote method) were utilised to determine the required sample size. Analysis was conducted on historic measured data recorded at four different wind farms within the Eskdalemuir Consultation Zone: Ewe Hill, Glenkerie, Langhope Rig and Crossdykes (Xi Engineering Consultants, 2023).

Of the four statistical methods employed, the relative delta method and the asymptote method were found to be the most reliable techniques for assessing the variation and stability of seismic measurement sample sizes. Based on the analysis a minimum sample size of 40 provides a stable measurement and it is recommended that a minimum of 40 samples in the wind speed centred on 12 m/s (where the bin between 11.5 and 12.5 m/s) should be employed as standard practice of seismic measurements of wind farms.

16.2. Brief

Analysis is required to provide statistical evidence of the number of 10-minute seismic measurement data samples at 12 m/s wind speed required to achieve a “stable” normalised displacement power spectral density (PSD) interquartile mean (IQM). This Appendix summarises four statistical techniques used to define the number of 10-minute seismic data samples required to achieve a stable result.

16.3. Method

16.3.1. Dataset selection

Four datasets from previous seismic measurement campaigns conducted by Xi were used: three Phase 4 measurements (which are publicly available) (Ewe Hill, Glenkerie, Langhope Rig) and Crossdykes (which are not publicly available). Details of these measurement campaigns are in Table 6.

Table 6 – Summary of datasets used in stability analysis.

Wind Farm	Client	Data start and end	OEM (Model)	Number of WTGs	Number of 12 m/s wind speed data bins	Chosen instrument	Public domain
Ewe Hill (Xi Engineering Consultants, 2023)	Scottish Government	22/10/2021 - 24/11/2021	Siemens (SWT-2.3-93 VS)	22	205	SL3	Yes
Glenkerie (Xi Engineering Consultants, 2023)	Scottish Government	16/06/2021 - 07/10/2021	Vestas (V80)	11	108	SL4	Yes
Langhope Rig (Xi Engineering Consultants, 2023)	Scottish Government	18/08/2021 - 21/10/2021	GE (GE1.6)	10	139	SL3	Yes
Crossdykes	Muirhall Energy	31/08/2021 - 02/06/2022	Nordex (N133)	10	246	SL1	No

Datasets were chosen based upon the following criteria:

- Dataset contains more than 100 10-minute seismic measurement samples at a 12 m/s wind speed.
- Data quality was considered good (results were clear, instruments location condition was good, operational signal to background noise was high).
- Chosen wind farms provide a variety of OEMs and models.

16.3.2. Dataset preparation for statistical analysis

The aim of the analysis is to determine what number of 10-minute seismic measurement samples at a 12 m/s wind speed are required to achieve a stable and reliable displacement PSD IQM (and subsequently seismic amplitude value). To determine this, five different sample sizes were considered: **5, 10, 15, 20, 30, 50 and 100**.

From the pool of 12 m/s samples for each wind farm, a normalised displacement PSD IQM was generated using a number of randomly selected samples. Normalisation was to a single turbine at 1 km from the chosen instrument. Random selections were performed 100 times for each sample size (5, 10, 15, 20, 30, 50 and 100) giving 100 IQM displacement PSDs for each sample size (i.e. the dataset was randomly resampled using a *Bootstrap* approach).

The seismic amplitudes were then calculated from each of these PSDs using the respective wind farm turbine location data. Frequency-distance weighting was applied to the normalised data based on distance to the Eskdalemuir Array (EKA). Five different distances from the EKA were chosen to investigate distance effects on stability and variation: **10, 15, 20, 30 and 50 km**.

The standard deviation, mean and coefficient of variation (CoV) values were calculated for each sample size and distance from the EKA for each wind farm.

Plots of calculated CoV values versus number of samples were generated for each distance from the EKA. From these plots, lines of best fit were calculated based on two different equations for use in statistical analysis:

$$\boldsymbol{y = a\,e^{b\,n} + c\,e^{d\,n}} \qquad (1)$$

$$\boldsymbol{y = a\,e^{b\,n} + c} \qquad (2)$$

16.3.3. Statistical analysis of variation and stability

Four different statistical techniques were used for analysis of variation and stability in seismic amplitude levels calculated from normalised displacement PSD IQMs generated using different sample sizes and distances from the EKA. These four methods are the **elbow method, relative delta in CoV, absolute threshold of CoV** and the **asymptote method.**

Best fit lines from Equation 1 were used for the first three methods while Equation 2 was used for the asymptote method.

