Eskdalemuir Wind Turbine Seismic Vibration

Assessment of Headroom

Presented to The Scottish Government

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Document Summary

The detection capabilities of the Eskdalemuir seismic array (EKA) is protected from seismic vibration produced by wind turbines with an algorithmic tool. This tool employees a modelled worst-case turbine to estimate the cumulative impact of all turbines within 50 km of EKA. The cumulative is then compared to a threshold level that has now been met, preventing the development of further wind energy capacity in the consultation zone. It has been proposed that additional seismic measurement of turbines would allow the removal of the safety margin used in the worst-case turbine algorithm and provide headroom for additional capacity. The EKA algorithm has been run in simulation presented without safety factors (i.e. based on historic measured data) and shows that there is a high likelihood that a measurement campaign would allow at least an additional 585 MW capacity within consultation zone. The additional capacity may be significantly higher (>2 GW) dependant on development area and turbine type.

		Date	Version	Amendment
Originator	Dr B Marmo	20th Feb 2020	v1	Issue
Review	Dr M P Buckingham	24th Feb 2020	v2	Review
Review	R Horton	24th Feb 2020	v3	Review
Review	Dr B Marmo	24th Feb 2020	v4	Release

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1 INTRODUCTION

With good wind conditions and close proximity to population centres, southern Scotland has excellent potential for onshore wind generation. However, much of this region falls within the Eskdalemuir consultation zone and limits wind development. The zone is formed by a 50 km radius (representing nearly 10% of Scotland's total land area) surrounding the Eskdalemuir seismic measuring station (EKA) which is operated by the Ministry of Defence. To protect the EKA, wind turbines built in the area must operate within a seismic vibration budget. Each turbine contributes to the budget based upon a worst-case hypothetical turbine. With the vibration budget in the consultation zone reached there is no possibility to further develop and invest in the wind resource available in the region.

By design, the algorithm used to represent the worst-case turbine includes considerable factors of safety such that it over-estimates the cumulative seismic vibrations produced by wind turbines. An approach to reducing the safety margin is to directly measure the seismic output of turbines in the consultation zone. This would be a considerable undertaking. The work presented here is an estimate (based on a small sample of publicly available data as outlined in the method below) of the headroom that would be released by a measurement campaign and how that would equate to additional wind energy capacity in megawatts. The outcome of the work can then be used for a cost-benefit analysis related to embarking on a measurement campaign. In order to ease conversations around the project, results have been presented in both nanometers and megawatts.

2 TECHNICAL BACKGROUND

Xi were commissioned by the Eskdalemuir Working Group (EWG) in 2013 to develop a robust physics-based approach to estimating the worst-case ground vibration produced by wind turbines. Xi developed such an algorithm which is currently used by the MoD to calculate the worst-case cumulative effect of all wind turbines on EKA; see "*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" (2014).

The physics-based approach uses an algorithm that creates a displacement spectrum (frequency vs seismic amplitude) that represents the seismic output measured at 1 km from any given turbine when the wind speed at a height of 80 m is 12 m/s. The premise behind the physics-based algorithm is that the wind energy that passes through a wind turbine can be considered to be portioned to electrical energy and lost energy. Losses will consist of energy converted to noise, frictional heat, seismic energy etc. Thus, some proportion of the energy passing through the rotor is converted to seismic vibration. The wind energy passing through the rotor is a function of wind speed and the swept area of the rotor. Thus, assuming that the proportion of wind energy that is lost to seismic vibration is constant it is possible to scale the seismic vibration based on blade length (to give swept area) and hub height (giving wind speed relative 12 m/s at a height of 80 m). The input requirements for the algorithm are therefore hub height and rotor diameter which are commonly submitted with a planning application making the algorithm a viable for the purpose of estimating seismic vibration at the planning stage of a wind farm's development.

The algorithm was fitted using seismic data from operational wind farms in southern Scotland which was collected in 2012. These wind farms were Craig wind farm consisting of four Nordex N80 turbines with a hub height of 60 m and rotor diameter of 80 m; Clyde wind farm consisting of 152 Siemens 2.3 MW turbines with a hub height of 78.3 m and rotor diameter of 93 m and; Dun Law wind farm 26 Vestas V47 turbines with a hub height of 40 m and a rotor diameter of 47 m. As of 2020 these machines represent an older generation of turbine.

A key observation from the measurement of these three wind farms was that the seismic spectra produced by wind farms either related to blade-pass (Craig and Dun Law), or structural resonances (Clyde). Due to the limited public data available on seismic emissions from wind turbines, a conservative 'worst-case' approach was adopted. This worst-case turbine algorithm assumes that any given turbine produces *both* forms of seismic vibration, i.e. blade-pass *and* structural resonance. Continuing this conservative approach, the algorithm includes a factor of safety by over-fitting the empirical data by ~20% to account for uncertainty in the seismic output of different makes and models of wind turbines.

"Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project" was reviewed by the Ministry of Defence Subject matter experts (Dr D Bowers) who subsequently presented to the CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization) and was ultimately accepted by the Scottish Government. Adopting the new algorithm opened up over 1GW of onshore wind power within the 50km Eskdalemuir zone compared to the MoD's earlier approach.

3 METHOD

The method presented here is based on steps required to derive an estimate of the *headroom* in the budget due to the amount that the worst-case algorithm over-estimates the cumulative amplitude of all turbines in the Eskdalemuir consultation zone (built, consented and in planning). In effect, this is an analysis of the likely seismic level if all wind farms were measured and therefore required no safety factor. As noted above, the safety factors are two-fold:

- The algorithm over-fits the empirical data such that the cumulative amplitude calculated by the EKA budget has a ~20% factor of safety.
- The algorithm considers that all wind turbines produce seismic vibration by blade pass AND structural resonance

The representation of the wind turbine in the algorithm was tightly fitted to Craig wind farm to remove the factor of safety related to blade-pass (Figure 1). The representation of the wind turbine in the algorithm was tightly fitted to Clyde to remove the factor of safety related to structure resonances (Figure 2).

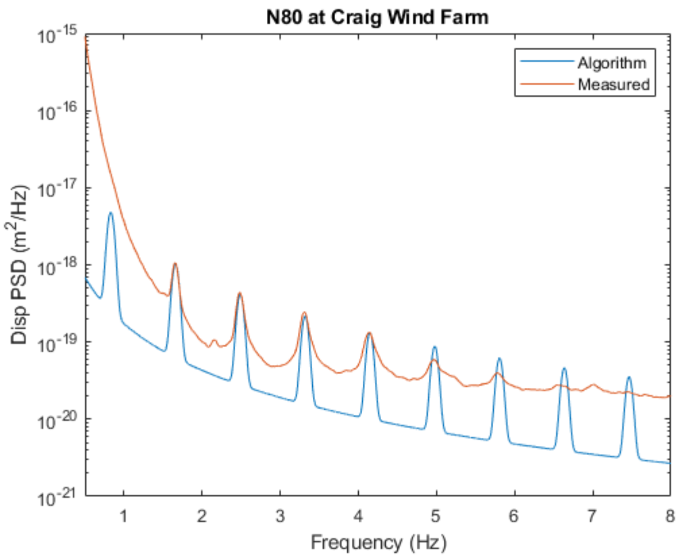

Figure 1 – Algorithm fitted to blade-pass dominated spectra measured at Craig wind farm. Please note the noise floor (level of troughs between peaks) was not fitted to Craig data in the 2014 Report, but rather the Clyde data set.

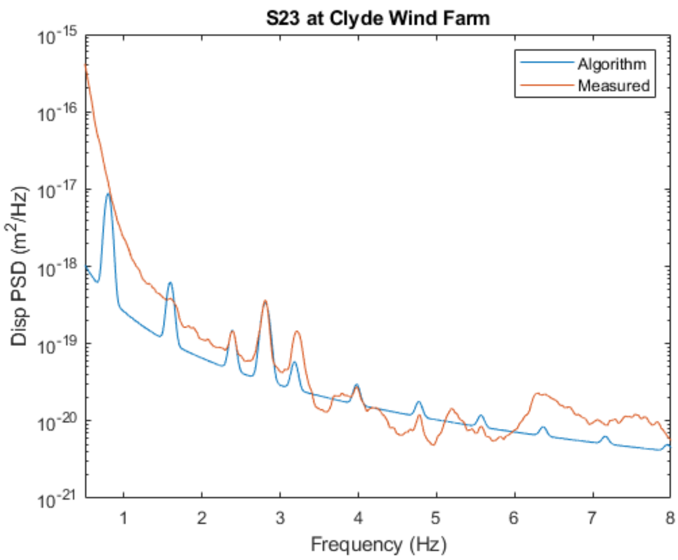

Figure 2 Algorithm fitted to structural resonance dominated spectra measured at Clyde wind farm.

To remove the worst-case of assuming two forms of seismic vibration production (blade-pass and structural resonance) the cumulative levels have been calculated assuming Clyde is representative off all wind turbines (structural resonance only) and assuming Craig is representative off all wind turbines (blade-pass only). Thus, four simulations are presented:

1. Standard EKA budget algorithm (unmodified worst-case wind turbine)
2. Safety factor removed but turbines produce seismic vibration from both blade-pass and structural resonance (i.e. Standard EKA algorithm with 20% safety factor removes)
3. Structural resonance fitting empirical data from Clyde wind farm
4. Blade-pass only fitting empirical data from Craig wind farm

The parameters used to define each of these representations are listed in Table 1. These four simulations use the same population (see section 3.2) of wind turbines and results compared.

Coefficients	Standard EKA	20% Safety factor removed	Clyde fitted data	Craig fitted data
Blade pass amplitude multiplier	2.87E-25	3.87E-25	2.87E-25	3.87E-25
Blade pass amplitude exponent	1.76	2.25	4	2.25
Blade pass shape parameter	0.04	0.04	0.04	0.04
Bending mode amplitude multiplier	9.23E-26	2.62E-26	2.62E-26	0.00E+00
Frequency of bending mode	2.808	2.808	2.808	2.808
Bending mode shape parameter	0.05	0.05	0.05	0.05
Operational broadband noise multipliers	2.23E-26	2.23E-26	2.23E-26	2.23E-26
Tip Speed (m/s)	77.49	77.49	77.49	69.49

Table 1 – Parameters used in the four different representations of wind turbines seismic output. The parameters relate to those described in Section 8.2.1 of *Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*

3.1 Simulations

All simulations presented here were performed using bespoke code written using the commercially available software package Matlab. The codes used follow the methods described in "*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" and are consistent with those used to calculate the EKA budget.

3.2 Wind turbine population

Calculations are based on the wind turbines in the EKA budget spreadsheet that was issued to Xi on the 3rd of February 2020. According the Ministry of Defence, this spreadsheet was current on the 20th January 2020. The spreadsheet includes turbines locations as OS Grid references, turbine hub heights and rotor diameters. The budget is currently over-subscribed. The budget threshold of 0.336 nm is breached when the third wind turbine at Faw Side is included.

To calculate headroom in the budget, we consider all possible turbines that could be built without breaching the budget threshold. Thus, simulations are based on turbines in all farms up to and including Cliffhope (submitted 29/09/2017) and the first two turbines from Faw Side (submitted 11/01/2018). All four simulations are run on this population.

3.3 Estimate of headroom of installable capacity

The output of the four different approaches to represent seismicity of wind turbines is a predicted cumulative amplitude in nanometers (nm). Subtracting these levels from the budget threshold (0.336 nm) gives the headroom in nanometers. Equating the headroom in nanometers to an estimate of additional wind energy capacity that could be installed is non-trivial as it depends very much on where the additional turbines are placed. The impact of wind turbines on EKA is very strongly dependent on its distance from the seismic array; a single turbine 10 km from EKA has the same impact as ~80 turbines placed 50 km away.

The installable capacity in megawatts was calculated by adding wind turbines randomly within the consultation zone between 10 km and 50 km from EKA. This randomised placement does not consider terrain, culture (towns) or pre-existing wind farms. The turbines were assumed to equate to the largest currently being installed (e.g. Middle Muir wind farm):

- Rotor diameter = 93.5 m
- Hub height = 117 m
- Power = 3.4 MW

The effect of the different ways that the turbines are represented based on the parameters listed in Table 1 are shown in Figure 3. Turbines were added sequentially until the budget threshold was reached (0.336nm). The number of turbines and their combined power was calculated. The simulation was then re-run by once again randomising the position of each turbine. The simulation was iterated in this way 1000 times for each scenario and the additional capacity taken as the mean (average) of all the simulations. The standard deviation of the additional capacity was also calculated for each simulation and represents the spread of data within the 1000 iterations of the model, where 68% of the additional capacity results fall with one standard deviation from the mean value.

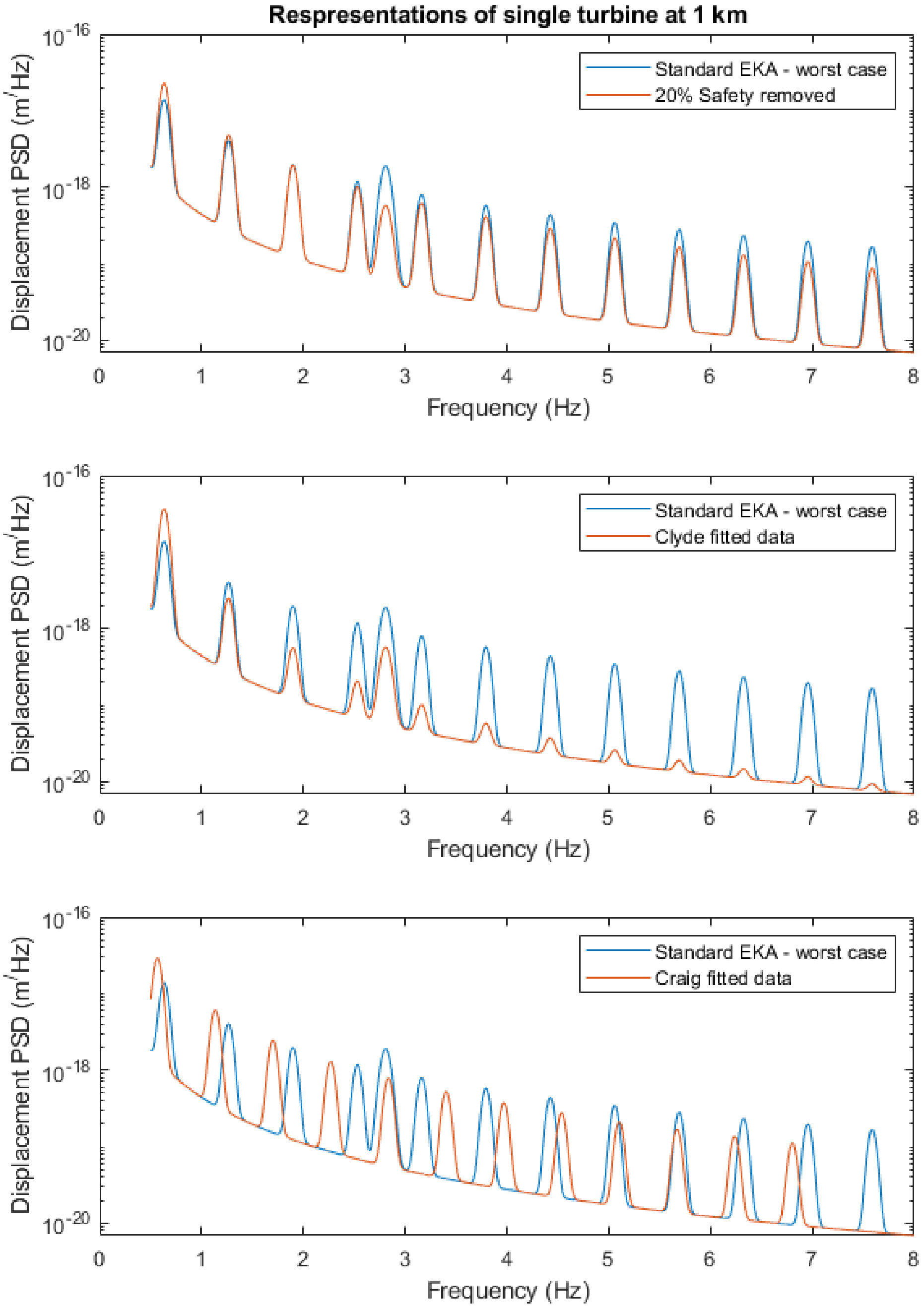

Figure 3 – Comparison of the spectra for the four different ways to represent the seismic output of turbines when applied to a turbine with rotor diameter of 93.5 m and a hub height of 117 m.

4 RESULTS

4.1 Standard EKA

The turbines used for the headroom calculation in nanometers were those up to and including the second turbine at Faw Side. When calculated using the standard EKA algorithm 0.004 nm of budget remained after Faw Side T2 is included. This corresponds to an average of 47.3 MW of additional capacity installed randomly.

4.2 20% safety factor removed

When the 20% safety factor is removed the headroom is 0.066 nm and equates to an additional 664.8 MW of installed capacity with a standard deviation of 162 MW.

4.3 Clyde fitted data (structural resonances only)

When turbines are assumed to produce seismic vibration by structural resonances only and are best represented by data from Clyde wind farm the additional headroom is 0.149 nm. This value for headroom equates to an additional capacity of 2900 MW with a standard deviation of 354 MW.

4.4 Craig fitted data (blade pass only)

When turbines are assumed to produce seismic vibration by blade-pass only and are best represented by data from Craig wind farm the additional headroom is 0.075 nm. This value for headroom equates to an additional capacity of 772 MW with a standard deviation of 186 MW.

4.5 Summary of results

	Cumulative budget	Headroom	Additional capacity (MW)		Additional number of turbines	
	nm	nm	Mean	STD	Mean	STD
Standard EKA	0.332	0.004	47.3	32.6	14.9	9.6
20% Safety factor removed	0.270	0.066	664.8	162.0	196.5	47.7
Clyde fitted data	0.187	0.149	2900.4	345.4	854.1	101.6
Craig fitted data	0.261	0.075	772.2	186.8	228.1	54.9

Table 2 – Headroom calculations for different representation of seismic output from wind turbines based on the EKA budget spreadsheet up to the second turbine at Faw Side. The additional capacity is based on the random population of the consultation zone with 3.4 MW wind turbines. The zone was randomly populated in 1000 simulations and the mean should the average additional installed capacity and STD is the stand deviation of the 1000 simulations in MW.

5 DISCUSSION

The simulations presented here assume that should headroom become available that it would be built out using large modern wind turbines such as those currently being installed at Middle Muir wind farm. In fact, increased capacity in the consultation zone would more likely include a range of different sized turbines. However, for the purposes of converting headroom to installed capacity, it seems reasonable to use turbines likely to be installed by large developers that will consume the largest proportion of headroom.

The simulations use a random placement of turbines in the consultation zone to estimate additional capacity. Many factors may preclude the placement of wind turbines such as cultural sites, pre-existing wind farms, aviation restrictions etc. A more informed placement of turbines based on these type of restrictions is an item proposed for future work packages It is recommended that this piece of work is followed up by a recalculation of the headroom based on observed data obtained from more recently installed turbines in the area which may have even lower seismic outputs. This will also increase the size of the data set and reduce uncertainties. For the purpose of estimating how nanometers of headroom relate to additional megawatts, the author believes it is reasonable to randomly populate the consultation zone.

It has been proposed that the gathering of further empirical seismic data from wind farms would remove the necessity of the worse-case algorithm and its in-built safety factors. Based on the assumptions presented, there is a high likelihood that such an approach could lead to the installation of at least an addition 500 MW of wind energy capacity. Conservatively, the removal of the 20% factor of safety while retaining the seismic vibration from both blade-pass and structural resonances results in 664 MW.

When the turbines are directly related to empirical data, the headroom and additional capacity is higher. When data from Craig wind farm is used to modelled turbines the produce seismic vibration dominated by blade-pass the head room is 0.075 nm equating to an addition capacity of 772 MW. Considering that the standard deviation of the Craig simulations was 187 MW, there is an 84% likelihood that the addition capacity will be greater than 585 MW (772 MW – 187 MW).

When the turbines are based on the structural resonance dominate spectra from Clyde wind farm the headroom is 0.149 nm equating to an additional capacity of 2.9 GW. The seismic power is significantly greater in the blade-pass peaks than in structural resonances; this is due in part to there being many blade-pass peaks compared to the single resonant peak. For this reason, the standard EKA algorithm greatly over-estimates (Figure 3) the contribution of Clyde wind farm and turbines that produce seismicity via structural resonance.

It is likely that the headroom derived from measurement of wind farms in the consultation zone will have a mixture of seismic vibration production by blade-pass and by structural resonance. It follows therefore that the measured headroom values will lie between those of Craig (0.075 nm) and Clyde (0.149 nm), and the additional capacity between 772 MW and 2.9 GW. If the proportion of turbines that are dominated by structural resonances within the consultation zone is high, then it is possible that gigawatts of additional capacity could be installed. It is likely that the proportion of turbines in the area with seismicity produced by structural resonance will be significant given that two of the largest contributes to the budget allocation, name Ewe Hill and Clyde wind farms both have Siemens S2.3 turbines installed.

6 CONCLUSION

An estimate of the headroom provided by measuring wind turbines in the Eskdalemuir consultation zone has been made by closely fitting the EKA algorithm to data from Clyde and Craig wind farms. The population of wind turbines used in all simulations was all possible turbines that could be built without breaching the budget threshold up to and including turbine 2 at Faw Side. This approach effectively removes the EKA algorithm's factors of safety. Based on this approach there is a high likelihood that at least an additional 585 MW could be installed within the consultation zone. Should the proportion of turbines with structural resonance in the zone be high (compared to blade-pass) then it is possible that the additional capacity may be greater and exceed 1GW.

Xi Engineering Consultants

Eskdalemuir Wind Turbine Seismic Vibration

Extrapolation of Potential Installed Capacity Based on Observed Seismic Output of Modern WTGs with future scenario planning

Presented to The Scottish Government

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Document Summary

The detection capabilities of the Eskdalemuir seismic array (EKA) are protected from seismic vibration produced by wind turbines with an algorithmic tool. This tool employs a modelled worst-case turbine to estimate the cumulative impact of all turbines within 50 km of EKA. The cumulative budget level is then compared to a threshold level which has now been met, preventing the development of any further wind energy capacity in the consultation zone. It has been proposed that a large-scale measurement campaign of turbines would allow the removal of the safety margin used in the worst-case turbine algorithm and provide headroom for additional capacity. The likely additional budget head room that could be released by conducting an audit is examined here based on a recent measurement at the Middle Muir wind farm and is further supplemented with analysis of historic data from Clyde and Craig wind farms.