16.3.3.1. Elbow method

The elbow method involves visually inspecting the best fit lines on the plots of CoV versus number of samples and identifying the point where the curve starts to flatten.

16.3.3.2. Relative delta in CoV

This method involves calculating the relative change in CoV between incremental points of the line of best fit using the following Equation 3:

$$\Delta \boldsymbol{CoV} = \frac{\boldsymbol{CoV_{n-1} - CoV_n}}{\boldsymbol{CoV_{n-1}}} \times \boldsymbol{100}\% \qquad (3)$$

A threshold of 0.1% was taken as a conservative threshold in ΔCoV where the data was determined to be stable as changes of just 0.1% represent greatly diminished returns in variation.

16.3.3.3. Absolute threshold of CoV

This method involves finding the number of samples where a certain CoV is reached. In scientific practice, a **5%** variation is commonly used as a conservative benchmark where a result can be considered stable and reliable.

16.3.3.4. Asymptote method

Equation 2 is used to generate the best fit line and calculate the asymptote of the plot (from this equation the asymptote is the *c* component, where the remainder of the equation is set to 0). The asymptote method involves finding the point where the CoV reaches a value that is a small margin above the asymptote value. From literature, this small margin to find the point of diminishing returns can be taken anywhere from 1 to 5 %. From inspection of the data, 1% is too conservative and yields a requirement of 100 samples for all cases, therefore a **5%** margin above the asymptote was defined as the point where data can be considered stable.

16.4. Results

For each wind farm, the two figures show the best fit lines calculated using Equations 1 and 2, respectively, at different distances from the EKA. Results calculated using the absolute CoV threshold method (black x) and relative CoV delta method (blue circles) are shown on the lines in the first figures, while the results calculated using the asymptote method (coloured x) are shown on the lines in the second figures. The elbow method results are not shown on the plots as these were qualitatively/visually assessed rather than numerically. Each section also has a summary table for each wind farm showing the required sample sizes according to each statistical method and distance from the EKA.

16.4.1. Ewe Hill

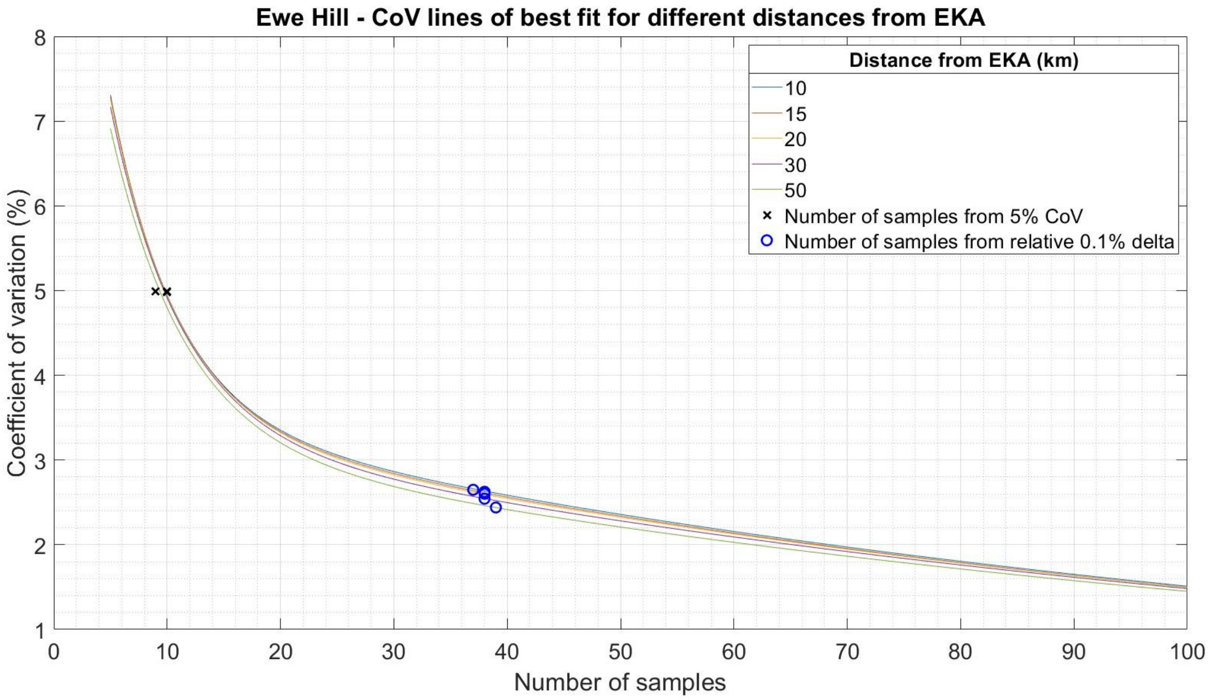

Figure 23 – Best fit lines for different distances from the EKA, calculated from Equation 1 for Ewe Hill with absolute threshold CoV and relative delta CoV results marked on the lines.

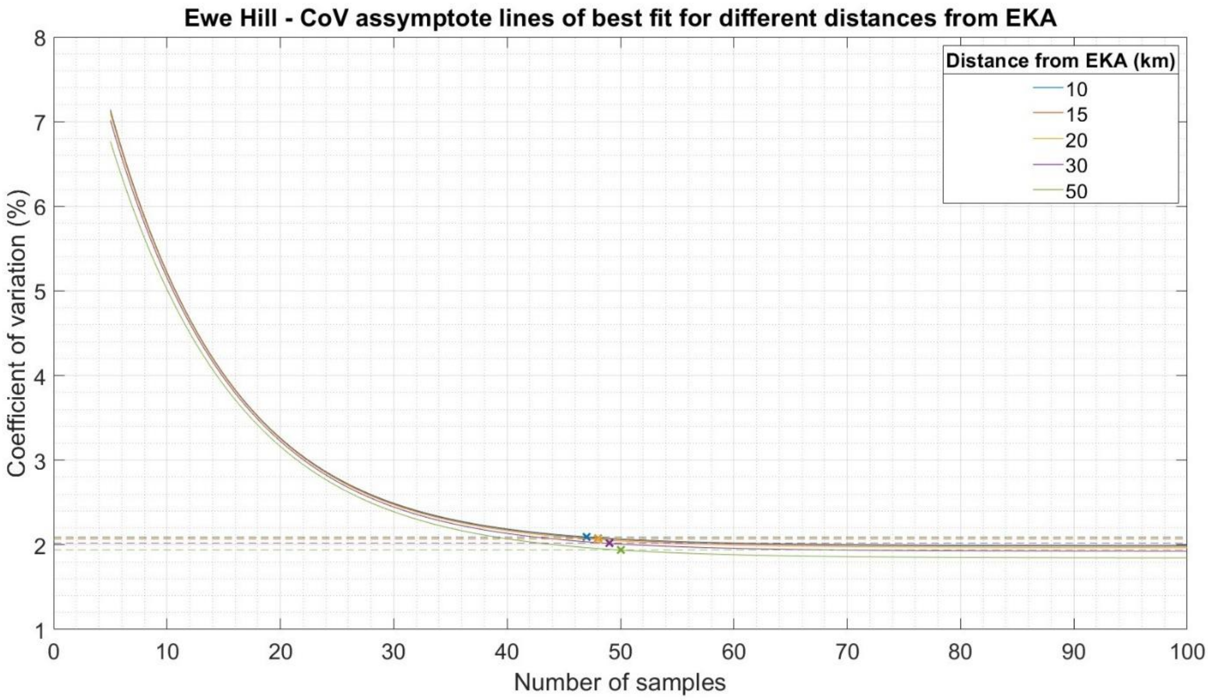

Figure 24 – Best fit lines for different distances from the EKA calculated from Equation 2 for Ewe Hill with the number of samples calculated by the asymptote method marked on the lines.

Table 7 – Required sample size for statistically stable results for Ewe Hill, according to different methods and distances from the EKA.

Statistical Method	Number of samples required for stability - Ewe Hill (vs distance from EKA)				
	10 km	15 km	20 km	30 km	50 km
Elbow Point	15	15	15	15	15
Absolute CoV	10	10	10	10	9
Relative CoV	37	38	38	38	39
Asymptote	47	48	48	49	50