The Middle Muir analysis shows that there is significant head room and that there is a reasonable expectation of upwards of 480 MW of additional capacity. The capacity may be higher based on Clyde data which estimates 1.2 GW of additional wind energy. An analysis was also conducted on the size of the exclusion zone, showing that expanding the exclusion zone to 15km would triple the available capacity. Additional measures which would further increase capacity are also discussed.

		Date	Version	Amendment
Originator	Dr B Marmo	17th July 2020	v1	Issue
Review	Dr MP Buckingham	21st July 2020`	v2	Review
Review	R Horton	21st July 2020`	v3-6	Review
Review	Dr MP Buckingham	23rd July 2020	v7	Release

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1 INTRODUCTION

With good wind conditions and close proximity to population centres, southern Scotland has excellent potential for onshore wind generation. However, much of this region falls within the Eskdalemuir consultation zone and limits wind development. The zone is formed by a 50 km radius (representing nearly 10% of Scotland's total land area) surrounding the Eskdalemuir seismic measuring station (EKA) which is operated by the Ministry of Defence. To protect the EKA, wind turbines built in the area must operate within a seismic vibration budget of 0.336nm (Appendix A – Budget). Each turbine contributes to the budget based upon a worst-case hypothetical turbine. With the vibration budget of 0.336nm in the consultation zone reached there is no possibility to further develop and invest in the wind resource available in the region.

By design, the algorithm used to represent the worst-case turbine includes considerable factors of safety such that it over-estimates the cumulative seismic vibrations produced by wind turbines. An approach to the removal of the safety margin, and to therefore allow further wind capacity, is to directly measure the seismic output of turbines in the consultation zone. This would be a considerable undertaking. An estimate of head room that would be released by a measurement campaign has previously been made based on a small sample of publicly available data dating to 2011 from Craig wind farm and 2013 from Clyde wind farm. That analysis is supplemented in this report by adding new seismic data from the relatively modern Senvion turbines at Middle Muir wind farm. The outcome of the work can be used for a cost-benefit analysis related to embarking on a future seismic audit of a statistically significant number of wind turbines makes and models in the consultation zone. This document will present the extrapolation of potential Installed capacity in the Eskdalemuir Consultation Zone based on the observed seismic output of modern wind turbine generators (WTGs) and will include future scenario planning. In order to ease conversations around the project, results have been presented in both nanometres and megawatts.

The analysis of results for Middle Muir and the previous data sets from Craig and Clyde wind farms are used to access and inform three key areas:

1. The budget head room that a measurement may provide in nanometres
2. How this head room may be converted to installable capacity in megawatts
3. How increasing the exclusion zone at the centre of the consultation zone affects installable capacity

Additional measures which could further increase deployment potential are also discussed.

2 TECHNICAL BACKGROUND

Xi were commissioned by the Eskdalemuir Working Group (EWG) in 2013 to develop a robust physics-based approach to estimating the worst-case ground vibration produced by wind turbines. Xi developed an algorithm which is currently used by the Ministry of Defence (MoD) to calculate the worst-case cumulative effect of all wind turbines on the EKA; see "*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" (2014).

The physics-based approach uses an algorithm that creates a displacement spectrum (frequency vs seismic amplitude) that represents the seismic output measured at 1 km from any given turbine when the wind speed at a height of 80 m is 12 m/s. The premise behind the physics-based algorithm is that the wind energy that passes through a wind turbine can be considered to be portioned to electrical energy and lost energy. Losses will consist of energy converted to noise, frictional heat, seismic energy etc. Thus, some proportion of the energy passing through the rotor is converted to seismic vibration. The wind energy passing through the rotor is a function of wind speed and the swept area of the rotor. Thus, assuming that the proportion of wind energy that is lost to seismic vibration is constant, it is possible to scale the seismic vibration based on blade length (to give swept area) and hub height (giving wind speed relative 12 m/s at a height of 80 m). The input requirements for the algorithm are therefore hub height and rotor diameter which are commonly submitted with a planning application making the algorithm viable for the purpose of estimating seismic vibration at the planning stage of a wind farm's development.

The algorithm includes a Frequency Dependant Weighting Function (FDWF) which accounts for the variation in transmission of low and high frequencies, to determine what is detected at the array. This function would be used to design distant specific mitigation measures if required.

The algorithm variables were adjusted in order to best match or 'fit' the algorithm with the seismic data. The algorithm was fitted using seismic data from operational wind farms in southern Scotland which was collected in 2012. These wind farms were Craig wind farm consisting of four Nordex N80 turbines with a hub height of 60 m and rotor diameter of 80 m; Clyde wind farm consisting (at the time of measurement) of 152 Siemens 2.3 MW turbines with a hub height of 78.3 m and rotor diameter of 93 m and; Dun Law wind farm 26 Vestas V47 turbines with a hub height of 40 m and a rotor diameter of 47 m. As of 2020 these machines represent an older generation of wind turbine.

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3 BUDGET HEAD ROOM ASSESSMENT

To estimate the amount of headroom in the budget due to the amount that the worst-case algorithm over-estimates the cumulative amplitude, the wind turbine spectra used by the algorithm was tightly fitted to newly collected data from Middle Muir wind farm and the existing measurements of Craig and Clyde wind farms. This, in effect, removes the safety factor and better determines the likely seismic level if all wind farms were measured.

The revised algorithms that are fitted closely to data are then used to determine the cumulative level by all wind farms in the EKA queue, i.e. it is assumed that measurements at Middle Muir are representative of all wind turbines in the MoD queue, then that Clyde is representative, then Craig. The budget is currently over-subscribed. The budget threshold of 0.336 nm is breached when the third wind turbine at Faw Side is included. To calculate headroom in the budget, we consider all possible turbines that could be built without breaching the budget threshold. Thus, simulations are based on turbines in all farms up to and including Cliffhope (submitted 29/09/2017) and the first two turbines from Faw Side (submitted 11/01/2018). The budget que issued to Xi Engineering (Appendix A – Budget) does not include sites which were submitted into planning after Faw Side.

3.1 Method

3.1.1 MEASUREMENT OF MIDDLE MUIR WIND FARM

Middle Muir wind farm consists of 15 Senvion wind turbines each with 114 m rotor diameters and the power capacity of 3.4 MW. Eight of the turbines have 93 m hub heights and seven have 79 m hub heights (Figure 1). A seismic survey of Middle Muir was conducted between 5th May and 1st June 2020 using four Guralp 6TD medium motion seismometers. The neighbouring Andershaw wind farm (Figure 1) was operational during this period and its seismic levels will also have been detected at all four sensor locations. Andershaw consists of eleven Vestas 117 turbines. Full details of the measurement can be found in Appendix D – Measurement report.

Of the four sensors deployed, Sensor 1 had the best signal to noise ratio and was furthest from turbines in the Andershaw wind farm (Figure 1)). Multiple sensors are deployed to cover sensor failure and local site conditions. It is accepted practice that the sensor with lowest background noise be used to represent the site. For these reasons, the analyses in this report are based on results from Sensor 1 (Figure 2). The seismic amplitude from the Middle Muir wind farm were normalised to a single wind turbine measured at a distance of 1 km using the methodology defined in "*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" (2014). The seismic amplitudes of the 3.4 MW Senvion turbines at Middle Muir are comparable to 2.5 MW Nordex turbines at Craig and 2.3 MW turbines at Clyde (Figure 3). It should be noted that the measured seismic levels include background noise from other sources than just wind turbines. As measurements have not been conducted before and after installation, it is not possible to remove the background noise at this stage. Generally, the Middle Muir turbines have lower amplitudes at frequencies below 4.5 Hz than that of Craig and Clyde, and greater amplitude at frequencies greater than 5 Hz (Figure 3).

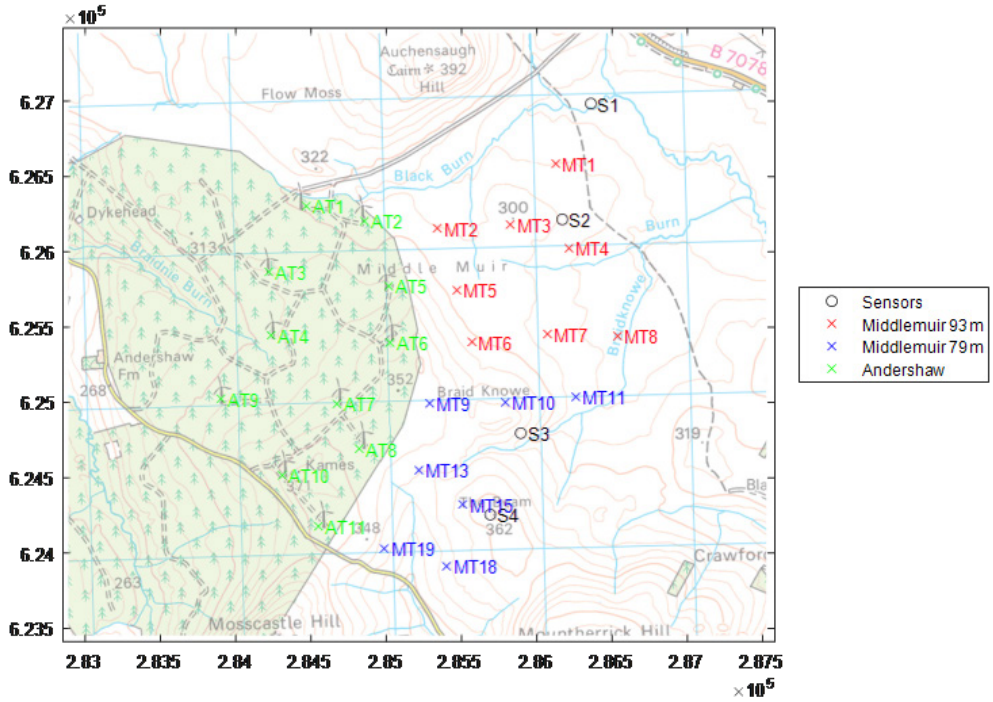

Figure 1 – Location map of seismic sensors and the wind turbines in the Middle Muir and Andershaw wind farms. The different hub heights of the Middle Muir turbines are also shown.

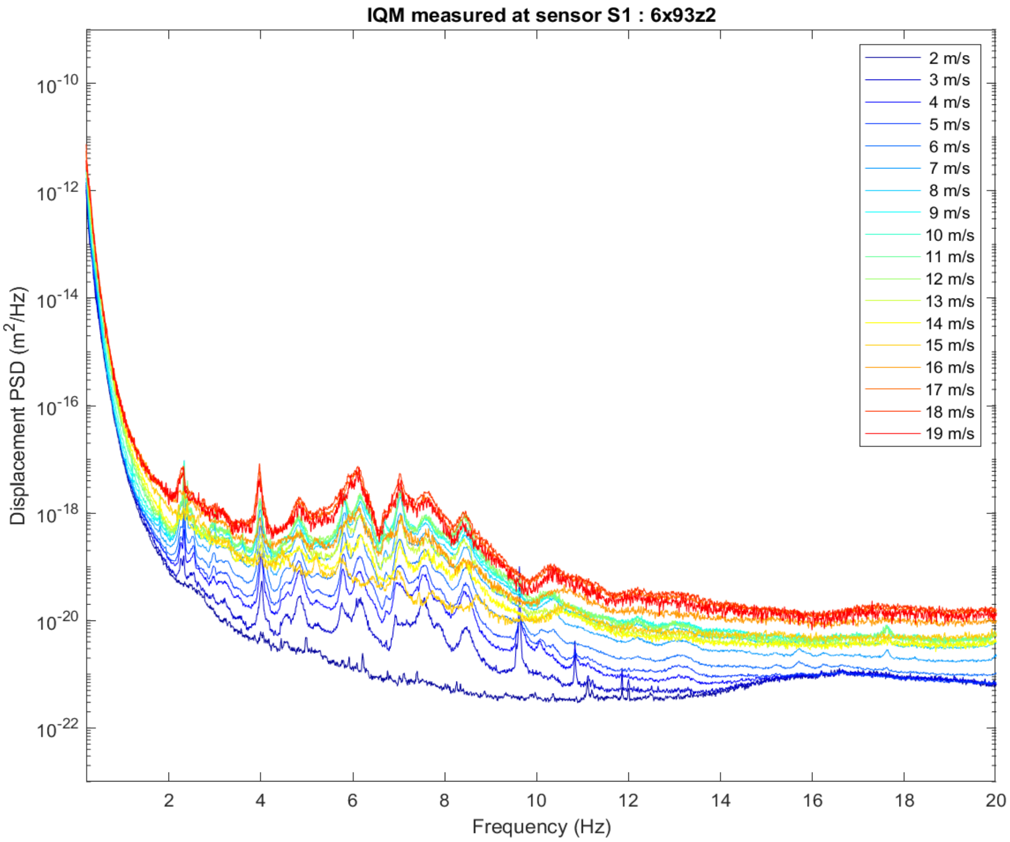

Figure 2 - Frequency spectra recorded by S1 with respect to different wind speeds on the range from 1 to 19 m/s.

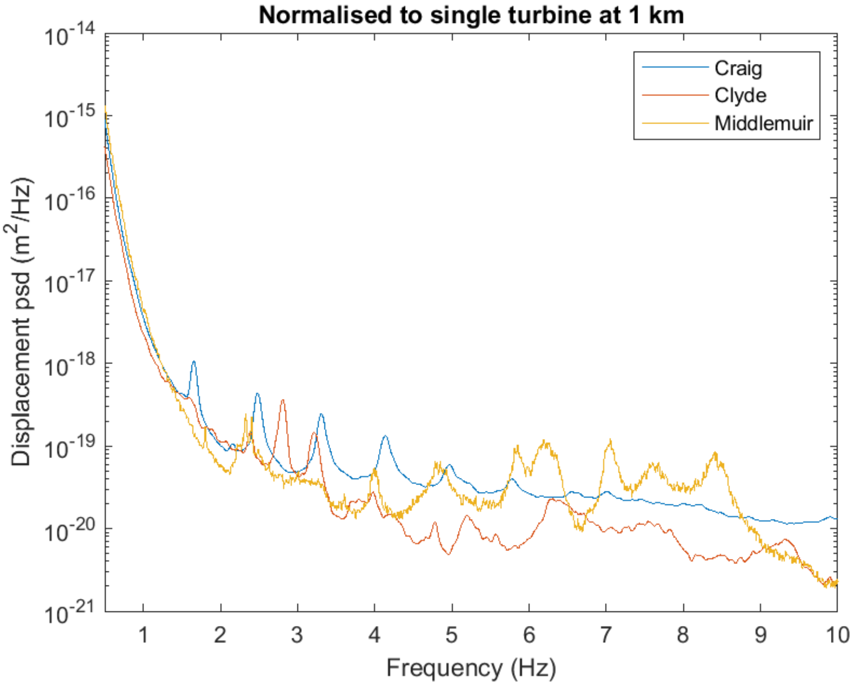

Figure 3 - Comparison of a Senvion turbine at Middle Muir normalised to 1km compared to Siemens S2.3 at Clyde and Nordex N80 at Craig.

3.1.2 FITTING ALGORITHM TO DATA

The algorithm's representation of wind turbine spectra was tightly fitted to the data recorded at Sensor 1 in the 12 m/s wind speed bin. The cumulative amplitude from all turbines in the Middle Muir and Andershaw wind farms were predicted based on each of their hub heights, rotor diameters and distance to Sensor 1. The coefficients used by the algorithm to represent wind turbines were adjusted and the algorithm iterated until a tight fit was achieved between data and algorithm. The algorithm coefficients that best represent the turbines at Middle Muir-Andershaw are listed in Table 1.

The representation of the wind turbine in the algorithm was tightly fitted to Craig wind farm to remove the factor of safety related to blade-pass (Figure 5). The representation of the wind turbine in the algorithm was tightly fitted to Clyde to remove the factor of safety related to structure resonances (Figure 6). The algorithm coefficients that best represent the turbines at both the Craig and Clyde wind farms are listed in Table 1.This will allow an analysis of results that will give insight into the seismic output of the turbines without the over estimation included as part of the safety factor built into the current algorithm used by the MOD.

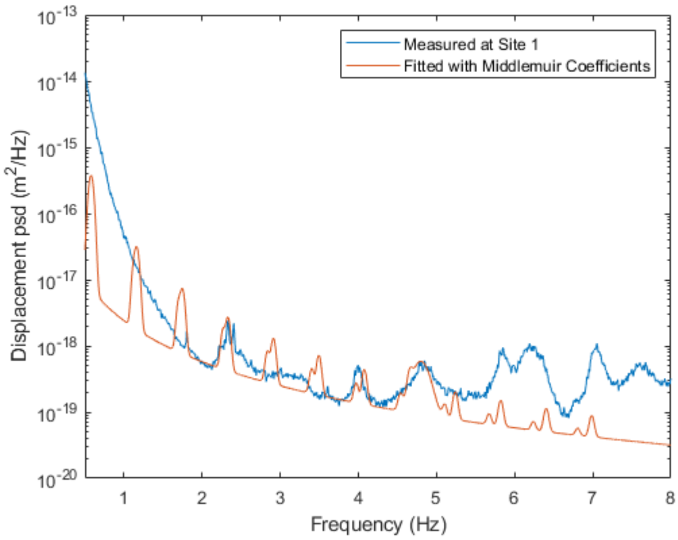

Figure 4 – Comparison of measured spectra at Middle Muir to algorithm with fitted coefficients

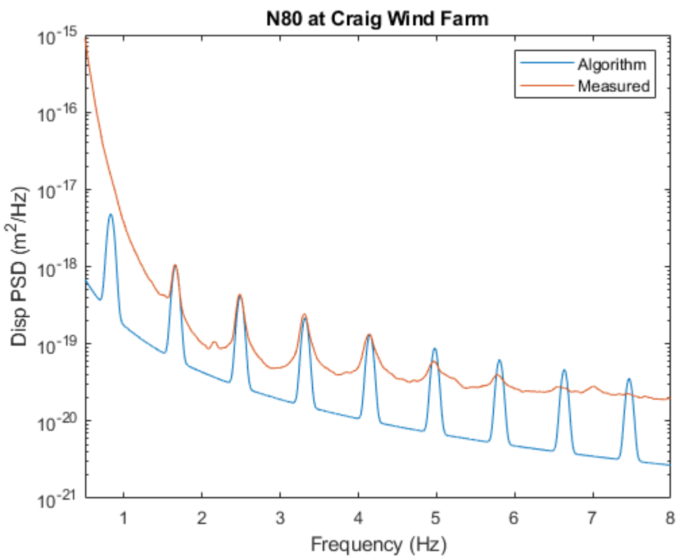

Figure 5 – Algorithm fitted to blade-pass dominated spectra measured at Craig wind farm. Please note the noise floor (level of troughs between peaks) was not fitted to Craig data in the 2014 Report, but rather the Clyde data set.

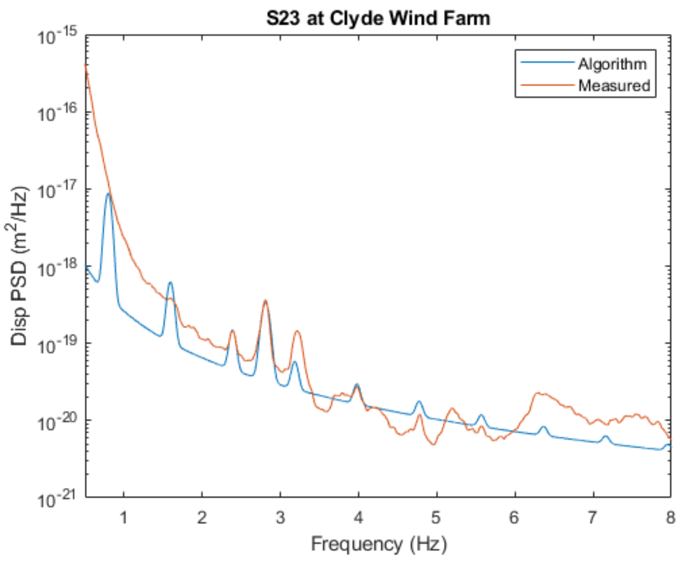

Figure 6 Algorithm fitted to structural resonance dominated spectra measured at Clyde wind farm.

Coefficients	Standard EKA	Middle Muir / Andershaw	Clyde fitted data	Craig fitted data
Blade pass amplitude multiplier	2.87E-25	8.00E-25	2.87E-25	3.87E-25
Blade pass amplitude exponent	1.76	3.5	4	2.25
Blade pass shape parameter	0.04	0.03	0.04	0.04
Bending mode amplitude multiplier	9.23E-26	8.10E-27	2.62E-26	0.00E+00
Frequency of bending mode	2.808	4.8	2.808	2.808
Bending mode shape parameter	0.05	0.1	0.05	0.05
Operational broadband noise multipliers	2.23E-26	3.50E-26	2.23E-26	2.23E-26
Tip Speed (m/s)	77.49	69.5	77.49	69.49

Table 1 – Parameters used in the four different representations of wind turbines seismic output. The parameters relate to those described in Section 8.2.1 of ***Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project***

3.1.3 HEAD ROOM QUEUE ASSUMPTIONS

Calculations are based on the wind turbines in the EKA budget spreadsheet that was issued to Xi on the 3rd of February 2020. According the Ministry of Defence, this spreadsheet was current on the 20th January 2020, but does not include any sites submitted after Faw Side. The spreadsheet includes turbines locations as OS Grid references, turbine hub heights and rotor diameters (Appendix A – Budget). The head room calculations are based on all turbines that are currently in the queue that do not breach the 0.336 nm threshold; i.e. all farms up to and including Cliffhope (submitted 29/09/2017) and the first two turbines from Faw Side (submitted 11/01/2018).

3.2 Results – head room calculation

The head room based on fitting the algorithm to data from each wind farm are listed in Table 2. If the turbines at Middle Muir are a good representation of all turbines in the queue, then the head room in the budget is 0.097 nm. If the Siemens turbines at Clyde are representative then the head room increases to 0.149 nm, and if the Craig turbines are representative then the head room is 0.075 nm. Table 2 lists the over-estimate of turbine contribution taken as the ratio between the difference to the standard EKA estimate, and the standard EKA estimate (0.332 nm). The amount of head room is dependent on the make and model of the turbine.

	Turbine	Cumulative Amp (nm)	Head Room (nm)	Over-estimate (%)
Threshold		0.336		
Standard EKA		0.332	0.004	
Middle Muir / Andershaw	Senvion / Vestas	0.239	0.097	28.0
Clyde	Siemens	0.187	0.149	43.7
Craig	Nordex	0.261	0.075	21.4

Table 2 – Calculation of head room based on fitting the algorithm to data. The calculation of cumulative amplitude and head room assume that the listed turbines are a good representation of the all turbines in the queue.