16.4.2. Glenkerie

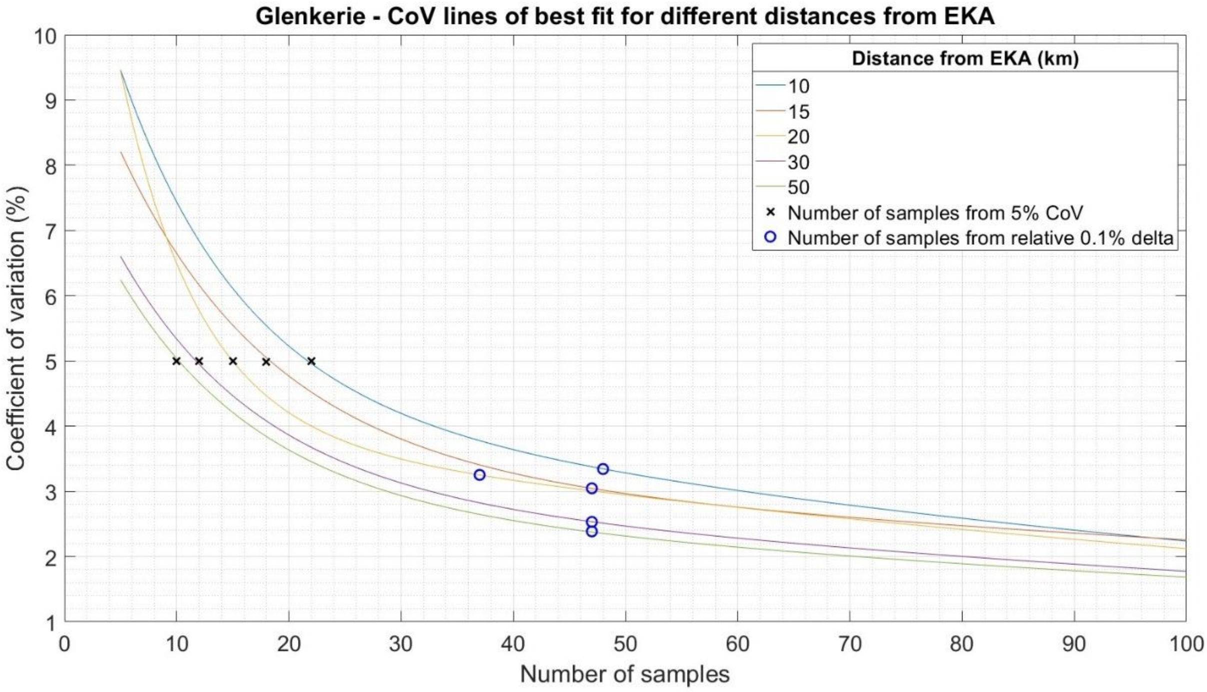

Figure 25 – Best fit lines for different distances from the EKA, calculated from Equation 1 for Glenkerie with absolute threshold CoV and relative delta CoV results marked on the lines.

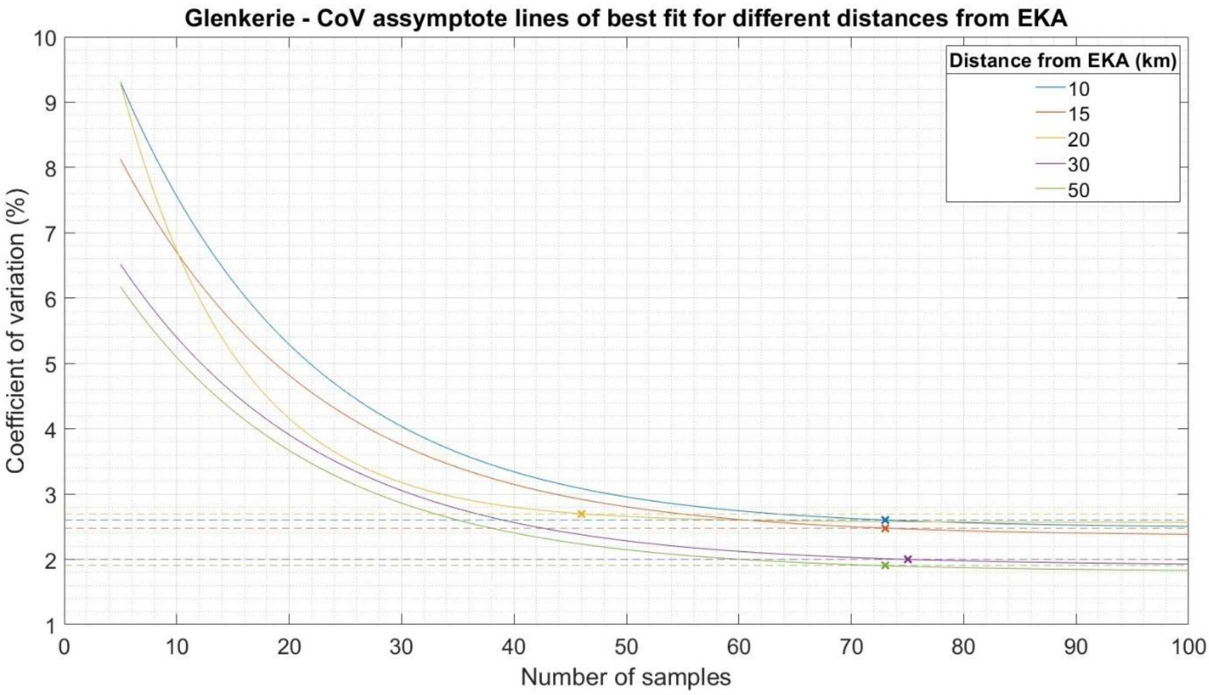

Figure 26 – Best fit lines for different distances from the EKA calculated from Equation 2 for Glenkerie with the number of samples calculated by the asymptote method marked on the lines.

Table 8 – Required sample size for statistically stable results for Glenkerie, according to different methods and distances from the EKA.

Statistical Method	Number of samples required for stability - Glenkerie (vs distance from EKA)				
	10 km	15 km	20 km	30 km	50 km
Elbow Point	30	30	20	30	30
Absolute CoV	22	18	15	12	10
Relative CoV	48	47	37	47	47
Asymptote	73	73	46	75	73

16.4.3. Langhope Rig

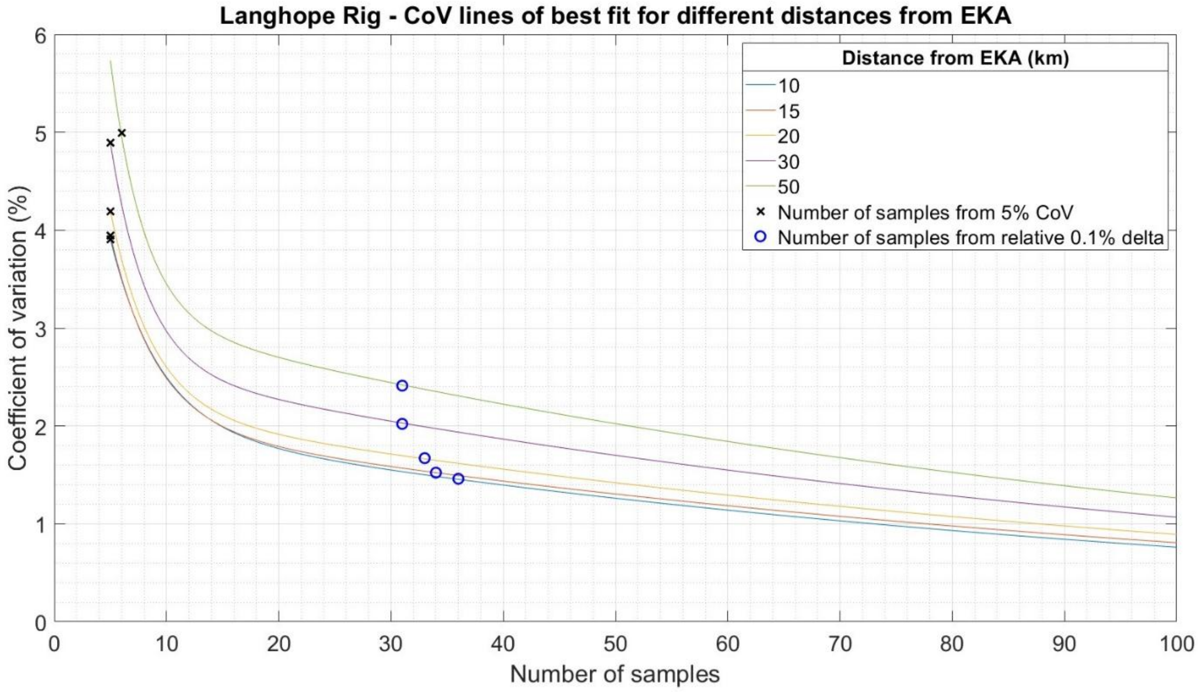

Figure 27 – Best fit lines for different distances from the EKA, calculated from Equation 1 for Langhope Rig with absolute threshold CoV and relative delta CoV results marked on the lines.