4 POSSIBLE ADDITIONAL CAPACITY

Estimating the additional wind energy capacity that the budget head room in nanometres relates to is non-trivial. The impact of wind turbines on EKA is strongly dependent of the distance between the turbine and the seismic array; a single turbine 10 km from EKA has the same impact as ~80 turbines placed 50 km away. Thus, the number of megawatts that each nanometre of head room corresponds to is very dependent on where additional turbines are placed, and also the type of turbines as previously discussed. To help assess the additional capacity, five scenarios have been simulated where the consultation zone is populated with wind turbines in different ways:

- Scenario 1 – Populated the area following the method in the 2014 report to inform the radius of the exclusion zone. This employed a "developable area" as defined by RES.
- Scenario 2 – Populated the consultation zone evenly with no restrictions due to cultural or geographic factors.
- Scenario 3 – Populated the consultation zone evenly with restrictions related to cultural, geographic factors and pre-existing or planned wind turbines.
- Scenario 4 – Populated with weighting towards the 50 km edge of the consultation zone. Include restrictions related to cultural, geographic factors and pre-existing or planned wind turbines.
- Scenario 5 – Populated with weighting towards the 10 km edge of the exclusion zone. Include restrictions related to cultural, geographic factors and pre-existing or planned wind turbines.

Of these five population patterns, Scenario 3 is the most robust with respect to estimating additional capacity in megawatts. Scenarios 4 and 5 are included here to demonstrate how sensitive the consumption of budget overhead is to turbine placement. Scenarios 1 and 2 do not contribute significant additional information and have been included as appendices for completeness (please see, Appendix B – Scenario 1 and Appendix C – Scenario 2).

4.1 Method

A randomised iterative approach to the addition of wind turbines to the consultation zone was used to estimate how the budget head room relates to additional capacity in megawatts. Turbines equivalent to the largest currently being installed (e.g. those at Middle Muir) were added randomly within the consultation zone between 10 km and 50 km from EKA. The size of turbines added in the simulation were:

- Hub height = 93.5 m
- Rotor Diameter = 117 m
- Power = 3.4 MW

The simulations avoided placement of turbines on populations centres (e.g. town such as Langholm, Hawick, etc.), reservoirs and their embankments (e.g. Kielder Water) or within 10 rotor diameters of wind turbines existing or in planning (Figure 7). In all, 16% of the consultation zone between 10 and 50 km was excluded due to cultural or geographic reasons.

The simulation proceeds by adding turbines sequentially to random locations until the budget threshold was reached (0.336nm). The number of turbines and their combined power was calculated. The simulation was then re-run, again by randomising the position of each turbine within the zone. The simulation was iterated in this way 1000 times for each scenario and the additional capacity taken as the mean (average) of all the simulations. The standard deviation of the additional capacity was also calculated for each simulation and represents the spread of data within the 1000 iterations of the model, where 68% of the additional capacity results fall with one standard deviation from the mean value.

The distribution in Scenario 3 was linear, i.e. the possibility of turbine placement is independent of distance from the EKA (Figure 8). Scenarios 4 and 5 have non-linear distributions that are weighted towards the 50 km boundary and 10 km exclusion zone respectively (Figure 8). Scenario 4 plotting of turbines can be seen in (Figure 9) The troughs in the distributions at 30 and 42 km shown in Figure 8 are due to the high numbers of possible positions having been excluded from the simulations due to the presence of existing wind farms and cultural centres at those radii from EKA.

All simulations presented here were performed using bespoke code written using the commercially available software package MATLAB. The codes used follow the methods described in "*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" and are consistent with those used to calculate the EKA budget.

Figure 7- Regions avoided in Scenarios 3 to 5. Avoided population centres are shown in red, water ways in blue and pre-existing and planned wind turbines are purple crosses. The 10 km exclusion zone is shown as is the 50 km boundary of the consultation area.

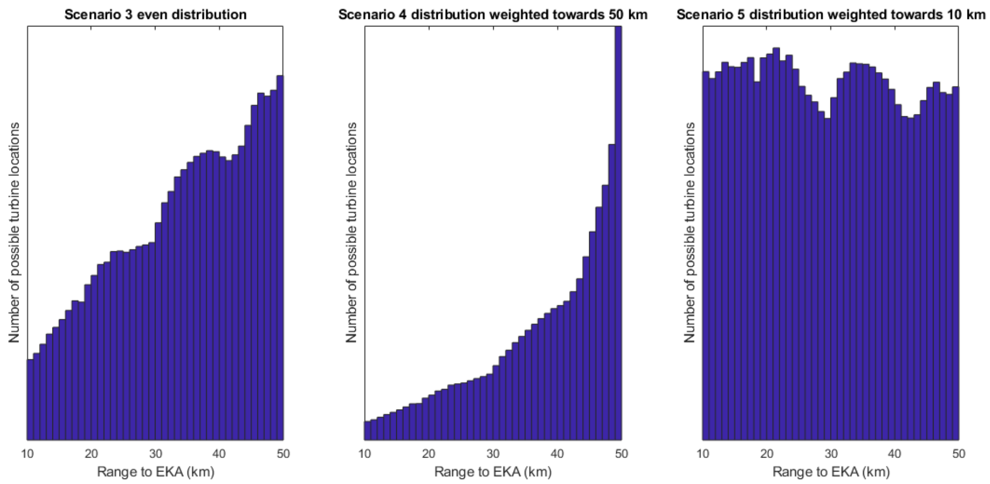

Figure 8 – Distribution of wind turbine additions for the three different scenarios; even; weighted towards 50 km; weighted towards 10 km. In each iteration of the simulation the turbines range is random and the simulation continuous until the budget threshold is breached. Therefore, number of turbines in each simulation is different and the y-axis is therefore only indicative (thus, the authors have not included numbers on the y-axis).

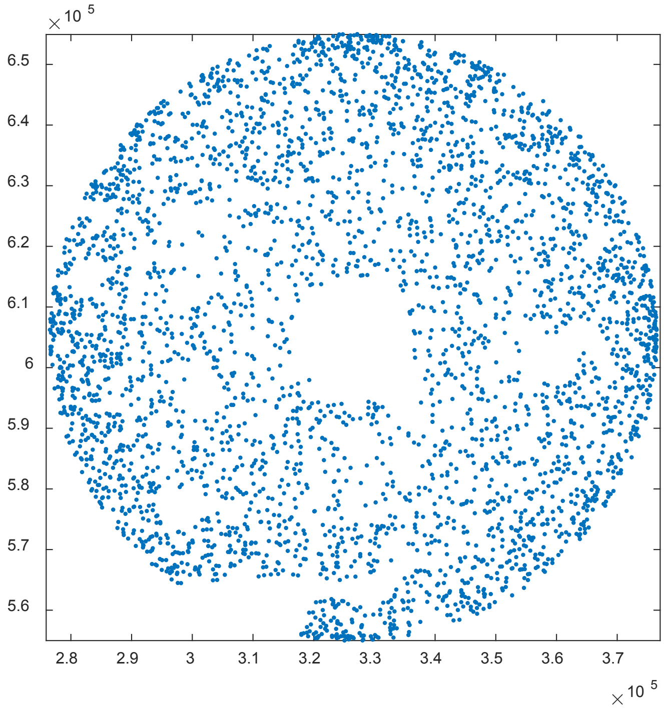

Figure 9 Location map of turbines distributed under scenario 4 – distribution weighted towards 50km

4.2 Results

The amount of additional wind energy capacity that the head room may allow assuming an even spread of turbines through the consultation zone are listed in Table 3. The additional capacity and number of turbines listed in Table 3 are taken as the mean of 1000 simulations and the uncertainty is taken as one standard deviation. The additional capacity is dependent on the available head room, which in turn is dependent on the type of turbine used to calculate the head room. If the Senvion turbines at Middle Muir are representative of all turbines in the consultation zone resulting in head room of 0.097 nm, then 476±142 MW of additional capacity would likely result from the even distribution of ~141 3.4 MW turbines. Should the Siemens turbines at Clyde be representative then an additional 1.1±0.18 GW is likely and if the Nordex turbines at Craig are representative then the additional capacity would likely be 310±92 MW.

The additional number of turbines and related capacity is strongly dependent on the distribution of those turbines. Table 4 lists how the head room converts to additional capacity when more turbines are built close to 50 km, while Table 5 lists how the head room converts to additional capacity when more turbines are place close to 10 km. For the given weighting in the distribution there is a four-fold increase in additional capacity when the distribution is weighted towards 50km compared to 10 km (Table 6).

Scenario 3	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	26.3 ± 20.8	8.7 ± 6.2
Middle Muir	0.097	476.9 ± 142.2	141.3 ± 36.5
Clyde	0.149	1179.8 ± 180.5	348.0 ± 53.1
Craig	0.075	310.2 ± 87.4	92.2 ± 28.4

Table 3 – Consumption of head room by an even distribution of 3.4 MW turbines. Estimates of additional capacity and number of turbines when the that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Scenario 4	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	46.7 ± 36.0	14.7 ± 10.6
Middle Muir	0.097	872.5 ± 222.8	257.6 ± 65.5
Clyde	0.149	2147.6 ± 330.7	632.6 ± 97.3
Craig	0.075	558.0 ± 165.1	165.1 ± 52.5

Table 4 – Consumption of head room the distribution of 3.4 MW turbines that is weighted towards 50 km. Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Scenario 5	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	11.9 ± 11.2	4.3 ± 3.5
Middle Muir	0.097	216.9 ± 58.4	64.8 ± 17.2
Clyde	0.149	547.6 ± 89.7	162.1 ± 26.4
Craig	0.075	144.3 ± 43.8	43.4 ± 14.0

Table 5 – Consumption of head room the distribution of 3.4 MW turbines that is weighted towards 10 km. Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Middle Muir - summary	Head room nm	Additional Capacity MW	Number of turbines
Scenario 3 – Linear Distribution	0.097	476.9	141.3
Scenario 4 – Weighted to 50 km	0.097	872.5	257.6
Scenario 5 – Weighted to 10 km	0.097	216.9	64.8

Table 6 – Summary of how the distribution of turbines affects the additional number of turbines and capacity before the threshold is breached. These values are when the simulation uses measured data from Middle Muir is used for each additional turbine.

5 EXCLUSION ZONE ANALYSIS - CAPACITY

5.1 Method

An analysis of the relationship between the radius of the exclusion zone and the additional installable capacity was conducted. The radius of the exclusion zone was varied and the simulations re-run assuming even distribution of 3.4 MW turbines following a similar approach to Scenario 3. The analysis was conducted assuming that Middle Muir is representative of all turbines in the queue and that the head room is 0.097 nm.

5.2 Results

The increase in additional capacity with increase to the exclusion zone is listed in Table 7 and shown in Figure 10. The additional capacity if additional turbines are added evenly increases from 476 MW for an exclusion zone of 10 km to 1.2 GW when the exclusion zone is 15 km and 3.0 GW when it is 20 km (Table 7).

Exclusion zone radius	Additional capacity	
	Mean	Standard Deviation
km	MW	MW
10	476.1	120.7
11	573.1	124.0
12	700.0	132.5
13	862.3	139.9
14	1043.9	144.5
15	1272.8	148.1
16	1518.2	157.4
17	1826.9	158.9
18	2192.9	161.9
19	2583.4	168.2
20	3069.7	183.3

Table 7 - Variation in additional capacity with the size of the exclusion zone based on Middle Muir measurements being representative and the consumable head room being 0.097 nm. An even distribution in the remaining consultation zone was assumed with some regions excluded due to cultural or geographic reasons.

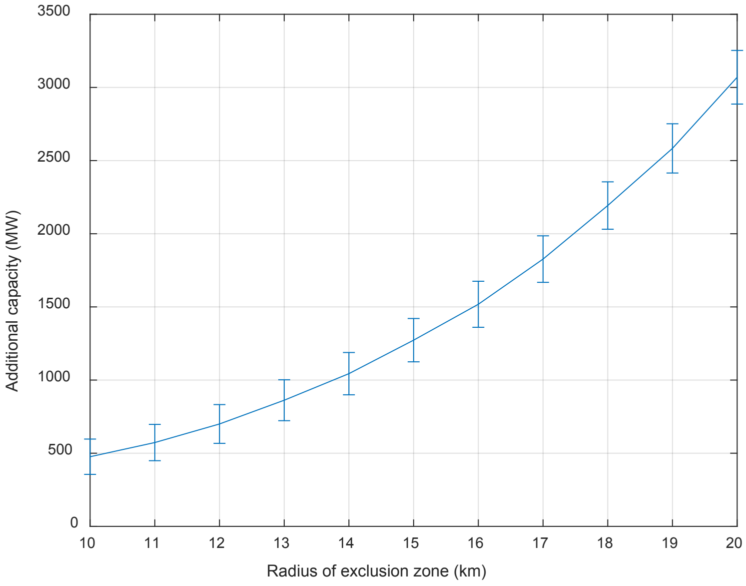

Figure 10 – Variation in additional capacity with the size of the exclusion zone based on Middle Muir measurements being representative and the consumable head room being 0.097 nm. An even distribution in the remaining consultation zone was assumed with some regions excluded due to cultural or geographic reasons. The uncertainty bars show one standard deviation around the mean capacity of 1000 simulations for each radii.

6 EXCLUSION ZONE ANALYSIS – SENSITIVITY TO A LARGE CLOSE WIND FARM

6.1 Method

Given that wind turbines commonly are placed in farms rather than single randomly distributed deployments, an analysis of the sensitivity to a large farm being placed directly on the boundary of the exclusion zone was conducted. The radius of the exclusion zone was varied, and 3.4 MW turbines sequentially placed at the radius of exclusion until the threshold was breached. The analysis was conducted with the algorithm based on Middle Muir results. The standard EKA algorithm was also used as a source of comparison. To allow the analysis to provide informative results initially no turbines were placed at Faw Side (in all other analyses present here Faw Side turbines 1 and 2 have been included).

6.2 Results

The exclusion zone is currently 10 km. Without Faw Side turbines 1 and 2, the head room based on Middle Muir being representative data, increases to 0.1286 nm (from 0.097 nm). The 0.1286 nm of head room would be consumed by placing seven 3.4 MW turbines at 10 km resulting in the additional capacity of 23.8 MW. The number of turbines on the edge of the exclusion zone that would exhaust the head room increases to 35 for a 15 km exclusion zone, and 137 for a 20 km exclusion zone (Table 8, Figure 11 and Figure 12).

In comparison, when the standard algorithm is used the head room without Faw Side turbines 1 and 2 is 0.0481 nm (increased from 0.004 nm). This head room is consumed by the first 3.4 MW turbine placed on a 10 km exclusion zone boundary. An 11 km exclusion zone would be exhaust with two wind turbines at this distance; this is equivalent to Faw Side 1 and 2, which are both ~ 11km from EKA (Table 8). Based on the standard EKA algorithm the number of turbines on the edge of the exclusion zone that would exhaust the head room increases to seven for a 15 km exclusion zone, and 29 for a 20 km exclusion zone (Table 8).

Range	Middle Muir		EKA Standard	
Exclusion zone (km)	Power MW	Number of turbines	Power MW	Number of turbines
10	23.8	7	3.4	1
11	34	10	6.8	2
12	47.6	14	10.2	3
13	64.6	19	13.6	4
14	88.4	26	17	5
15	119	35	23.8	7
16	159.8	47	34	10
17	210.8	62	44.2	13
18	275.4	81	57.8	17
19	360.4	106	74.8	22
20	465.8	137	98.6	29
21	598.4	176	125.8	37
22	761.6	224	159.8	47
23	969	285	200.6	59
24	1220.6	359	255	75
25	1533.4	451	319.6	94

Table 8 – Number of turbines that could be placed on any given exclusion zone before the threshold is reached based on Middle Muir being representative. For this analysis no turbines were initially placed at Faw Side. The EKA standard algorithm is compared; the first two turbines at Faw Side are ~ 11km which is reflected in this table were the EKA algorithm allows two turbines at that distance.

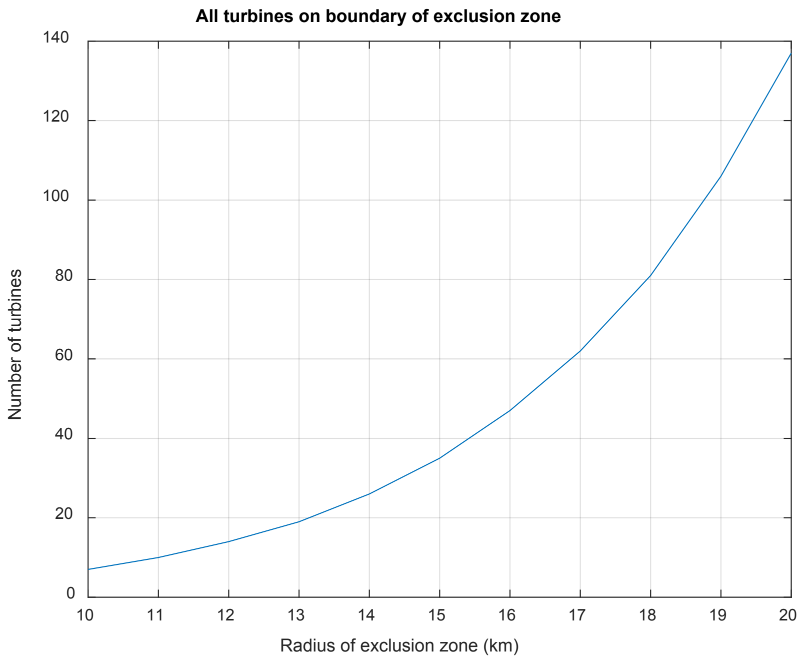

Figure 11 – Number of turbines that can be placed on the exclusion zones with different radii without breaching the budget threshold based on Middle Muir results.

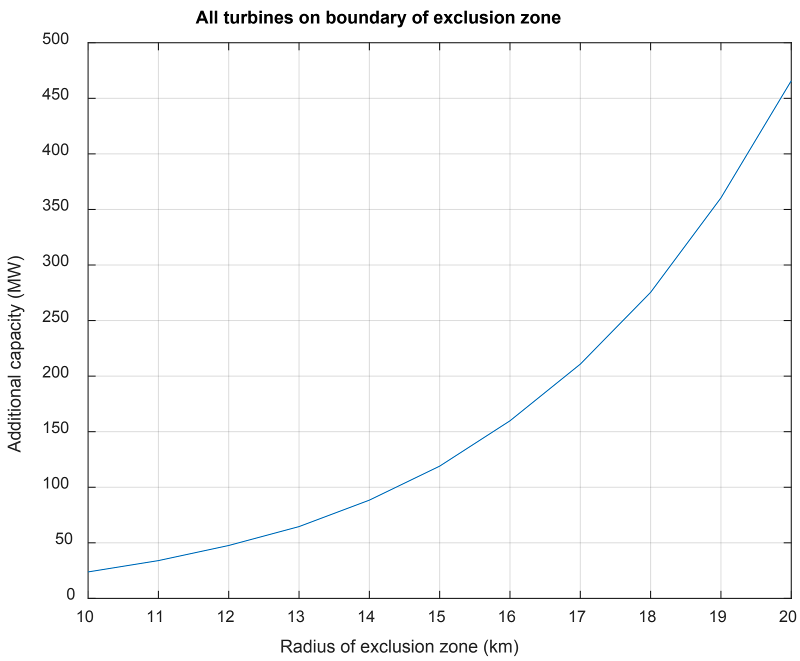

Figure 12 – Additional capacity related to 3.4 MW turbines placed on the exclusion zones with different radii without breaching the budget threshold based on Middle Muir results.

7 DISCUSSION

7.1 Head room

The work presented here seeks to establish whether significant head room would be released if assessment of wind turbine generated seismicity using an algorithm with a safety factor was to be replaced by actual measurement of wind turbines. In all cases examined, which include four different turbine makes (Siemens, Nordex, Senvion and Vestas), the standard EKA algorithm over-estimates the wind turbines seismic levels. This is observation is expected as it reflects the safety factor designed into the standard EKA algorithm; the algorithm is serving its primary purpose, that of protecting the detection capabilities of the Eskdalemuir seismic array.

To estimate the amount of head room that direct measurement would provide, the algorithm was tightly fitted to measurements at Middle Muir, Clyde and Craig. This provided three modified algorithms that do not contain safety factors. The approach implies that in each analysis the data set chosen is representative of all turbines. Following this approach, the head room for the latest measurement at Middle Muir is 0.097 nm, with a range of all analyses from 0.075 nm and 0.149 nm corresponding to an over-estimate by the standard EKA algorithm in the range of 21.3 to 43.6%.

Based on these analyses (Table 2) it is clear that the seismic level and the related head room calculations are dependent on the make and model of the turbine. The consultation zone includes many different makes and scales of turbine, it is therefore likely that the head room will be a blend and lie somewhere between 0.075 nm and 0.149 nm. Given that the several large wind farms within the consultation zone such as Clyde and Ewe Hill that make significant seismic contributions to EKA and have Siemens S2.3 turbines installed there is a reasonable expectation that the head room is likely to be towards the higher side of the range.

7.2 Increased capacity

The simulations presented here assume that, should headroom become available, it would be built out using large modern wind turbines such as those currently being installed at Middle Muir wind farm. In fact, increased capacity in the consultation zone would more likely include a range of different sized turbines. However, for the purposes of converting headroom to installed capacity, it seems reasonable to use turbines likely to be installed by large developers that will consume the largest proportion of headroom.

The simulations use a random placement of turbines in the consultation zone to estimate additional capacity. The simulations considered the avoidance of areas due to geographic reasons such as water ways, existing and planned wind farms, and residential areas. However, there are other reasons that areas may be avoided that are not considered here such as aviation, sights of special scientific interest and other planning restrictions. A more complete analysis would require input from the wind turbine sector on such restrictions. For the purpose of estimating how nanometres of headroom relate to additional megawatts, the author believes it is reasonable to randomly populate the consultation zone with the exclusion due to the cultural and geographic reasons as reported.

It has been proposed to conduct a large-scale measurement campaign and audit of seismic levels produced by wind turbines in the consultation zone. Based on the assumptions presented, it is reasonable to believe that the head room provided by such a campaign would result in the additional wind energy capacity of between 310 MW and 1.2 GW. Based on the most modern measurement at Middle Muir the additional capacity is 480 MW. As noted above, the high side of the head room range is based on Siemens turbines at Clyde, and given the contributions of Clyde and Ewe Hill wind farms it is likely that the additional capacity may be towards the higher side of the 310 MW to 1.2 GW range.