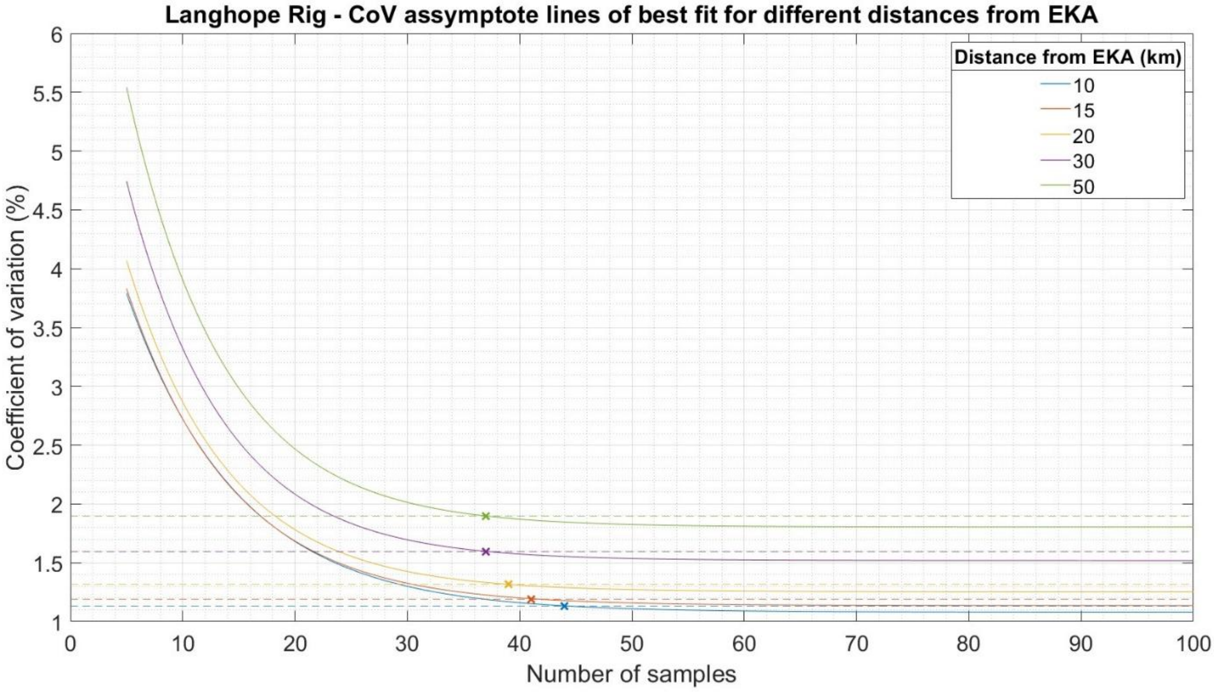

Figure 28 – Best fit lines for different distances from the EKA calculated from Equation 2 for Langhope Rig with the number of samples calculated by the asymptote method marked on the lines.

Table 9 – Required sample size for statistically stable results for Langhope Rig, according to different methods and distances from the EKA.

Statistical Method	Number of samples required for stability – Langhope Rig (vs distance from EKA)				
	10 km	15 km	20 km	30 km	50 km
Elbow Point	15	15	15	15	15
Absolute CoV	5	5	5	5	6
Relative CoV	36	34	33	31	31
Asymptote	44	41	39	37	37

16.4.4. Crossdykes

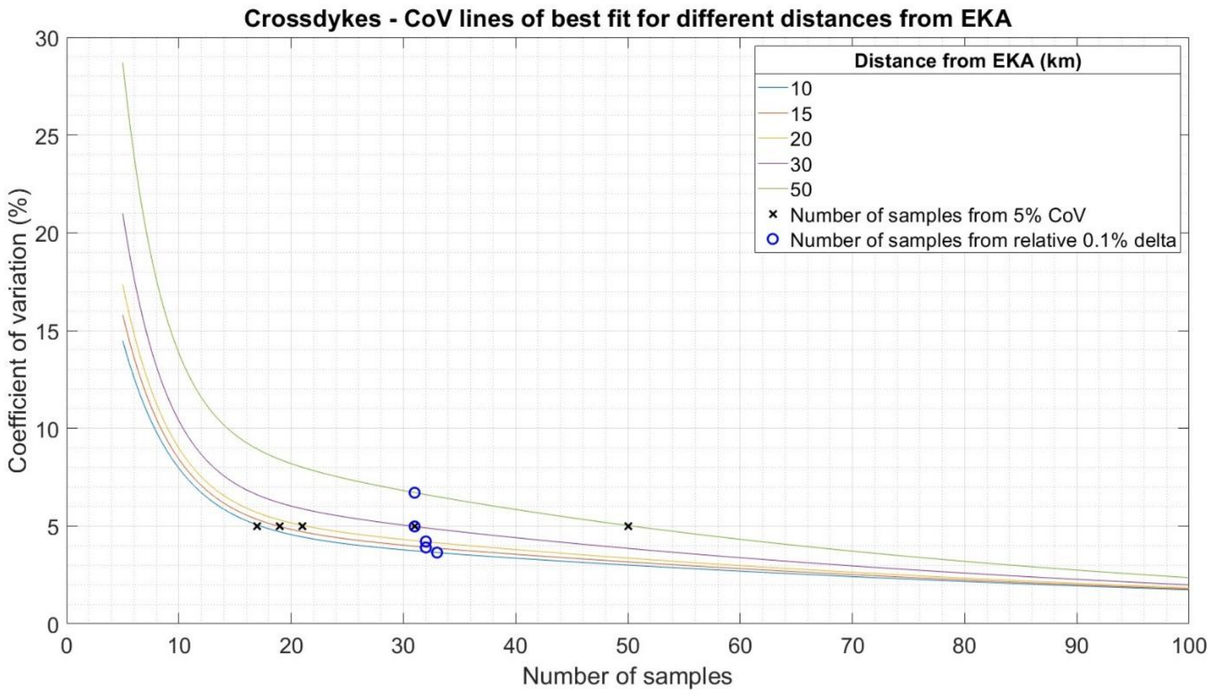

Figure 29 – Best fit lines for different distances from the EKA, calculated from Equation 1 for Crossdykes with absolute threshold CoV and relative delta CoV results marked on the lines.

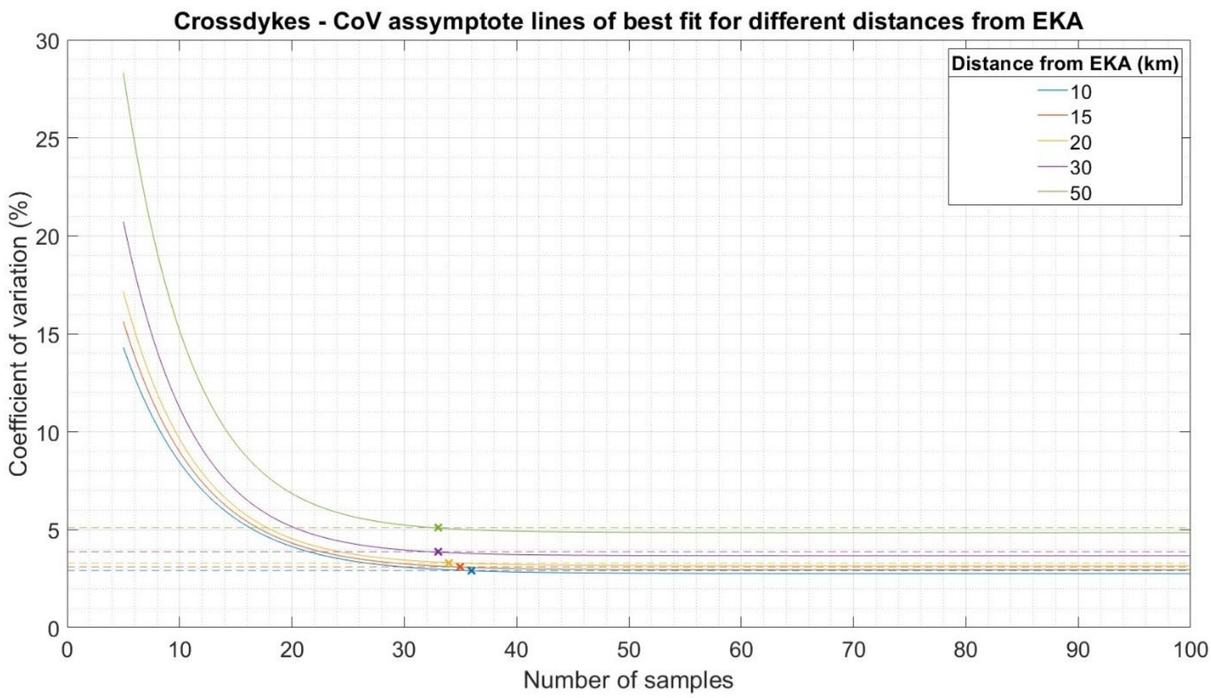

Figure 30 – Best fit lines for different distances from the EKA calculated from Equation 2 for Crossdykes with the number of samples calculated by the asymptote method marked on the lines.

Table 10 – Required sample size for statistically stable results for Crossdykes, according to different methods and distances from the EKA.