The amount of additional capacity is very dependent on the locations of additional wind turbines. An analysis was undertaken that compared weighting the addition of wind turbines towards the 50 km boundary of the consultation zone or the 10 km exclusion zone. There was a four -fold increase when turbine locations were weighted towards the 50 km radius compared to the 10 km exclusion zone. When turbines locations are weighted toward 50 km the additional capacity range increases to 600 MW to 2.1 GW. The strong dependence on additional capacity on distance from EKA may provide an incentive to excluding turbine development close to EKA by increasing the exclusion zone from 10 km.

7.3 Exclusion zone

The conversion of any budget over head to additional capacity would be increased by expansion of the exclusion zone from its current 10 km. Using the algorithm based on Middle Muir and assuming random placement of turbines the additional capacity increases from 476 MW with a 10 km exclusion zone to 1.2 GW for a 15 km zone, to 3.0 GW for a 20 km zone. It should be noted that 3.0 GW implies the addition of 900 new wind turbines which may be prohibitive on ground outwith seismic level such a visual impact.

The amount of additional capacity is very sensitive to large wind farms being placed close to the exclusion zone. While a full audit of the consultation zone may release enough budget to build 300 MW to 1.2 GW of capacity, if the first seven turbines were placed on the 10 km exclusion zone the budget would be saturated with only 23.8 MW installed (Table 8). This implies that audit would need to be conducted in concert with a change to the exclusion zone.

7.4 Potential areas for additional budget

7.4.1 BACKGROUND NOISE

The measured data used for the calculation of budget using data from Middle Muir, Clyde or Craig included background noise which is not generated by wind turbines. The background noise comes from natural sources or from localised human activities. As all three sites were not measured prior to installation, one is not able to accurately remove the noise caused by non-turbine sources. Removing the background seismic energy to calculate the contribution just wind turbines make would further increase the budget. Conducting before and after installation measurements of sufficient length would allow quantification of background noise and provide a means of removing this energy from the calculations. Removal of background noise would effectively reduce the seismic levels of the turbines and further increase capacity in the region.

7.4.2 REVISED BUILDABLE AREA

If the exclusion areas in scenarios 3 – 5 were to be assessed by wind farm developers for no build zones for reasons other than pre-existing turbines, population centres and waterways, this would allow for more accurate placement of turbines within the area which might lead to increased capacity.

7.4.3 TURBINE SPECIFIC DEPLOYEMENT

As has been shown in this report, the specific make, model and size of turbines has a profound impact on the budget. If the issues facing developers here were of cumulative noise, the turbines with the lowest noise levels would be sought for deployment. Having a documented measurement method would allow manufacturers to provide data to developers in order that the turbines with least seismic impact were deployed. Ideally a measurement which would remove the background noise would allow developers to see which potential turbines would have the least effect. The FDWF would be used to determine which turbines were best suited to the proposed distance from the array.

7.4.4 TURBINES WITH MITIGATION

In the original Styles 2005 Eskdalemuir working group report ‘Microsiesmic and Infrasound of low frequency Noise and Vibration from Windfarms, Recommendations on the siting of windfarms in the vicinity of Eskdalemuir, Scotland’ it was proposed that turbines within 7.5km of the exclusion zone should deploy mitigation technologies to further reduce the seismic contribution of the wind farms. As has been shown, a single farm on the edge of an exclusion zone can rapidly consume the entire budget. If for example, wind turbines within the 15-20Km zone were required to reduce seismic levels to a level the site would have if it were at 20km then capacity would be greatly improved. Technologies exist which isolate buildings and large structures from seismic waves, in essence using the similar technologies to isolate the turbine foundation would have the desired effect.

8 CONCLUSION

A seismic survey of the Middle Muir wind farm has shown that the seismic contribution of it, and the neighbouring farm at Andershaw, are over-estimated by the standard EKA algorithm by ~28%. The algorithm was tightly fitted to data from Middle Muir and previous data sets from Craig and Clyde wind farms to assess the amount of head room that direct measurement of wind turbines may provide. The results were dependent on the make and model of turbines with a value of 0.097 nm for Middle Muir and a range between 0.075 nm and 0.149 nm for the three wind farms.

To estimate how budget head room may convert to megawatts of additional wind capacity turbines were distributed evenly through the consultation zone. Based on this even distribution the data from Middle Muir estimates an additional capacity of 480 MW. If the turbines at Clyde are representative of all wind turbines, then value for additional capacity would be 1.2 GW.

An increase in the exclusion zone would result in higher additional capacity. By increasing the radius of exclusion to 15 km the additional capacity increases threefold.

The amount of additional capacity is susceptible to a single large wind farm on the boundary of the exclusion zone; the additional capacity drops from 480 MW to 24 MW if just seven turbines were built 10 km away.

Additional measures to further increase the budget including mitigation for turbines close to the boundary have been discussed.

9 APPENDIX A – BUDGET

Wind Farm	Sub. Date	LPA Ref.	DIO Ref.	Number	Capacity (MW)	Mean Distance (km)	Amplitude (nm)	Cumulative Amp	Status
Bowbeat	01-Jul-02	-	7748	24	31.2	42.304	0.0044188	0.0044188	Consented
Carlesgill	01-Dec-03	-	2825	5	12.5	20.050	0.0316134	0.0319208	
Halkburn - Longpark	01-Feb-04	0400317FUL	2095	19	38	42.854	0.0054465	0.0323821	Consented
Langhope Rig	01-Jun-04	06/01236/FUL	4135	10	23	21.359	0.0446918	0.0551902	Consented 10 turbines 16 MW
Clyde	01-Nov-04	-	2153	152	456	29.993	0.0733031	0.0917567	Consented
Harestanes	21-Dec-04	IEC 3/77	1823	68	204	27.294	0.0505711	0.1047699	Consented
Dalswinton	01-Jan-05	P/SAFE/03/D/1	2101	15	30	35.872	0.0096082	0.1052096	Consented
Minsca	01-May-05	-	1961	17	42.5	24.816	0.0359210	0.1111727	Consented 16 Turbines 36.8 MW
Carcant	01-Oct-05	05/01884/FUL	2128	3	9.9	49.191	0.0007891	0.1111755	Consented 3 Turbines 6.9 KW
Ewe Hill	01-Nov-05	IEC 3/65	1513	22	50.6	19.016	0.0753808	0.1343214	Consented
Andershaw	01-Jul-07	CL/07/0454	4530	11	36.3	46.623	0.0049779	0.1344137	Consented
Middle Hill - Glenkerie	01-Feb-08	07/02478/FUL	4473	11	22	29.240	0.0162102	0.1353876	Consented
Langshaw Farm	01-Apr-08	09/01140/FUL	8532	1	0.05	43.815	0.0001952	0.1353877	
Aikrigg Cottage	08-Sep-08	08/0879	7349	1	0.006	49.631	0.0000325	0.1353877	
Kingstown Ind Estate	27-Oct-08	SE/DC/08/1030	7073	1	0.015	47.432	0.0000402	0.1353877	
Lammerlaw Farm 7153	11-Nov-08	CL/08/0654	7153	1	0.011	44.266	0.0001259	0.1353878	
Brunstock Close	17-Dec-08	ARH/DC/08/1199	7291	1	0.006	48.525	0.0000269	0.1353878	
Minnygap	01-Aug-09	09/P/3/0340	3313	10	20	25.271	0.0283219	0.1383184	Consented
Carlesgill Ext	01-Sep-09	09/P/4/0342	7386	1	2.5	19.070	0.0157422	0.1392114	
Land East of Braidwood	15-Dec-09	09/01700/FUL	8716	1	0.006	34.538	0.0001388	0.1392115	
Westmill Farm	17-Mar-10	CL/10/0449	9302	1	0.11	44.374	0.0000920	0.1392115	
Windyknowe	07-Jun-10	CL/10/0239	9781	1	0.006	43.544	0.0000570	0.1392115	
Land NW of Ferniehaugh	15-Jul-10	10/00985/FUL	10654	2	0.06	48.043	0.0000926	0.1392115	
Lochmailing	05-Oct-10	11/P/3/0037	10203	1	0.015	40.750	0.0001460	0.1392116	
Threepwood	12-Oct-10	10/01421/FUL	11039	1	0.015	45.251	0.0000954	0.1392116	
Lauder B	12-Oct-10	10/01382/FUL	9508	2	0.12	49.762	0.0001156	0.1392117	
Rennieston Edge	17-Oct-10	10/00306/FUL	9248	1	0.06	41.055	0.0000722	0.1392117	
Meadowside Cottage	17-Jan-11	cl/11/0021	11918	1	0.02	44.196	0.0001247	0.1392118	
Mosshouses Farm	08-Feb-11	11/00123/FUL	10713	1	0.015	43.912	0.0000961	0.1392118	
Land SW of Larkhill	21-Feb-11	11/00195/FUL	12341	1	0.015	47.902	0.0000885	0.1392118	
Hall Burn	01-Mar-11	13/0865	8275	6	18	39.810	0.0055591	0.1393228	Consented
Muirlea Farm	15-Mar-11	CL/11/0098	12598	2	0.04	43.194	0.0001969	0.1393229	
Whinney Rig	02-May-11	11/P/4/0161	10724	1	0.1	36.110	0.0004222	0.1393235	
Hillfield	11-May-11	11/0339	13287	1	0.005	47.666	0.0000353	0.1393236	
Cargo Farm Cottage	12-May-11	11/0338	13259	2	0.04	47.000	0.0001359	0.1393236	
Land NW of The Batts	16-May-11	11/00621/FUL	13278	1	0.015	47.538	0.0000793	0.1393236	
Burnhouse	18-May-11	CL/11/0212	13323	1	0.015	42.998	0.0000927	0.1393237	
The Beeches	19-May-11	CL/11/0201	13339	1	0.02	46.052	0.0001074	0.1393237	
Symington Mains Farm	24-May-11	11/00560/FUL	13428	1	0.02	46.233	0.0001048	0.1393238	
Midhill	25-May-11	CL/11/0217	13375	1	0.015	43.596	0.0001320	0.1393238	
Newton of Wiston	25-May-11	CL/11/0220	13383	1	0.015	42.623	0.0000961	0.1393238	
Newtonhead	09-Jun-11	CL/11/0246	12599	1	0.06	49.599	0.0001432	0.1393239	
Gaups Mill	10-Jun-11	11/D/3/0008	13531	1	0.01	49.671	0.0000428	0.1393239	
South Melbourne Farm	17-Jun-11	cl/11/0256	13535	1	0.006	43.091	0.0000595	0.1393239	
Walston Braehead Farm	27-Jun-11	CL/11/0281	13636	3	0.18	45.465	0.0001964	0.1393241	
Easton Farm	06-Jul-11	CL/11/0298	13813	1	0.02	47.679	0.0000917	0.1393241	
Pumro Fell	15-Jul-11	08/P/3/0209	13897	1	0.0015	27.622	0.0000817	0.1393241	
Rivox	01-Aug-11	11/P/4/0262	14164	1	0.015	23.373	0.0006970	0.1393259	
Braco Farm	09-Aug-11	11/P/3/0457	12042	2	0.06	49.030	0.0000979	0.1393259	
Land at Arthurshiels	11-Aug-11	CL/11/0356	11876	1	0.02	44.804	0.0001206	0.1393260	
Hyndshawland	26-Aug-11	CL/11/0384	13354	1	0.02	43.699	0.0001338	0.1393260	
Clyde Extension	01-Oct-11	-	9428	54	162	29.897	0.0480399	0.1473756	Consented
Glentaggart	02-Oct-11	CL/11/0461	9521	5	17	47.921	0.0025728	0.1473981	
Kirkpatrick Hill	11-Oct-11	11/P/3/0442	13586	1	0.11	39.447	0.0001994	0.1473982	
East Millrig	21-Oct-11	CL/11/0457	13054	1	0.015	41.616	0.0001631	0.1473983	
Solwaybank	01-Nov-11	11/P/4/0354	1252	15	30	25.660	0.0341971	0.1513133	Consented
Mallshill	28-Nov-11	ST/DC/11/0999	15119	1	0.005	37.610	0.0001009	0.1513133	
Middle Muir	01-Dec-11	-	13264	15	51	45.566	0.0064290	0.1514498	Consented
Brockhouse	02-Dec-11	11/01571/FUL	15161	1	0.011	47.911	0.0000898	0.1514498	
Broomhills	15-Dec-11	SD/DC/11/1057	10723	1	0.01	40.228	0.0000994	0.1514499	
Land SW of Copland Farm	22-Dec-11	11/01651/FUL	13700	1	0.011	41.590	0.0001622	0.1514499	
Land N of Midtown Farm	03-Jan-12	ST/DC/12/0735	17167	1	0.05	47.861	0.0001350	0.1514500	
Birkenside Farmhouse	06-Feb-12	12/00109/FUL	12183	1	0.05	48.473	0.0001276	0.1514501	
Libberton Mains Farm	13-Mar-12	CL/12/0102	15796	1	0.02	47.089	0.0000976	0.1514501	
Cloich Forest	03-Apr-12	-	13930	18	54	42.540	0.0064902	0.1515891	Consented
Bankhouse	30-Apr-12	12/00206/FUL	16251	1	0.012	45.965	0.0000595	0.1515891	
Lammerlaw	10-May-12	CL/12/0194	8465	2	0.044	44.496	0.0001742	0.1515892	
Cormiston Farm	01-Jun-12	CL/12/0240	16509	1	0.02	41.107	0.0001699	0.1515893	
Hartsop	15-Jun-12	CL/12/0261	13194	1	0.015	40.894	0.0001480	0.1515894	
Parkhouse Farm	22-Jun-12	CL/12/0269	16645	2	0.04	44.068	0.0001451	0.1515894	
Shankfield Head	25-Jun-12	SE/DC/12/0445	13921	2	0.04	39.889	0.0001453	0.1515895	
Cambwell	26-Jun-12	12/00783/FUL	13920	1	0.011	39.850	0.0001918	0.1515896	
South of Hyndfordwells	10-Jul-12	12/00847/FUL	12365	3	0.18	45.343	0.0001986	0.1515898	
Rose Cottage	20-Jul-12	CL/12/0317	16870	1	0.006	44.818	0.0000506	0.1515898	

Wind Farm	Sub. Date	LPA Ref.	DIO Ref.	Number	Capacity (MW)	Mean Distance (km)	Amplitude (nm)	Cumulative Amp	Status
Hillend Farm	26-Jul-12	CL/12/0327	16872	1	0.011	39.670	0.0001952	0.1515899	
Glenkerie Extension	03-Aug-12	13/00552/FUL	18360	6	15	29.673	0.0112880	0.1520096	
Deanfoot Farmhouse	06-Aug-12	12/00950/FUL	13497	1	0.05	49.207	0.0001323	0.1520096	
Lion Hill	03-Oct-12	CL/13/0205	18491	4	9.2	29.266	0.0120426	0.1524859	
West of Hyndfordwells Farm	21-Oct-12	12/01275/FUL	13560	1	0.02	45.695	0.0000881	0.1524860	
Crookedstane Farm	03-Nov-12	CL/13/0206	18481	4	9.2	31.356	0.0096761	0.1527926	
Windy Edge	03-Dec-12	13/00789/FUL	18787	9	22.5	22.673	0.0357219	0.1569129	Consented
Blackdyke	02-Jan-13	SE/DC/12/0554	16952	1	0.01	44.372	0.0000670	0.1569129	
Cottage Farmhouse	16-Jan-13	13/00031/FUL	17847	1	0.011	49.289	0.0000792	0.1569129	
Lampits Farm 2	03-Feb-13	CL/13/0412	19375	1	0.25	49.982	0.0002113	0.1569130	
Land NW of West Morriston Farm	25-Mar-13	13/00312/FUL	16877	1	0.05	49.202	0.0001503	0.1569131	
Solway re-sub (Beckburn)	03-Apr-13	ST/DC/13/0866	6668	9	31.05	36.871	0.0095086	0.1572010	Consented
Land East of Mossbank	05-Apr-13	13/00108/FUL	18142	2	0.022	42.956	0.0002014	0.1572011	
Twentyshilling Hill	03-Jun-13	13/P/3/0260	9860	9	27	48.029	0.0025326	0.1572215	Consented
Townfoot	04-Jul-13	CL/13/0242	18601	1	0.01	43.872	0.0001306	0.1572215	
South Slipperfield Farmhouse	16-Jul-13	13/00839/FUL	12327	1	0.05	48.388	0.0001428	0.1572216	
Rose Cottage (9812)	15-Oct-13	CL/13/0394	9812	1	0.006	44.874	0.0000503	0.1572216	
Whitelaw Brae	22-Oct-13		19376	14	50.4	23.840	0.0489782	0.1646739	Consented
East of Newton of Covington	04-Nov-13	CL/13/0429	16682	2	0.04	44.564	0.0001385	0.1646740	
Bailey Town Farm	05-Nov-13	SO/DC/13/0862	10725	1	0.01	37.862	0.0002365	0.1646741	
Kilravoch	15-Nov-13	13/P/3/0477	19452	1	0.0012	39.320	0.0000311	0.1646741	
South Melbourne Farm 2	23-Dec-13	CL/13/0506	19700	1	0.011	42.846	0.0001439	0.1646742	
Birneyknowe	14-May-14	-	9816	15	60	28.533	0.0291214	0.1672293	Referred to DPEA
SW of Kettleshill Farmhouse	03-Jul-14	14/00746/FUL	20757	1	0.012	48.240	0.0000488	0.1672293	
West of M6 Todhills	15-Aug-14	SO/DC/14/0062	20758	1	0.5	44.012	0.0006305	0.1672305	
Trough Head Farm	18-Aug-14		20832	2	0.02	36.462	0.0003841	0.1672310	
72 Carlisle Road	17-Feb-15	CL/15/0046	22021	2	0.17	44.795	0.0003275	0.1672313	
Clackmae Farm	25-Feb-15	15/00179/FUL	20306	1	0.1	44.963	0.0002292	0.1672314	
East of Whitslaid Farm	15-Apr-15	15/00407/FUL	22267	2	0.05	49.750	0.0001157	0.1672315	
Crossdykes	26-Jun-15	15/P/4/0142	21542	15	48	16.669	0.1585447	0.2304404	Consented
Whins Farm	21-Aug-15	15/P/4/0218	12953	1	0.085	32.860	0.0007654	0.2304417	
Loganhead	08-Oct-15	15/P/7/0273	21543	8	25.6	18.582	0.0800810	0.2439597	Application
Jockstown Farm	09-Oct-15	15/P/4/0272	23252	1	0.1	34.092	0.0007029	0.2439607	
Burnswark Garage	21-Dec-15	15/P/4/0332	23301	1	0.5	30.772	0.0009480	0.2439626	
Wauchope & Newcastleton Forests	13-Jan-16	-	23308	90	306	34.600	0.0419296	0.2475396	scoping
North Lowther	04-Feb-16	Section 36	23316	30	126	44.307	0.0107055	0.2477709	Application
Hopsrig	08-Apr-16		10035845	12	42	16.125	0.1111291	0.2715513	scoping and withdrawn
Harryburn Windfarm	08-Jun-16		21986	17	69.7	37.262	0.0141110	0.2719177	referred to DPEA
Pines Burn	14-Jul-16		23260	12	39.6	27.727	0.0310826	0.2736884	Applied
Muirhall Farm	06-Jan-17	CL/17/0009	10038485	7	22.4	36.908	0.0101450	0.2738764	Applied
Land SE of Scotston Bank Farm	15-Apr-17	10/00521/FUL	9462	3	0.045	40.959	0.0002204	0.2738765	
Barrell Law	14-Sep-17	17/01255/FUL	5909	7	24.5	19.395	0.0621187	0.2808328	Applied
Cliffhope	29-Sep-17	Section 36	10035955	46	322	31.394	0.0632612	0.2878698	pre- application
Faw Side	11-Jan-18	Section 36	10038385	49	343	12.872	0.6740235	0.7329234	pre-application

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10 APPENDIX B – SCENARIO 1

The 2014 Report, *Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*", populated the consultation zone by dividing it into anulus with 1 km thickness (e.g. 49 km to 50 km). Each anulus had a useable area ratio based on planning, wind resource and geographic considerations. The outer most anulus was populated with a 1 km spacing between wind turbines; once full (i.e. no more turbines can be added to the usable area), turbines were added to the next ring, and so on to the final 10-11 km ring. The approach was assumed to be the most efficient way to populate the consultation zone with respect to budget use. The analysis was used to determine the distance from EKA that the threshold was breached and thereby a distance to redefine the exclusion zone.

The usable area analysis was provided by RES; due to commercial confidence considerations no methodology used, or assumption made accompanied the analysis by RES. Further, the assumptions made in 2014 are likely no longer valid.

The 2014 report used also used a success rate (reflecting the success rate of planning applications) and a now defunct utilisation factor. For simplicity the success rate and utilisation factor are both set at one (i.e. all applications are successful, and the wind farms are fully utilised). In the analysis here, 3.4 MW turbines were used (Table 9 and Table 10). Based on these assumptions the Standard EKA algorithm is exhausted at 16.35 km from EKA (Figure 13). When the algorithm fitted to Middle Muir is used, the budget is exhausted at 13.58 km (Figure 14).

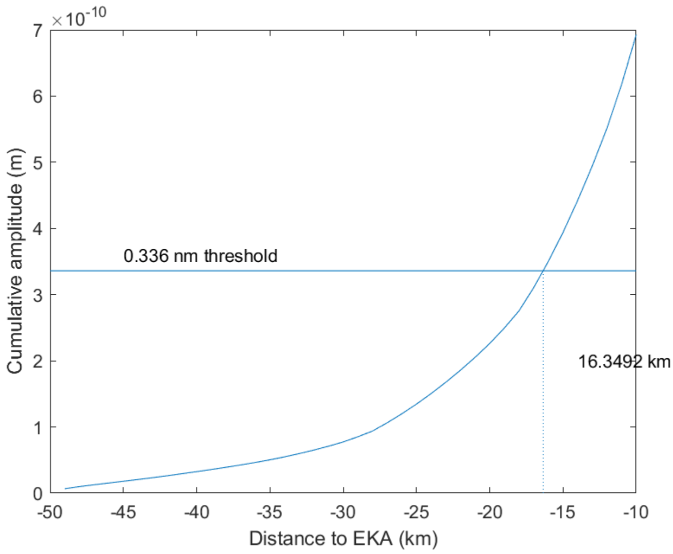

Figure 13 – Scenario 1 population from the outside towards the inside using the Standard EKA algorithm reaches the threshold at 16.35 km

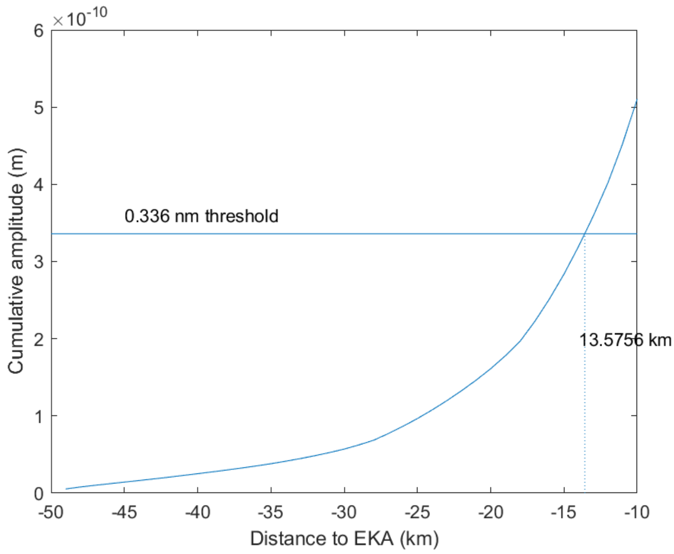

Figure 14 – Scenario 1 population from the outside towards the inside using the algorithm based on Middle Muir reaches the threshold at 13.58 km

Standard EKA algorithm									
Inner radius (km)	Outer radius (km)	Area (km^2)	Usable_ration	DevelopableArea (km^2)	Number Turbines	Annulus Amp (nm)	Running Amp_(nm)	Running Number	Running Capacity (MW)
49	50	311.02	10	31.10	32	0.00669	0.00669	32	108.8
48	49	304.73	10	30.47	31	0.00728	0.00989	63	214.2
47	48	298.45	10	29.85	30	0.00791	0.01267	93	316.2
46	47	292.17	10	29.22	30	0.00861	0.01531	123	418.2
45	46	285.88	10	28.59	29	0.00936	0.01795	152	516.8
44	45	279.60	10	27.96	28	0.01016	0.02062	180	612
43	44	273.32	10	27.33	28	0.01105	0.02339	208	707.2
42	43	267.04	10	26.70	27	0.01201	0.02630	235	799
41	42	260.75	10	26.08	27	0.01308	0.02937	262	890.8
40	41	254.47	7	17.81	18	0.01389	0.03249	280	952
39	40	248.19	7	17.37	18	0.01481	0.03571	298	1013.2
38	39	241.90	7	16.93	17	0.01582	0.03905	315	1071
37	38	235.62	7	16.49	17	0.01696	0.04258	332	1128.8
36	37	229.34	7	16.05	17	0.01827	0.04633	349	1186.6
35	36	223.05	7	15.61	16	0.01968	0.05034	365	1241
34	35	216.77	8	17.34	18	0.02178	0.05485	383	1302.2
33	34	210.49	8	16.84	17	0.02369	0.05974	400	1360

32	33	204.20	8	16.34	17	0.02585	0.06510	417	1417.8
31	32	197.92	8	15.83	16	0.02817	0.07093	433	1472.2
30	31	191.64	8	15.33	16	0.03082	0.07733	449	1526.6
29	30	185.35	10	18.54	19	0.03569	0.08517	468	1591.2
28	29	179.07	10	17.91	18	0.03937	0.09383	486	1652.4
27	28	172.79	14	24.19	25	0.04987	0.10626	511	1737.4
26	27	166.50	14	23.31	24	0.05543	0.11985	535	1819
25	26	160.22	13	20.83	21	0.06100	0.13448	556	1890.4
24	25	153.94	13	20.01	21	0.06744	0.15045	577	1961.8
23	24	147.65	11	16.24	17	0.07352	0.16745	594	2019.6
22	23	141.37	11	15.55	16	0.08027	0.18570	610	2074
21	22	135.09	10	13.51	14	0.08728	0.20518	624	2121.6
20	21	128.81	10	12.88	13	0.09505	0.22613	637	2165.8
19	20	122.52	11	13.48	14	0.10555	0.24955	651	2213.4
18	19	116.24	11	12.79	13	0.11655	0.27542	664	2257.6
17	18	109.96	16	17.59	18	0.14329	0.31047	682	2318.8
16	17	103.67	16	16.59	17	0.16186	0.35012	699	2376.6
15	16	97.39	14	13.63	14	0.18026	0.39380	713	2424.2
14	15	91.11	14	12.75	13	0.20115	0.44220	726	2468.4
13	14	84.82	11	9.33	10	0.22113	0.49441	736	2502.4
12	13	78.54	11	8.64	9	0.24390	0.55130	745	2533
11	12	72.26	13	9.39	10	0.27802	0.61743	755	2567
10	11	65.97	13	8.58	9	0.31430	0.69282	764	2597.6

Table 9 – Population from the edge inward using standard EKA algorithm

Middle Muir									
Inner radius (km)	Outer radius (km)	Area (km^2)	Usable_ration	DevelopableArea (km^2)	Number Turbines	Annulus Amp (nm)	Running Amp_(nm)	Running Number	Running Capacity (MW)
49	50	311.02	10	31.10	32	0.00543	0.00543	32	108.8
48	49	304.73	10	30.47	31	0.00586	0.00799	63	214.2
47	48	298.45	10	29.85	30	0.00632	0.01018	93	316.2
46	47	292.17	10	29.22	30	0.00682	0.01225	123	418.2
45	46	285.88	10	28.59	29	0.00735	0.01429	152	516.8
44	45	279.60	10	27.96	28	0.00792	0.01633	180	612
43	44	273.32	10	27.33	28	0.00854	0.01843	208	707.2
42	43	267.04	10	26.70	27	0.00922	0.02061	235	799
41	42	260.75	10	26.08	27	0.00996	0.02289	262	890.8
40	41	254.47	7	17.81	18	0.01052	0.02520	280	952
39	40	248.19	7	17.37	18	0.01116	0.02756	298	1013.2
38	39	241.90	7	16.93	17	0.01185	0.03000	315	1071
37	38	235.62	7	16.49	17	0.01264	0.03255	332	1128.8
36	37	229.34	7	16.05	17	0.01353	0.03525	349	1186.6
35	36	223.05	7	15.61	16	0.01449	0.03811	365	1241
34	35	216.77	8	17.34	18	0.01593	0.04131	383	1302.2
33	34	210.49	8	16.84	17	0.01722	0.04475	400	1360
32	33	204.20	8	16.34	17	0.01870	0.04850	417	1417.8
31	32	197.92	8	15.83	16	0.02029	0.05257	433	1472.2
30	31	191.64	8	15.33	16	0.02210	0.05703	449	1526.6
29	30	185.35	10	18.54	19	0.02547	0.06246	468	1591.2
28	29	179.07	10	17.91	18	0.02801	0.06845	486	1652.4
27	28	172.79	14	24.19	25	0.03534	0.07704	511	1737.4
26	27	166.50	14	23.31	24	0.03923	0.08646	535	1819
25	26	160.22	13	20.83	21	0.04316	0.09663	556	1890.4
24	25	153.94	13	20.01	21	0.04772	0.10777	577	1961.8
23	24	147.65	11	16.24	17	0.05206	0.11968	594	2019.6
22	23	141.37	11	15.55	16	0.05690	0.13252	610	2074
21	22	135.09	10	13.51	14	0.06198	0.14630	624	2121.6
20	21	128.81	10	12.88	13	0.06766	0.16119	637	2165.8
19	20	122.52	11	13.48	14	0.07540	0.17795	651	2213.4
18	19	116.24	11	12.79	13	0.08358	0.19660	664	2257.6
17	18	109.96	16	17.59	18	0.10343	0.22215	682	2318.8
16	17	103.67	16	16.59	17	0.11747	0.25130	699	2376.6
15	16	97.39	14	13.63	14	0.13151	0.28363	713	2424.2
14	15	91.11	14	12.75	13	0.14759	0.31973	726	2468.4

13	14	84.82	11	9.33	10	0.16311	0.35893	736	2502.4
12	13	78.54	11	8.64	9	0.18095	0.40197	745	2533
11	12	72.26	13	9.39	10	0.20784	0.45252	755	2567
10	11	65.97	13	8.58	9	0.23663	0.51066	764	2597.6

Table 10 - Population from the edge inward using algorithm based on Middle Muir data

11 APPENDIX C – SCENARIO 2

Scenario 2 populated the consultation zone randomly with no restriction to placement. The distribution was linear (i.e. not weighted to the either 10 km or 50 km radii). The simulation was iterated in this way 1000 times for each scenario and the additional capacity taken as the mean (average) of all the simulations. The standard deviation of the additional capacity was also calculated for each simulation and represents the spread of data within the 1000 iterations of the model, where 68% of the additional capacity results fall with one standard deviation from the mean value. The results are listed in Table 5.

Scenario 2	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	26.7 ± 22.4	8.8 ± 8.7
Middle Muir	0.097	496.2 ± 126.5	146.9 ± 37.2
Clyde	0.149	1217.4 ± 183.6	359.1 ± 54.0
Craig	0.075	323.9 ± 100.3	96.3 ± 29.4

Table 11 – Consumption of head room the distribution of 3.4 MW turbines Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Xi

12 APPENDIX D – MEASUREMENT REPORT

Eskdalemuir Wind Turbine Seismic Vibration

Technical report

Presented to Scottish Government

Issue Date: 23/07/2020

Document No: SGV 202 Technical Report Measurement Appendix v7

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Measurement Report Document Summary

A seismic measurement was conducted between the 5th of May 2020 and the 1st June 2020 at Middle Muir wind farm. The results obtained during the measurement are illustrated in this document. Across all sensors S1 and S3 recorded the quietest signals. No diurnal variation was recorded across all sensors. For wind speeds below the 12 m/s a clean seismic signature was recorded which has been attributed to the seismic output of the wind farm.

		Date	Version	
Originator	A Rodriguez	18 May 2020	v1	Internal Issue
Review	Dr MP Buckingham	20ST July 2020	v2	Review
Review	A Rodriguez	20th July 2020	v	review
Review	Dr MP Buckingham	22nd July 2020	v4	Review
Review	R Horton	22nd July 2020	v5	Review
Review	A Rodriguez	22nd July 2020	v6	Review
Final Review	DR M P Buckingham	22nd July 2020	v7	Release

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12.1 Measurement Report Introduction

The Eskdalemuir Working Group (EWG) was reformed for a third time in 2018 with a view to reviewing the Eskdalemuir Consultation Zone's vibration budget due to the new installed developments and improvements in wind turbine technology. Following this goal, the Scottish Government (SG) met with Xi Engineering (Xi) to discuss the possibility of increasing the amount of Renewable Energy generated in the Eskdalemuir region.

Currently, the algorithm used by the MoD to calculate the budget within the area takes a conservative approach. By design, the algorithm over-estimates the seismic contribution of each wind turbine. This conservative approach was taken to protect the functioning EKA in lieu of measured seismic data from each make and model of wind turbine within the EKA consultation zone. Obtaining actual seismic measurement data from the wind farms within the Eskdalemuir consultation zone would remove the necessity of the safety-factor built into the algorithm thereby releasing the budget and allowing further wind turbine development in the Eskdalemuir consultation zone.

Following this approach, a seismic measurement campaign was conducted in the Middle Muir Wind farm near Biggar. The measurement campaign was conducted between the 5th of May 2020 and the 1st of June 2020. Seismometer data set size varied due to individual sensor battery life and the day on which they were deployed. All seismometer sensors were fully operational between the 6th and 20th of May 2020. The wind speed data captured alongside the seismic data was provided by Banks Renewables Group (BR), which was captured by the SCADA system of each wind turbine on site. This document reports the findings of this campaign. These results are sufficient to allow a comparison of the results with the estimated output from the algorithm to determine to what extent the algorithm has overestimated this seismic activity.

12.2 Measurement Report Methodology

12.2.1 SEISMOMETER

The sensor type deployed during the measurement campaign was the Guralp 6TD medium motion seismometer. This choice of equipment matches that being used by AWE Blacknest who monitor the Eskdalemuir seismic array. The sensor, GPS position sensor, and some of the associated cabling can be seen in Figure 15 with the specification in Table 12. The digitisers of the 6TD sensor were in differential mode and their serial numbers are listed in Table 13.

Figure 15 - Guralp 6TD, GPS and cabling.

SYSTEM	
Configuration / Topology	Triaxial orthogonal (ZNE)
PERFORMANCE	
Velocity output	30 s (0.03 Hz) to 100 Hz standard Contact Güralp to discuss other frequency response options
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})
Cross axis rejection	> 60 dB
Linearity	> 95 dB
Lowest spurious resonance	> 450 Hz
Transfer function	User manual is available to download from the website. Each sensor is provided with full calibration details including measured sensitivity, measured frequency response and instrument poles and zeros
Calibration controls	On board signal; generator: sine wave, impulse and broadband noise
MASS / MONITORING CONTROL	
Sensor Mass positions	Three independent sensor mass position outputs (single ended)
Mass centre	Remotely controlled automatic mass centring
POWER	
Power consumption (at 12 V DC)	0.93 W
Power voltage range	11 - 28 V DC
ENVIRONMENTAL	
Operating temperature	-20 to +65 °C

Table 12 - Guralp 6TD specifications

Site Name	Serial number
S1	6x93
S2	6x95
S3	6o01
S4	6v17

Table 13 – Serial numbers of 6TD units used in the Middle Muir measurement

12.2.2 MIDDLE MUIR MEASUREMENT SETUP

Xi deployed four seismic sensors at Middle Muir wind farm sites. The sensors were deployed from the 5th May 2020 to the 1st of June 2020. Although some sensors weren't operational during the whole duration of the campaign due to battery life, a satisfactory number of wind speed bins were observed, and therefore the acquired data set has been assessed as sufficient to establish the seismic levels produced by the turbines. The sensors were deployed under the following procedure.

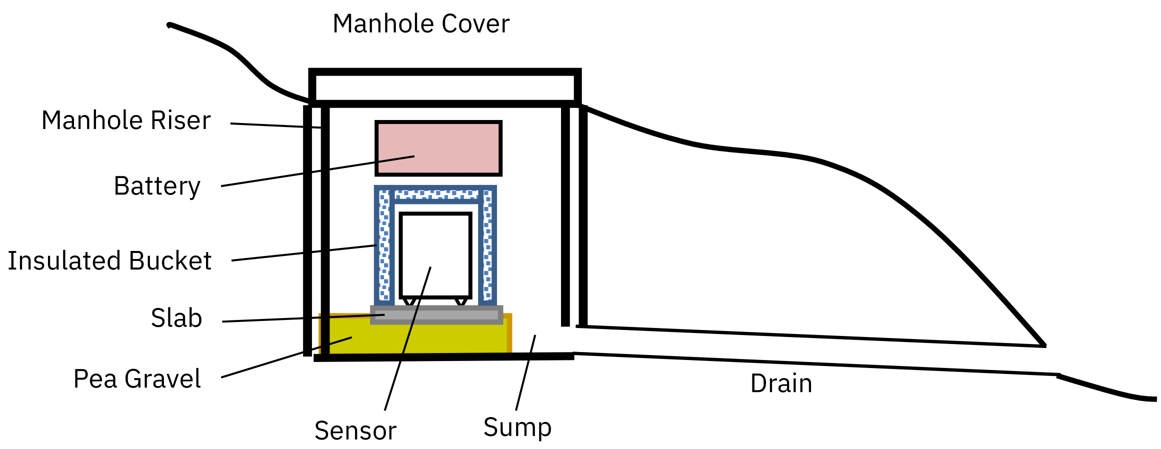


Figure 16: Typical Seismometer Pit Deployment

Figure 16 shows a graphical representation of the deployment. A deployment, using semi-permanent pits, was performed in order to leave potential for reuse of pits should any follow-up measurement be necessary – providing repeatability between measurements. A hole was dug with enough space to fit the sensor and protective case, approximately 600-700 mm deep. Once the hole was at a suitable depth to provide a good connection to ground borne seismic waves, a layer of fine gravel was compressed and levelled in the base of the hole, a marble slab was then laid and levelled on the gravel. The marble slab is necessary to maximise transmissibility between the ground and seismic sensor. The Guralp 6TD sensor was placed on top of the slab (Figure 17 - Installation of the sensors at two measurement locations. Sensor resting on the slab prior to being covered by insulation. Figure 17). The sensors were levelled and orientated to magnetic north. An insulating cover was placed on top of the sensor to protect it from moisture and maintain a stable temperature. Each sensor was powered by a 12v battery which was placed on top of the insulating cover within the seismic pit.

Figure 17 - Installation of the sensors at two measurement locations. Sensor resting on the slab prior to being covered by insulation.

The seismic vibration budget assumes vibration levels normalised at 1 km from the WTG. Seismic pits were prepared within the windfarm boundaries of Middle Muir. The preferred position of the seismic pits is between ~500 and 1500 m from the nearest WTG with closer positions preferred to provide a clearer signal. Local site conditions and boundary restrictions determine the exact location for a specific site. Table 14 shows the locations for the seismic pits. It is acceptable to place sensors closer to the turbine in order to adjust for site boundaries, avoid other noise sources, and to account for local terrain. The positions used in this measurement have been selected to provide a variety of location types with a view to observing the cleanest and quietest signals. The sensors were placed away from likely contributors to seismic background noise such as forestry, roads and other cultural activity (Figure 18).

Site	Latitude	Longitude	Easting	Northing	UTMzone
S1	55.523335 N	3.801658 W	286357	626985	30U
S2	55.516384 N	3.804354 W	285150	626216	30U
S3	55.503571 N	3.808140 W	285891	624796	30U
S4	55.498661 N	3.811107 W	285689	624255	30U

Table 14 - Latitude and longitude and grid reference of the sensor sites.

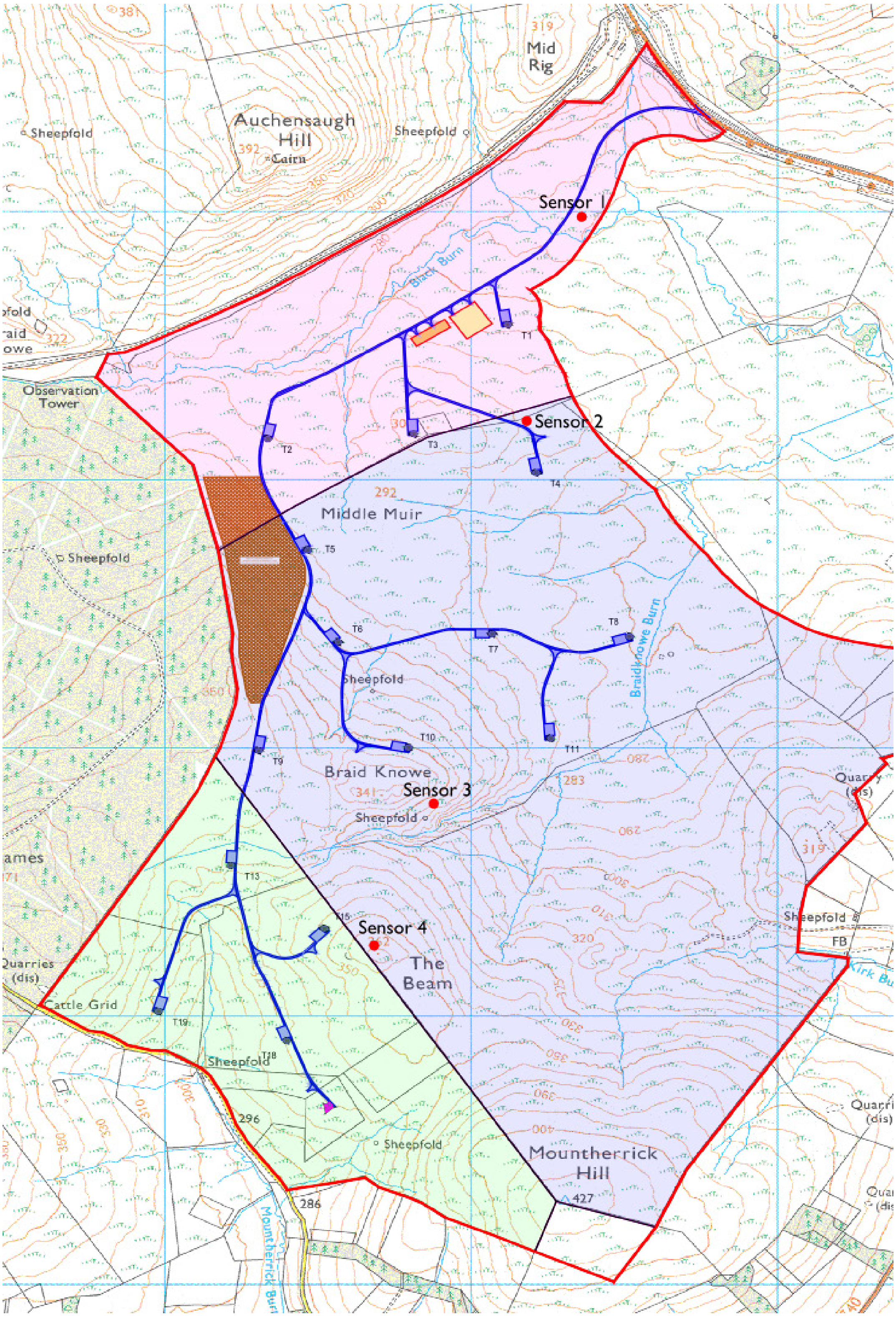


Figure 18 – Location of seismic sensors at the Middle Muir site

12.2.3 PROCESSING METHOD

The data from seismic sensors was processed following the methodology outlined in Scottish Government Report, *Seismic Vibration Produced by Wind Turbines in the Eskdalemuir Region* (2014). This method is used to convert the raw seismic data into displacement power spectral density (PSD) using the following steps:

1. The data recorded at sensors was stored in hour-long files. The data was extracted in 10-minute intervals, corresponding to the wind speed data. The EKA algorithm uses a standard of wind speed measured at 80 m. The wind speeds were based on those recorded synchronously by the anemometer that were extrapolated from 93 m to 80 m to bring them in line with the EKA algorithm using the log law:

$$v_{Hub} = v_{measured} * \frac{ln\left({Hub_z}/{z_r}\right)}{ln\left({Anemometer_z}/{z_r}\right)}$$

where z_r is the surface roughness length and taken to be 0.05 in line with the good practise guide ETSU-R-97.

2. The digital sensor output of the vertical axis was calibrated, including removal of any linear trend/mean, resulting in measured velocity (m/s) in the time domain.

3. Welch's method was applied to each of the data bins to produce velocity power spectral density (PSD). The MATLAB function *pwelch* was applied using 28 sections with a 50% overlap.