Statistical Method	Number of samples required for stability – Crossdykes (vs distance from EKA)				
	10 km	15 km	20 km	30 km	50 km
Elbow Point	15	15	15	15	15
Absolute CoV	17	19	21	31	50
Relative CoV	33	32	32	31	31
Asymptote	36	35	34	33	33

Table 11 – Summary of sample size results according to different statistical methods and distances from the EKA.

Wind Farm	OEM (Model)	Number of WTGs	Number of 12 m/s wind speed data bins	Chosen instrument	Statistical Method	Number of samples required for stability (vs distance from EKA)				
						10 km	15 km	20 km	30 km	50 km
Ewe Hill	Siemens (SWT-2.3-93 VS)	22	205	SL3	Elbow Point	15	15	15	15	15
					Absolute CoV (5%)	10	10	10	10	9
					Relative CoV (Δ0.1%)	37	38	38	38	39
					Asymptote (5%)	47	48	48	49	50
Glenkerie	Vestas (V80)	11	108	SL4	Elbow Point	30	30	20	30	30
					Absolute CoV (5%)	22	18	15	12	10
					Relative CoV (Δ0.1%)	48	47	37	47	47
					Asymptote (5%)	73	73	46	75	73
Langhope Rig	GE (GE1.6)	10	139	SL3	Elbow Point	15	15	15	15	15
					Absolute CoV (5%)	5	5	5	5	6
					Relative CoV (Δ0.1%)	36	34	33	31	31
					Asymptote (5%)	44	41	39	37	37
Crossdykes	Nordex (N133)	10	246	SL1	Elbow Point	15	15	15	15	15
					Absolute CoV (5%)	17	19	21	31	50
					Relative CoV (Δ0.1%)	33	32	32	31	31
					Asymptote (5%)	36	35	34	33	33

Table 12 – Mean and median of sample sizes calculated across all four wind farms for the different statistical methods

Statistical Method	All distances		10 km		15 km		20 km		30 km		50 km	
	Mean (±STD)	Median (±MAD)	Mean (±STD)	Median (±MAD)	Mean (±STD)	Median (±MAD)	Mean (±STD)	Median (±MAD)	Mean (±STD)	Median (±MAD)	Mean (±STD)	Median (±MAD)
Elbow Point	18 ± 6	15 ± 0	19 ± 8	15 ± 0	19 ± 8	15 ± 0	16 ± 3	15 ± 0	19 ± 8	15 ± 0	19 ± 8	15 ± 0
Absolute CoV (5%)	15 ± 11	10 ± 5	14 ± 8	14 ± 6	13 ± 7	14 ± 5	13 ± 7	13 ± 5	15 ± 11	11 ± 4	19 ± 21	10 ± 4
Relative CoV (Δ0.1%)	37 ± 6	37 ± 4	39 ± 7	37 ± 2	38 ± 7	36 ± 3	35 ± 3	35 ± 3	37 ± 8	35 ± 4	37 ± 8	35 ± 4
Asymptote (5%)	48 ± 14	45 ± 8	50 ± 16	46 ± 6	49 ± 17	45 ± 7	42 ± 6	43 ± 5	49 ± 19	43 ± 8	48 ± 18	44 ± 8

16.5. Discussion and conclusion

Four statistical techniques were used to investigate the number of samples required to attain a stable result.

As the elbow method is utilised with visual inspection, it can be said that this technique is likely the least robust of the four implemented.

The absolute CoV threshold method (using 5% as the threshold) yielded large deviations in results, where several of the results highlighted in Table 12 show standard deviations >50% of the mean number of samples and one result (50 km) has a standard deviation higher than the mean. This suggests this metric has too high a variation in results to offer an accurate assessment of required sample size.

The relative delta in CoV (using 0.1% as the target) and the asymptote method (using 5% margin above the asymptote) are conservative methods that target a sample size where subsequent increases in number of samples yield very minimal returns in stability. As such, these methods determine the requirement to be more than double the sample size compared to the elbow point and absolute CoV threshold methods. The deviation of the means and medians on the relative CoV delta method are the lowest of the three methods quantitative statistical methods.

From this analysis, it can be suggested that a **minimum sample size of 40 seismic data samples** should be collected to ensure the stability of final seismic amplitude values. This sample size was taken from the relative CoV delta method rounded up to the nearest 10 for simplicity (mean and median were 37). If a more conservative number is desired then a sample size of 50 seismic data samples could be required to be collected. This sample size is instead taken from the asymptote method rounded up to the nearest 10 for simplicity (mean and median were 48 and 45, respectively).