4. The resulting velocity data in the frequency domain was converted to displacement PSD (m^2/Hz) by dividing by a factor of $(2\pi f)^2$.

After this processing was performed, the data was subjected to statistical analysis. During the duration of each measurement, there will be results that are not indicative of the real behaviour. These results might be produced by an external factor such as cattle or human interaction in the surroundings of the sensor. In order to mitigate these interferences, the datasets were binned into 1 m/s wind speed bins and the interquartile mean was calculated at each discrete frequency. Hence, eliminating the outlying data falling outside the interquartile range.

12.3 Measurement Report Results

The data recorded was divided into ten-minute samples. The number of samples recorded at each site are listed in Table 15 and Table 16. Variations in sample size from each sensor are due to the individual battery life of each sensor. In all, 18,734 ten-minute samples were recorded. The wind speeds recorded during the survey at a height of 93 m varied from 0 m/s to 18 m/s.

Wind Speed (m/s)	S1			S2		
	Total	Day	Night	Total	Day	Night
1	20	13	7	66	34	32
2	89	56	33	144	76	68
3	103	51	52	190	117	73
4	233	136	97	345	207	138
5	416	210	206	593	343	250
6	451	318	133	575	422	153
7	322	255	67	343	274	69
8	236	193	43	239	193	46
9	91	75	16	97	75	22
10	75	67	8	98	67	31
11	62	47	15	75	47	28
12	54	27	27	57	30	27
13	65	37	28	68	40	28
14	41	29	12	41	29	12
15	37	30	7	37	30	7
16	59	50	9	59	50	9
17	42	31	11	42	31	11
18	7	2	5	7	2	5

Table 15 - Number of windspeed bins recorded for sensors S1 and S2.

Wind Speed (m/s)	S3			S4		
	Total	**Day**	**Night**	**Total**	**Day**	**Night**
1	8	3	5	57	27	30
2	51	29	22	119	62	57
3	73	30	43	154	89	65
4	171	107	64	300	192	108
5	309	149	160	532	318	214
6	331	219	112	489	350	139
7	244	191	53	302	236	66
8	157	136	21	193	159	34
9	36	36	0	73	54	19
10	24	24	0	56	31	25
11	28	28	0	53	33	20
12	10	10	0	39	25	14
13	15	15	0	56	32	24
14				35	23	12
15				30	23	7
16				48	39	9
17				37	26	11
18				7	2	5

Table 16 - Number of windspeed bins recorded for sensors S3 and S4

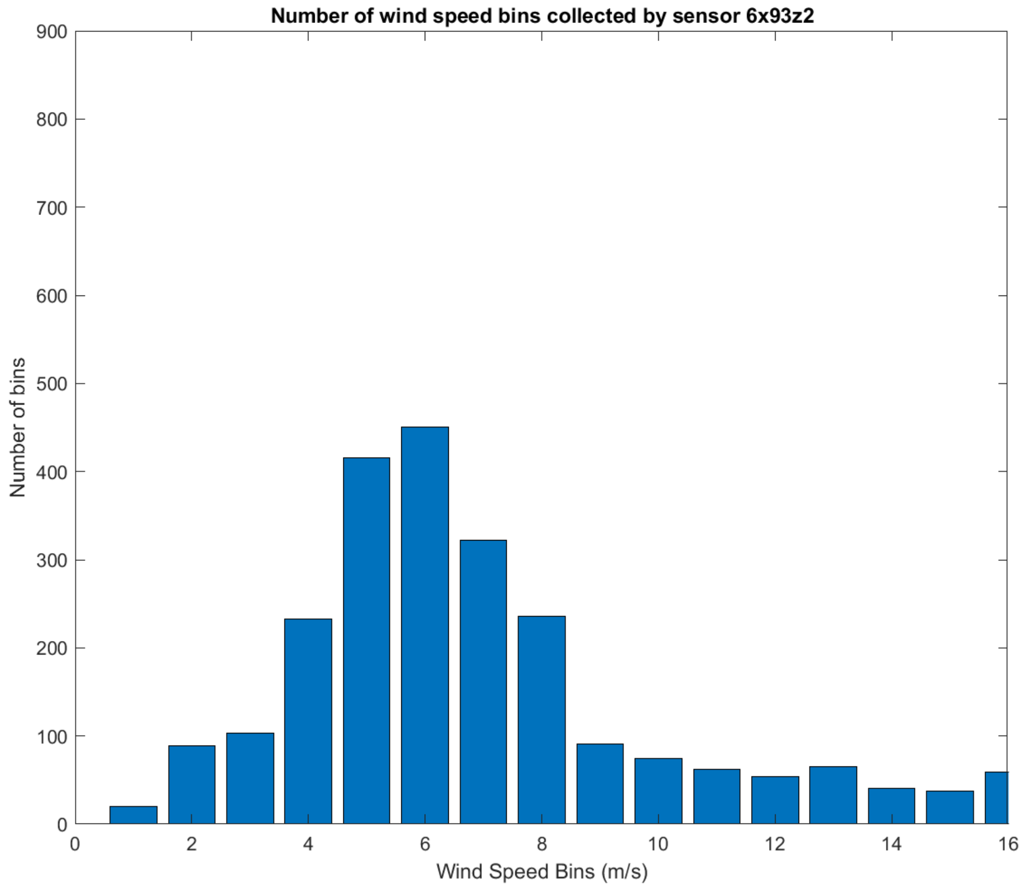


Figure 19: Wind speed bins distribution for S1.

The seismic amplitude measured in 1 m/s wind speed bins are shown in Figure 20 to Figure 23. The broadband seismic levels increase with wind speed across all four sensors as would be expected. This increase in seismic noise is caused by wind excitation of trees and the regolith (e.g. top soil) of local hills. The increase with wind speed is in line with expectations and previous wind turbine seismicity studies. The variation in signal noise is also wind speed dependent. At low wind speeds the background noise at low frequency (<10 Hz) is consistent across all four sites. However, as the wind speed rises, sites S2: 6x95, and S4: 6v17, recorded higher levels of background noise. This may be due to site specific reasons such as thickness of the regolith, wind direction, proximity to turbines, etc.

At low wind speed (<6 m/s) discrete spectral peaks are present in the recorded data. These peaks appear in between 2 and 12 Hz, more specifically, some of these peaks occur at 2.31, 4.05, 4.80, 6.19, 8.4, 9.60 and 10.71 Hz approximately. These peaks are likely due to seismic output of the turbines. This cannot definitively be confirmed without a pre and post construction measurement campaign which would help to determine which signals are attributable to local cultural and geographic sources. At higher wind speeds many of these spectra peaks are masked by the rising broadband noise attributed to the wind.

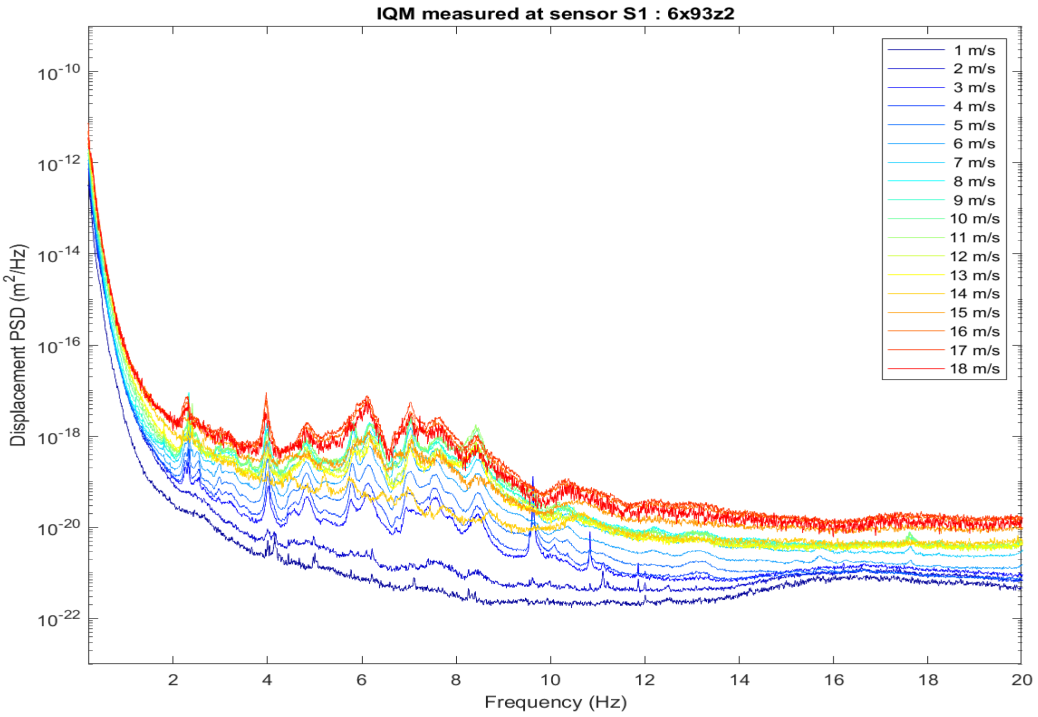


Figure 20: Frequency spectra recorded by S1 with respect to different wind speeds on the range from 1 to 18 m/s.

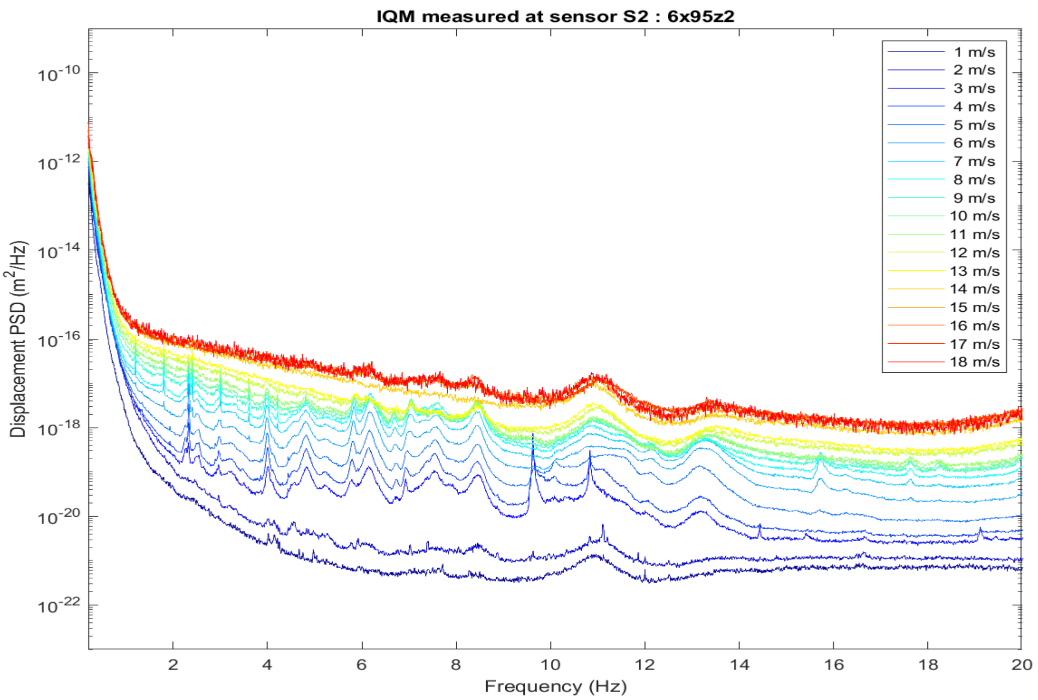


Figure 21: Frequency spectra recorded by S2 with respect to different wind speeds on the range from 1 to 18 m/s.

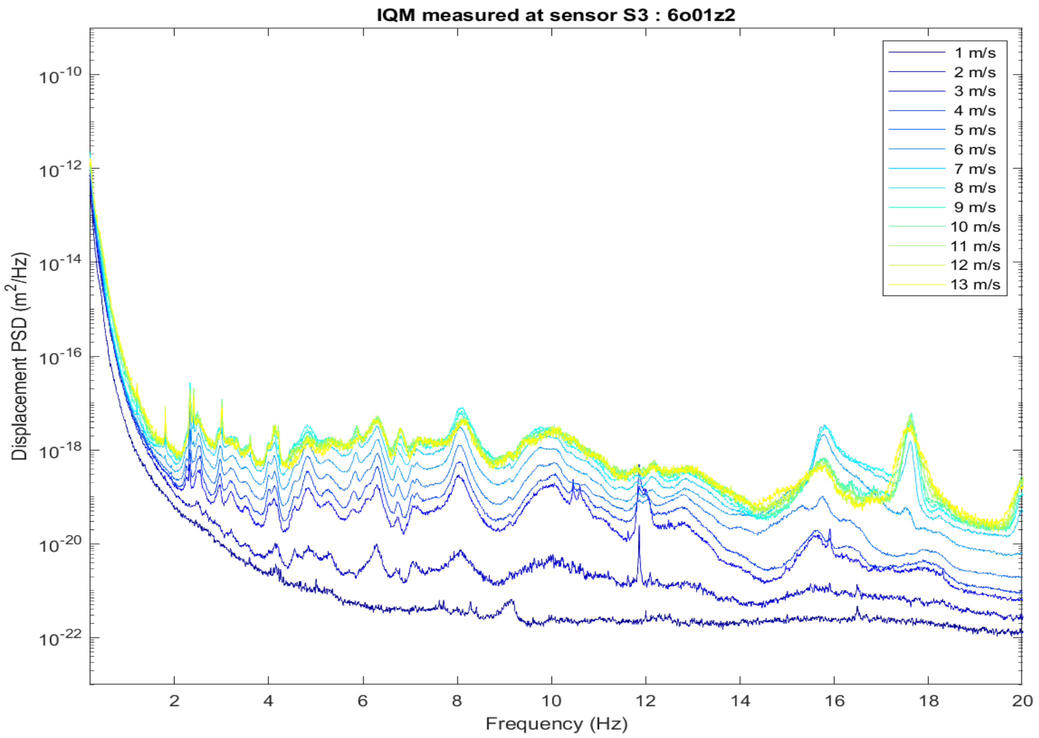


Figure 22: Frequency spectra recorded by S3 with respect to different wind speeds on the range from 1 to 13 m/s.

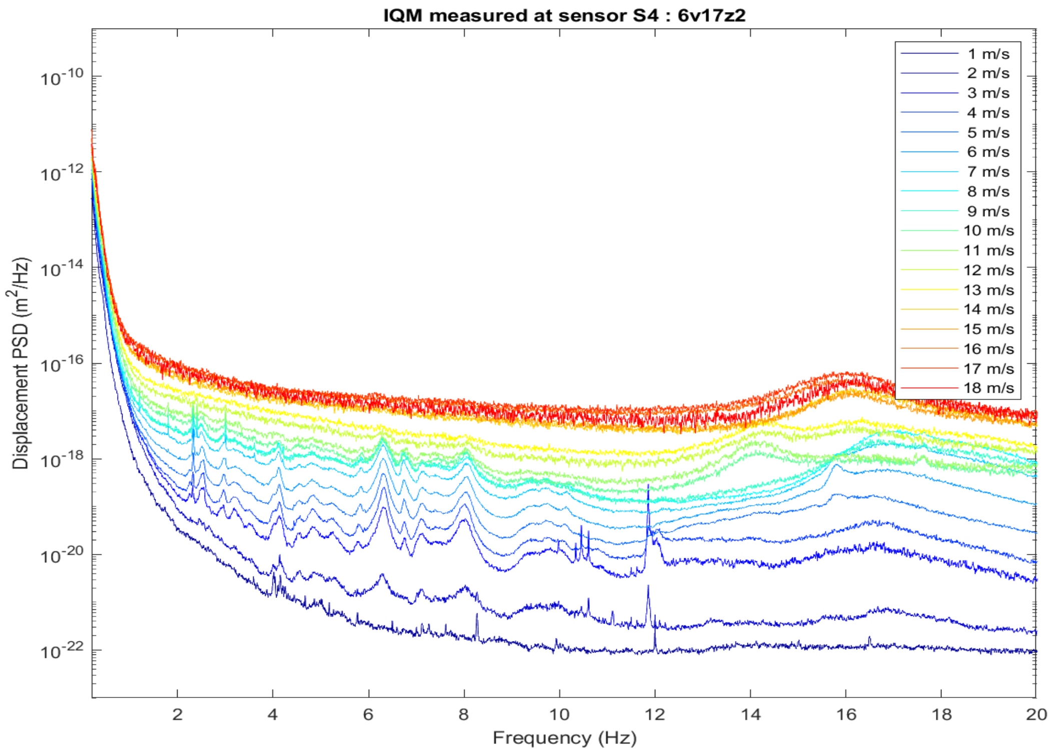


Figure 23: Frequency spectra recorded by S4 with respect to different wind speeds on the range from 1 to 18 m/s.

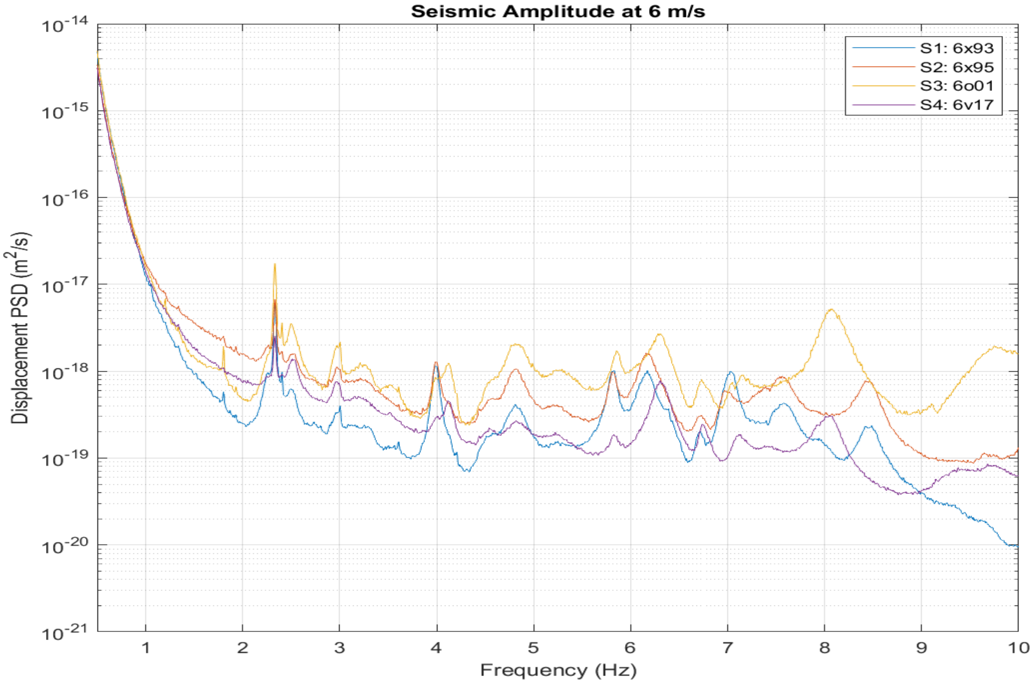


Figure 24: Comparison of signals across all four sensors at 6 m/s wind speed.

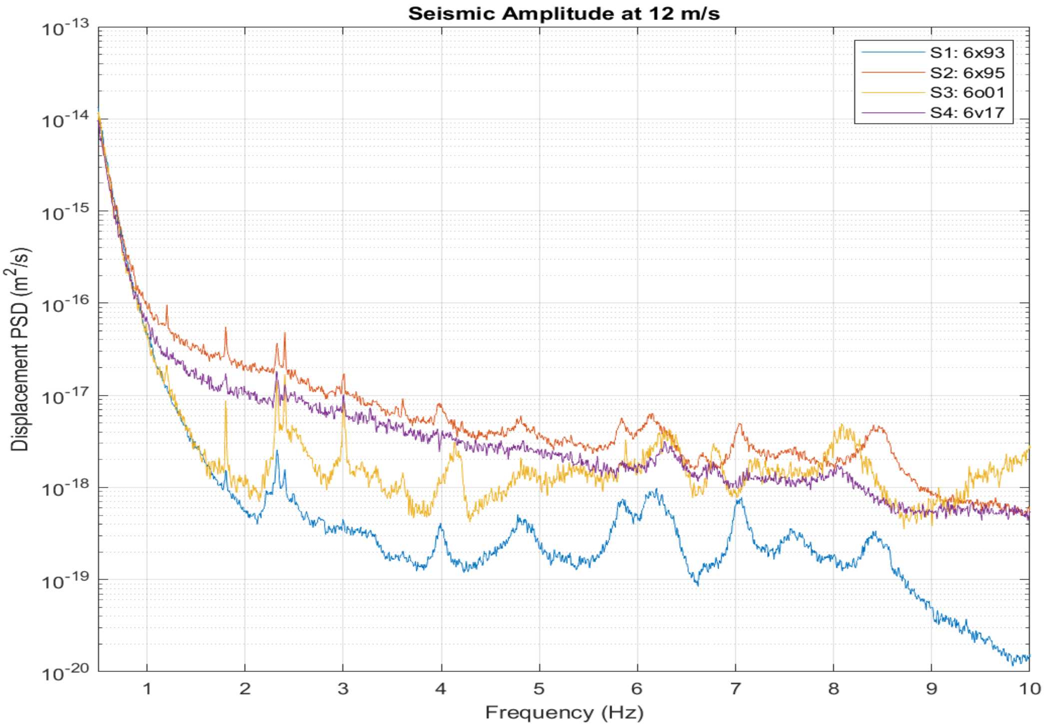


Figure 25: Comparison of signals across all four sensors at 12 m/s wind speed.

12.3.1 DIURNAL VARIATION

The data was binned by time to determine if there is a significant diurnal variation in the background seismic level. The daytime was taken as 7 am to 11 pm and the night-time taken as 11 pm to 7 am in order to remove background noise created by human activity, for example, road traffic. Across all the wind speed bins, there are no significant diurnal variations which could indicate that the frequency response illustrates the seismic signature of the turbines on site. Figure 26 shows the diurnal variation measured across all four sensors at 12 m/s. It is important to note that due to the battery life of S3, no night-time data was recorded on this sensor for wind speeds higher than 8 m/s (See Table 16) and therefore no diurnal comparison can be done for these wind speeds. In addition, wind speed bins with insufficient data, less than 6 samples, have been excluded from this calculation as they can contain non-representative data which could alter the results. The full set of figures for the diurnal variation are shown in Measurement Appendix C – Comparison of Diurnal variation.

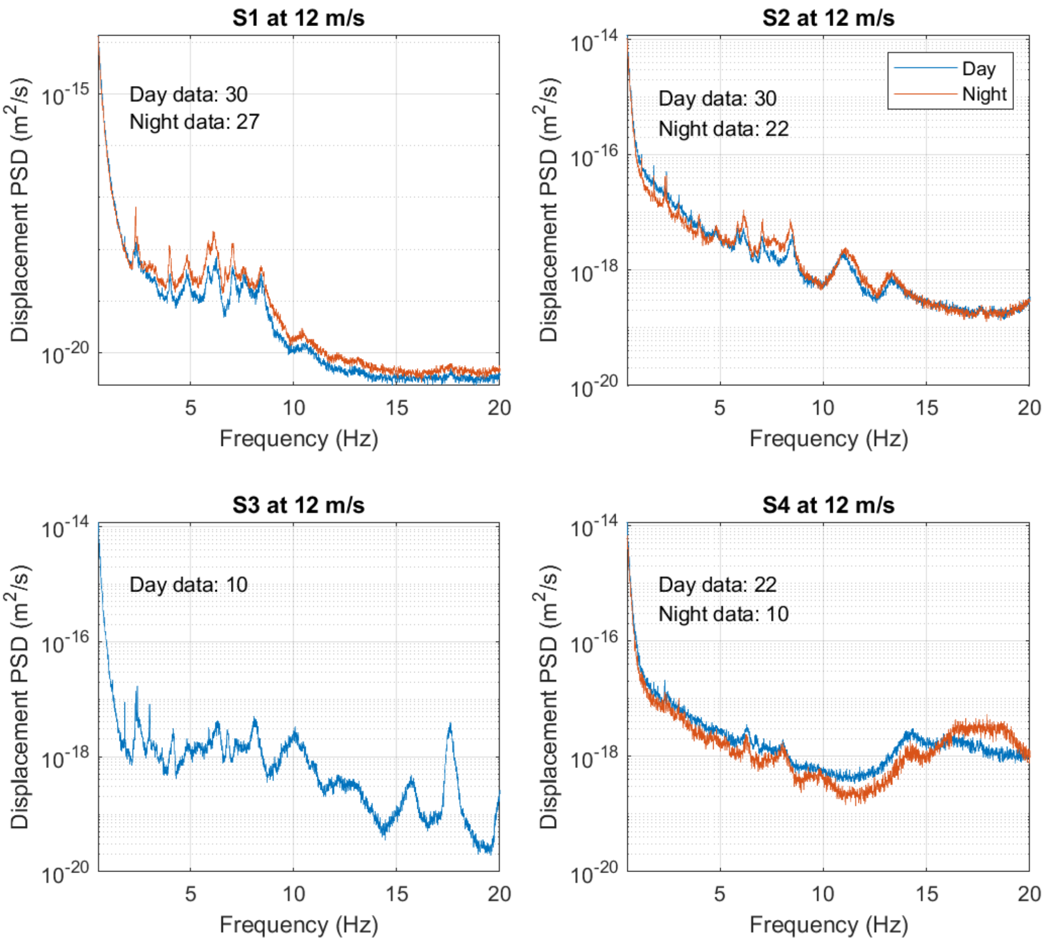


Figure 26: Diurnal variation - comparison of day and night data across all four sensors for 12 m/s wind speed.

12.4 Measurement Report Discussion

The seismic levels of four sites in Middle Muir wind farm were examined. The broadband seismic level increased with wind speed which is consistent with previous observations. Of the sites examined, S1 and S3 where the quietest across all wind speeds and S2 had the highest levels particularly at higher wind speeds (> 6m/s).

At low wind speeds (<7 m/s) some discrete spectral peaks were detected that can be attributed to the seismic signature of the farm. As wind speed increases, the ambient broadband noise levels increase, which results in some of these peaks being masked. The diurnal variation of seismic level captured across all sensors shows a consistent seismic level during both time periods which it is most likely seismic output of the site. This diurnal variation became less prominent as wind speed exceeded 13 m/s indicating that the seismic signal generated by the farm was masked at higher wind speeds.

12.5 Measurement Report Conclusion

- The seismic vibration level at Middle Muir site was measured at four locations which are reported above.
- Statistically significant data sets were captured for a range of windspeeds between 2 and 16m/s.
- Of the four sites examines S1 and S3 recorded the lowest background seismic levels and S4 the highest.
- There were significant seismic vibration levels attributed to the wind turbines on site particularly at wind speeds below 7 m/s.
- No significant diurnal variation was recorded across all sensors allowing full use of the data set captured for analysis.

12.6 Measurement Appendix A – Wind speed bins per sensor

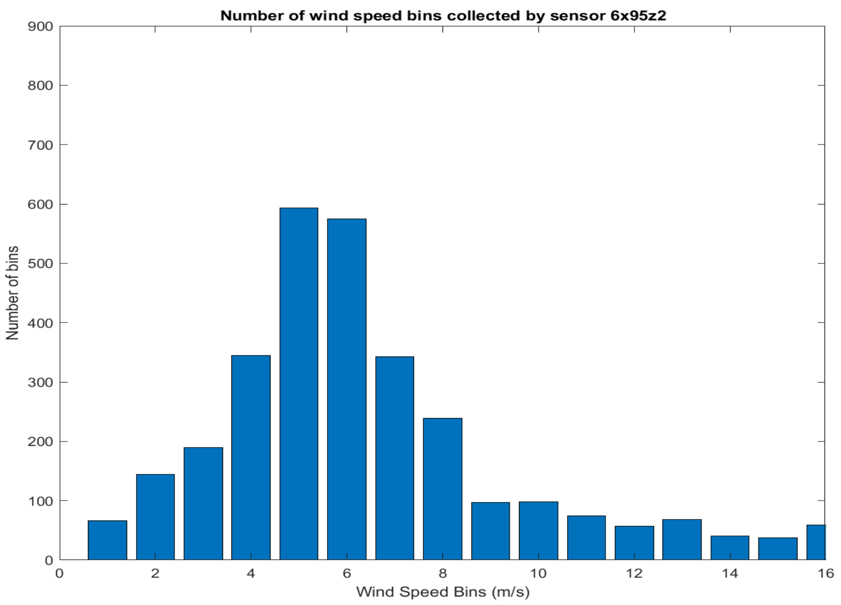


Figure 27 - Wind speed bins recorded by sensor S2: 6x95.

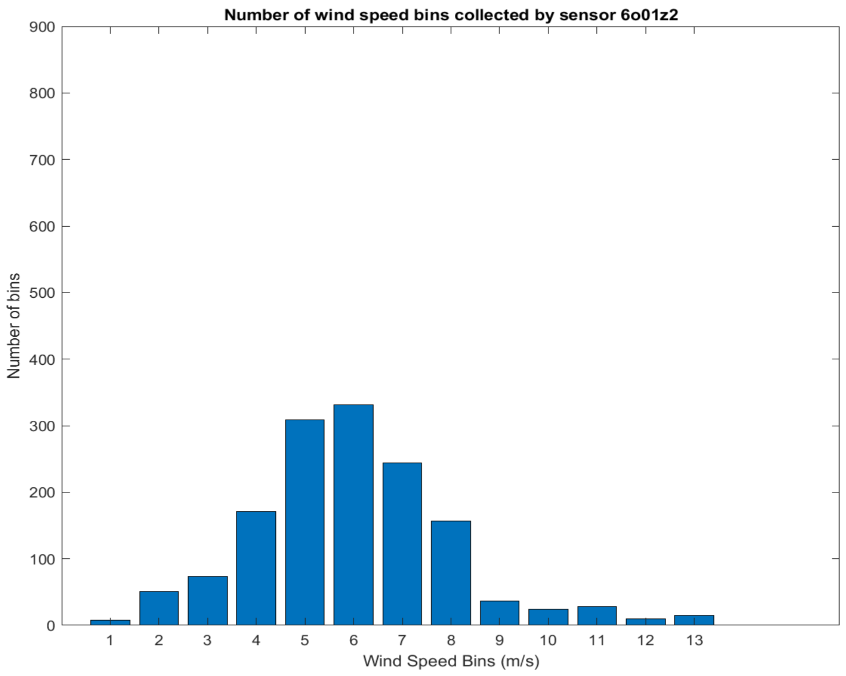


Figure 28 - Wind speed bins recorded by sensor S3: 6o01.

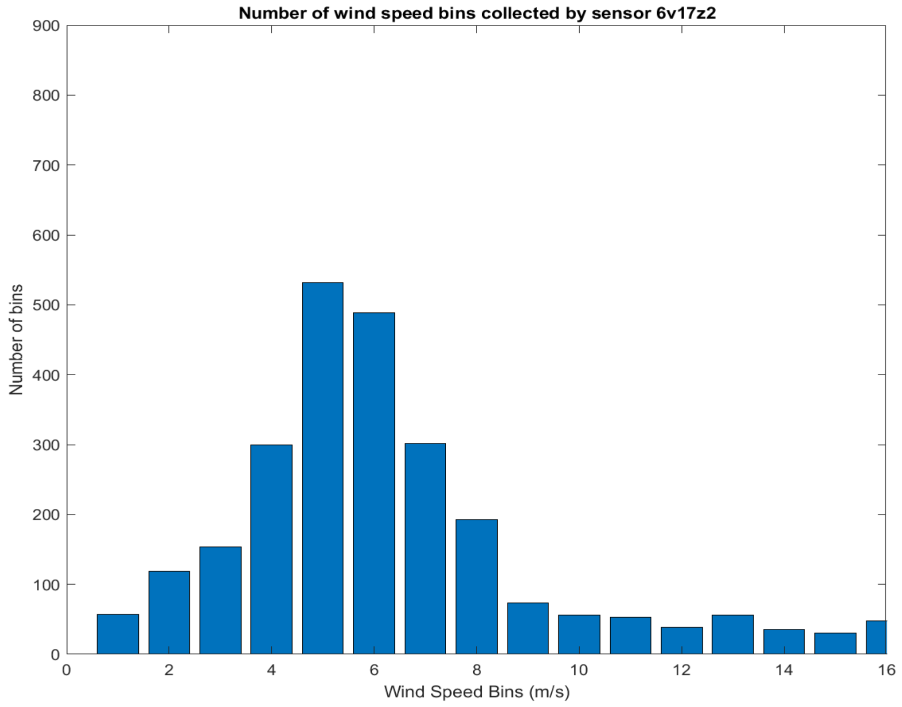
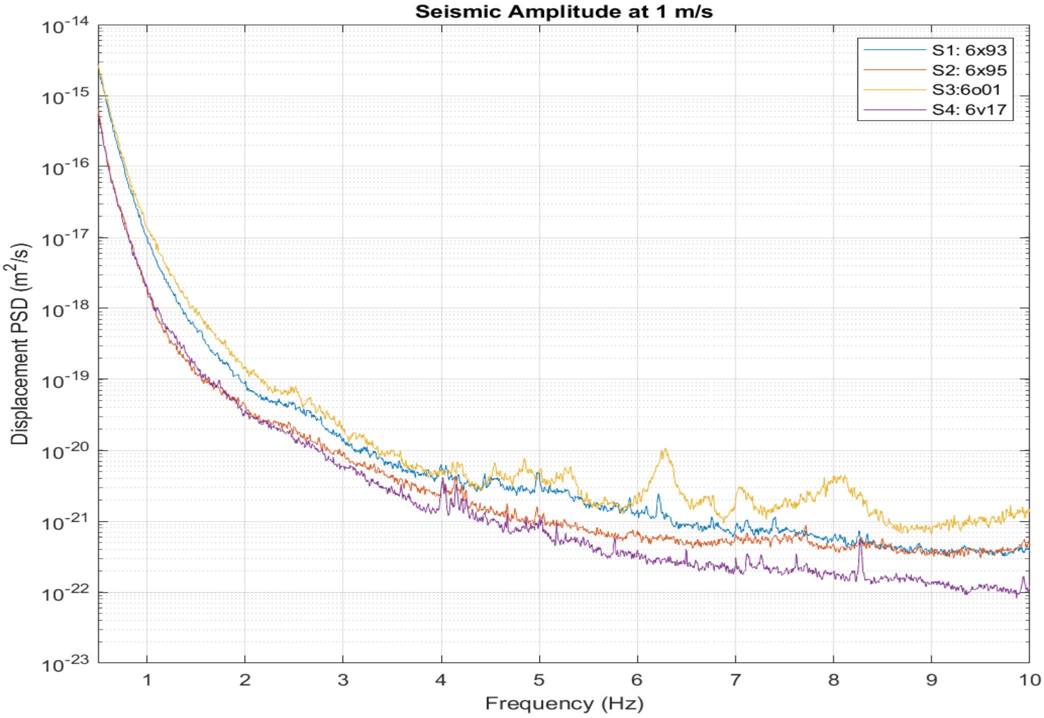
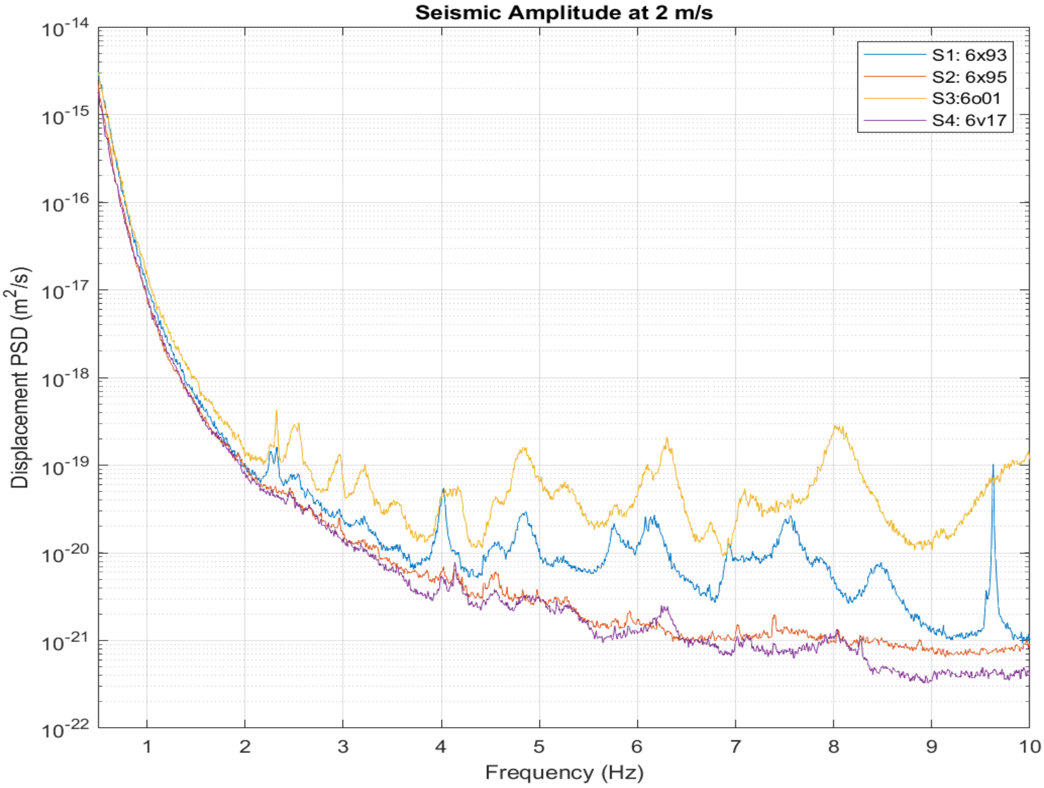
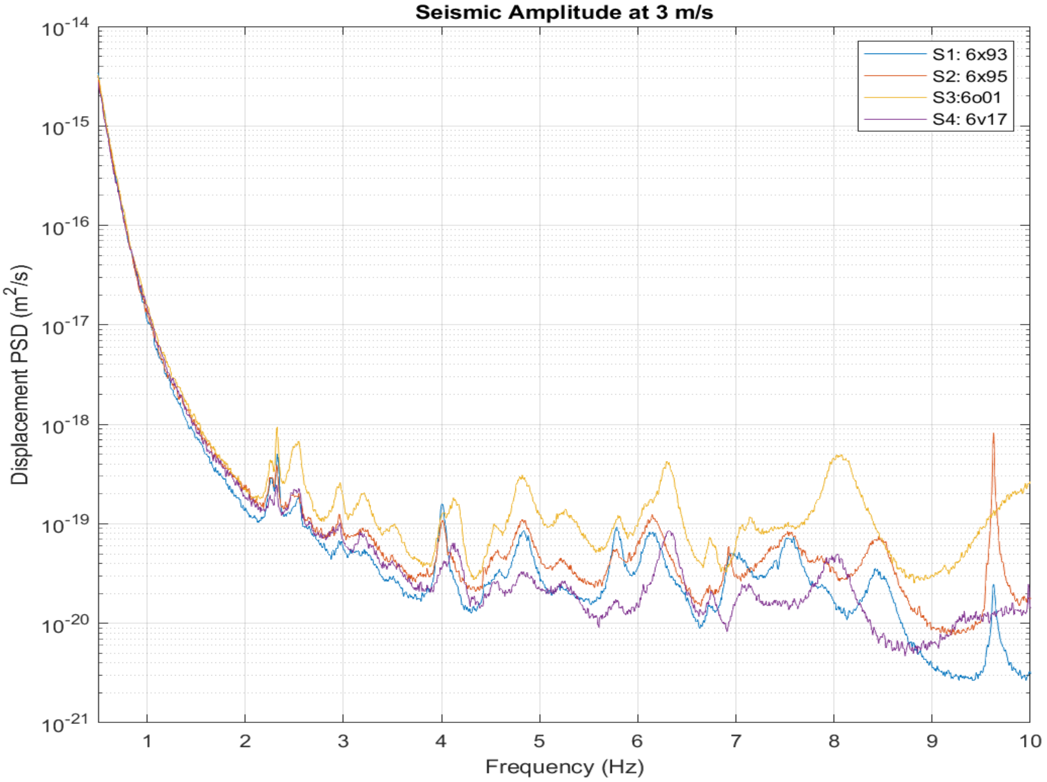


Figure 29 - Wind speed bins recorded by sensor S4: 6v17.

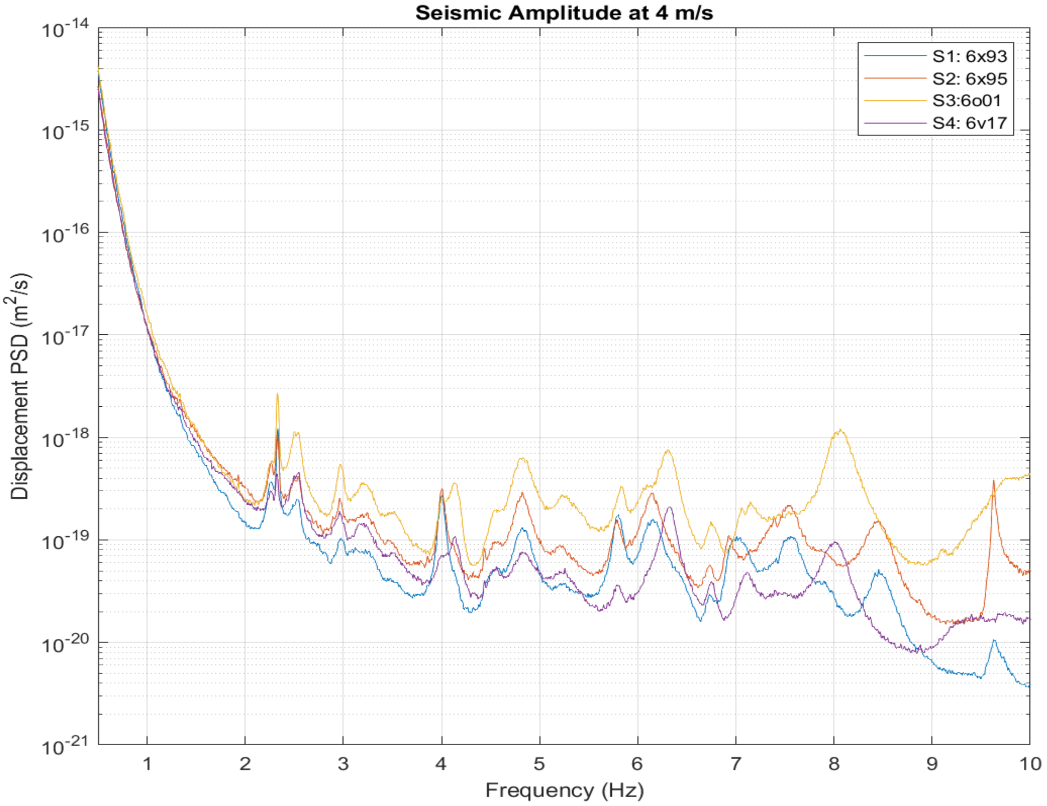
12.7 Measurement Appendix B – Frequency Spectra per Wind Speed





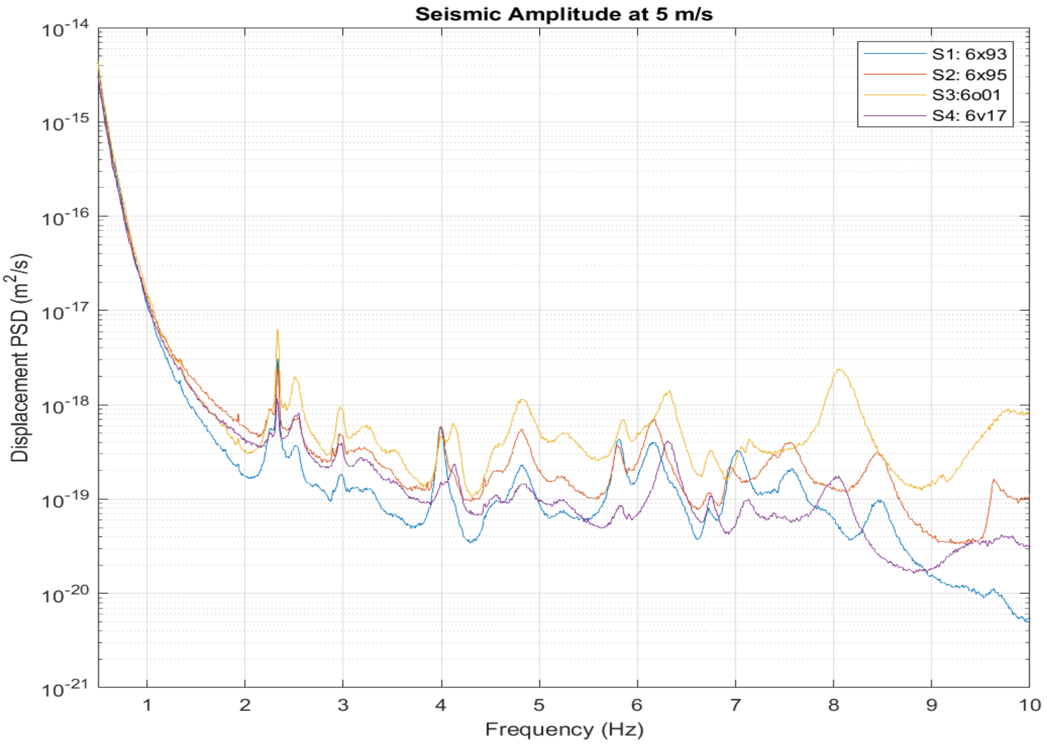


Seismic Amplitude at 3 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)



Seismic Amplitude at 4 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)

Xi


Seismic Amplitude at 5 m/s
Displacement PSD (m²/s)
Frequency (Hz)
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
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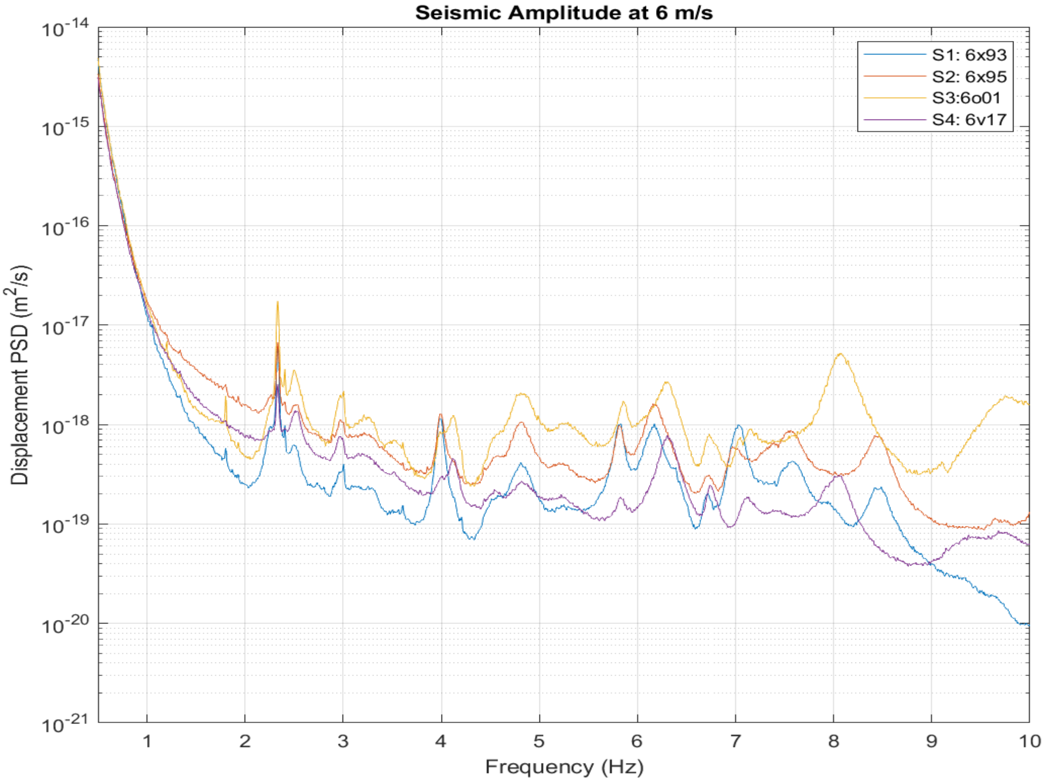
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
1 2 3 4 5 6 7 8 9 10


Seismic Amplitude at 6 m/s
Displacement PSD (m²/s)
Frequency (Hz)
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
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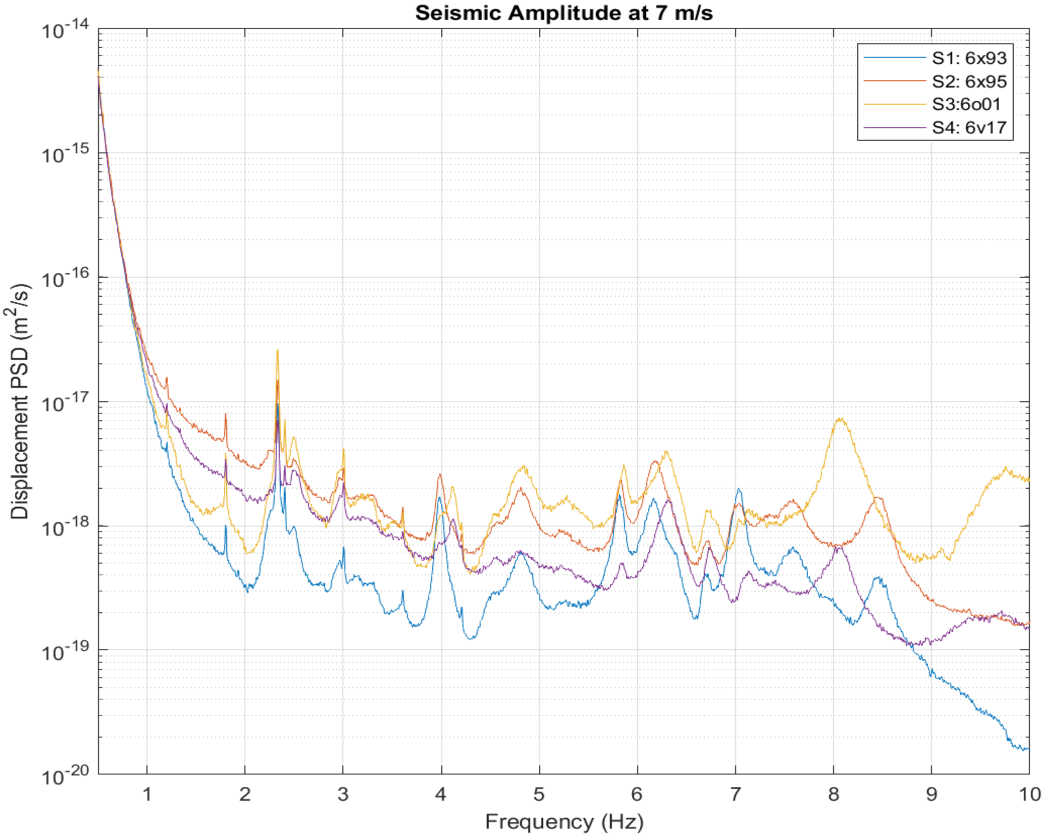
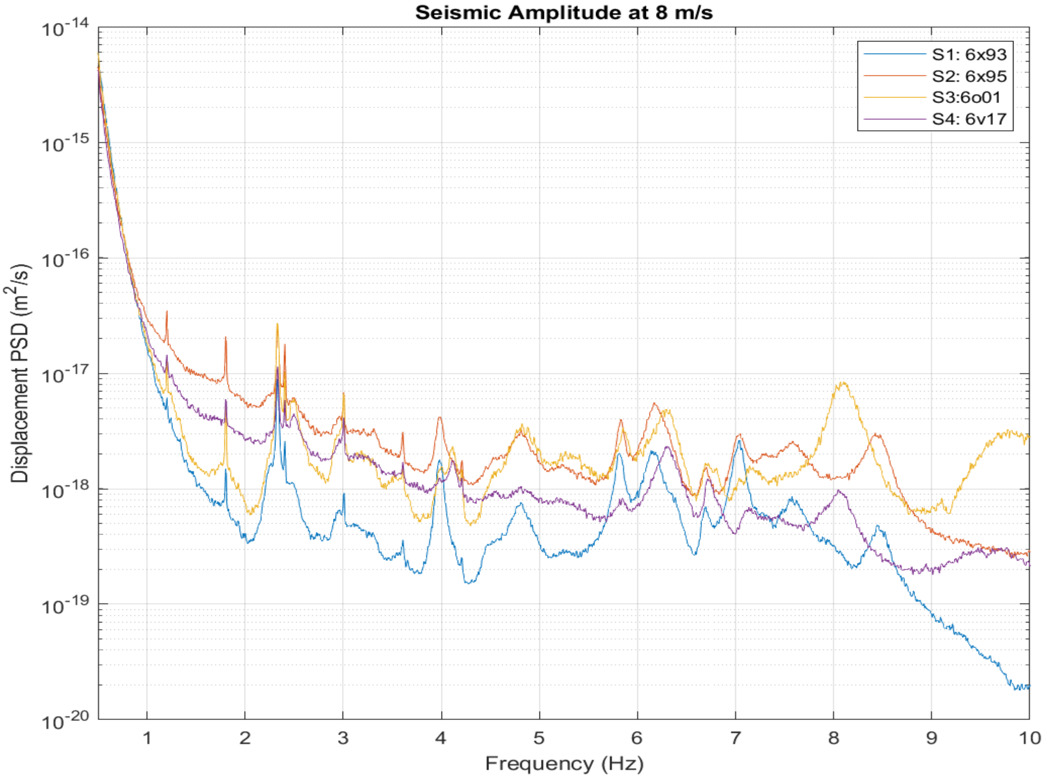
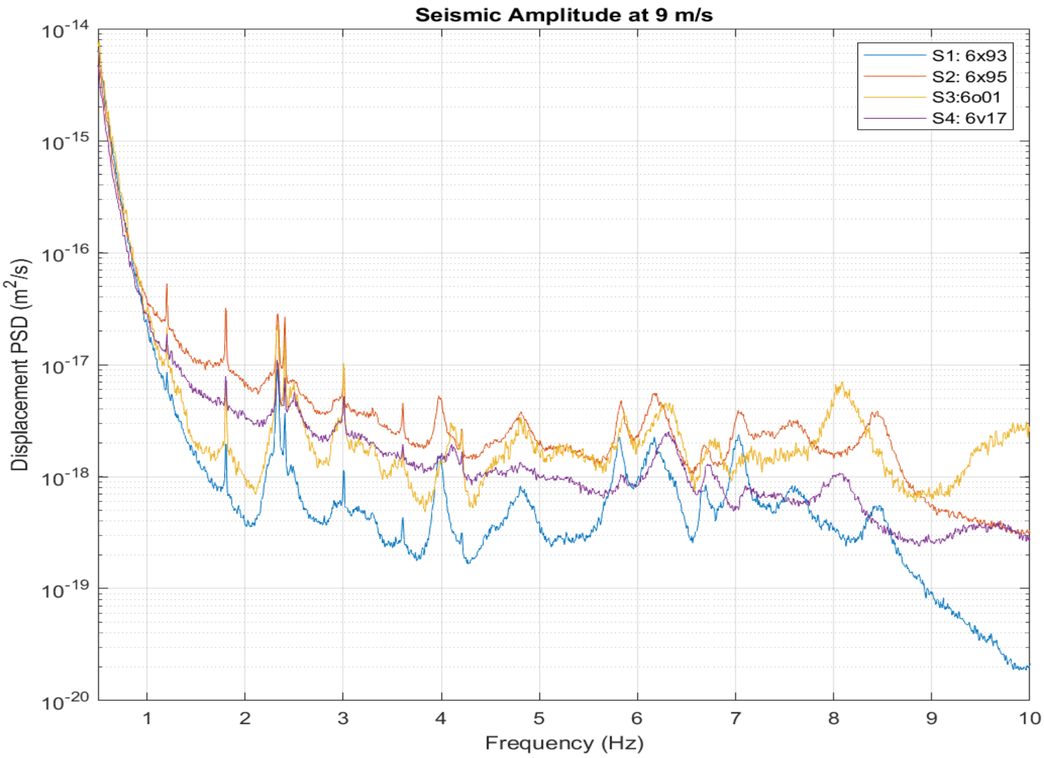
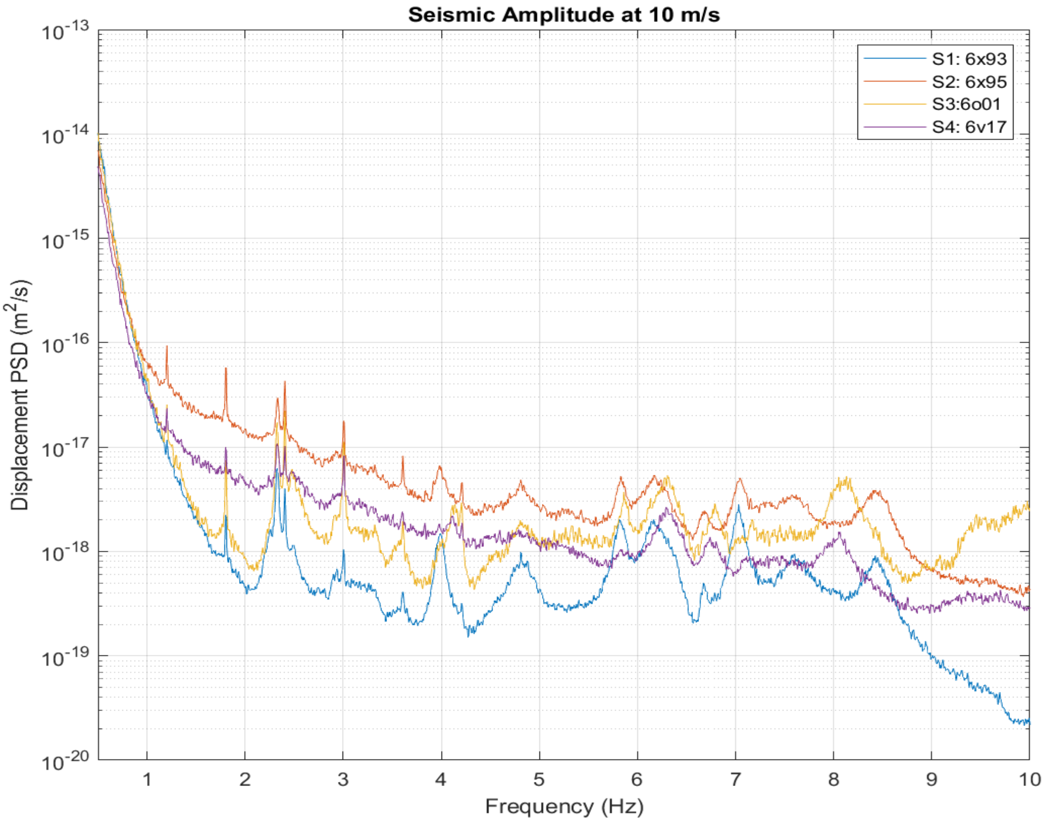
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
1 2 3 4 5 6 7 8 9 10

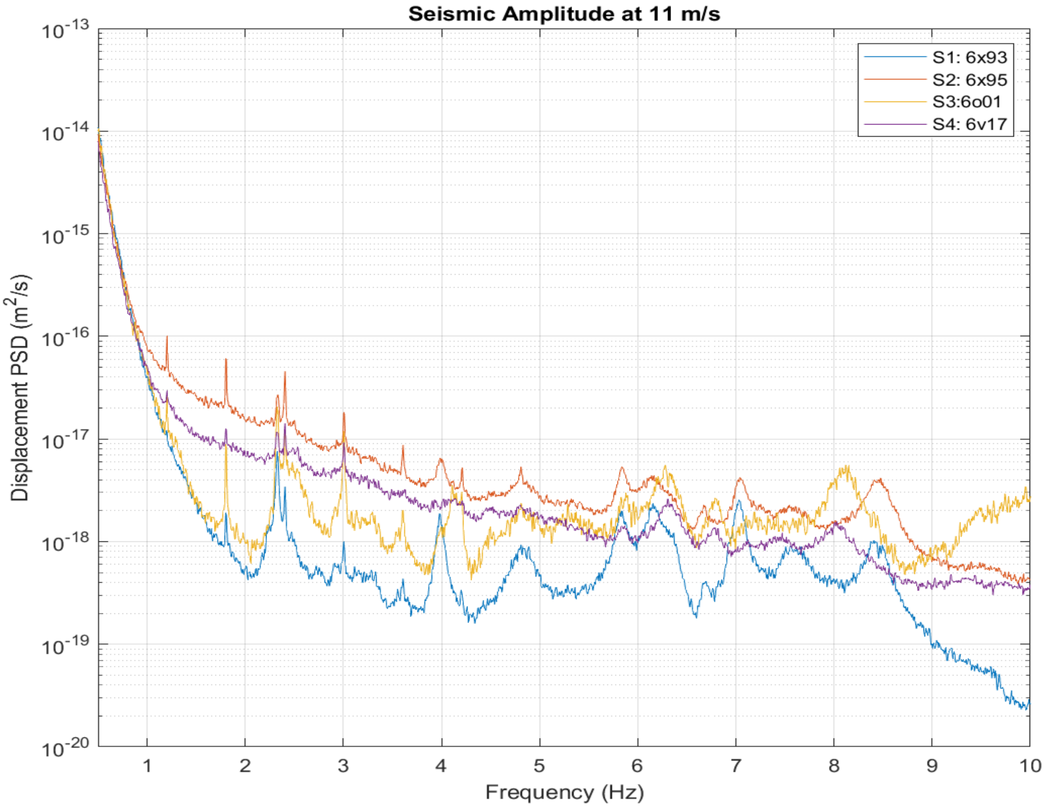
Xi

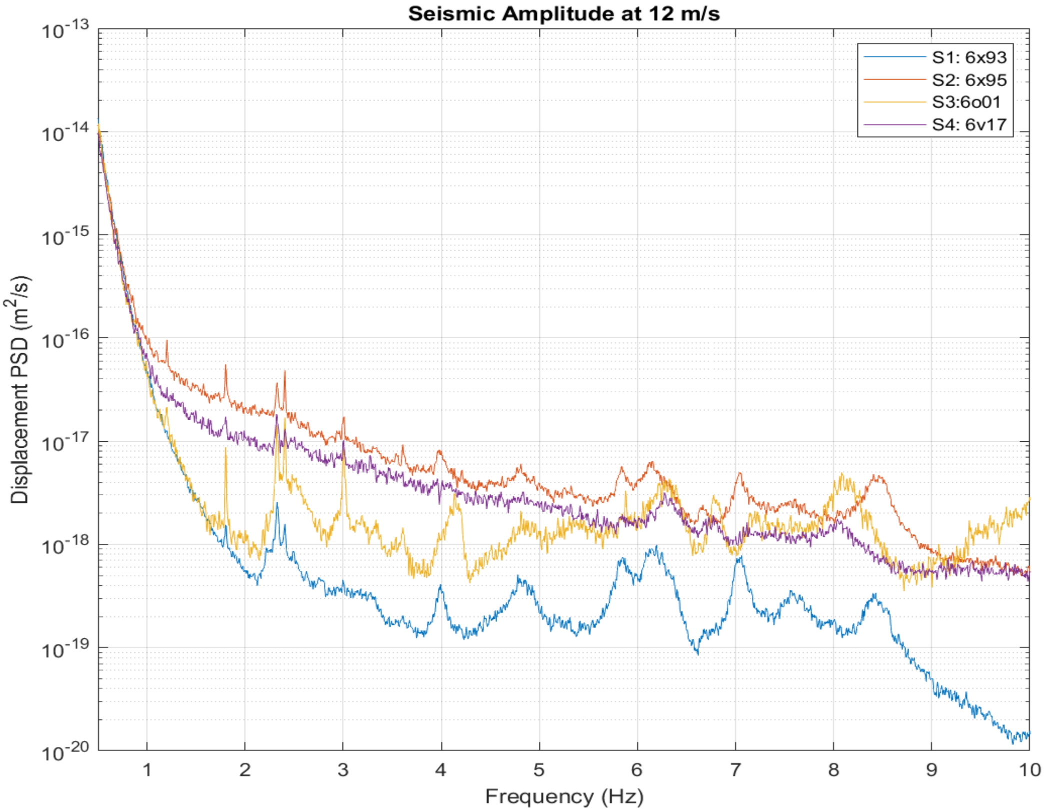

Seismic Amplitude at 7 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
1
2
3
4
5
6
7
8
9
10
Frequency (Hz)

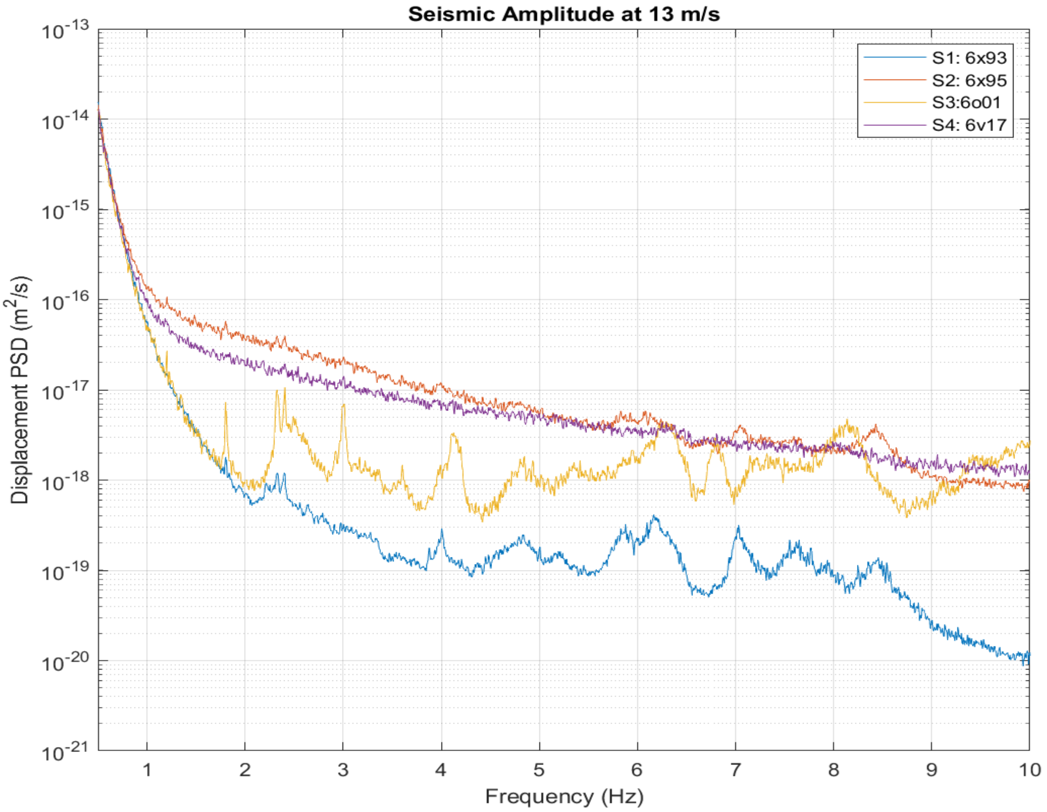

Seismic Amplitude at 8 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
1
2
3
4
5
6
7
8
9
10
Frequency (Hz)


Seismic Amplitude at 9 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)

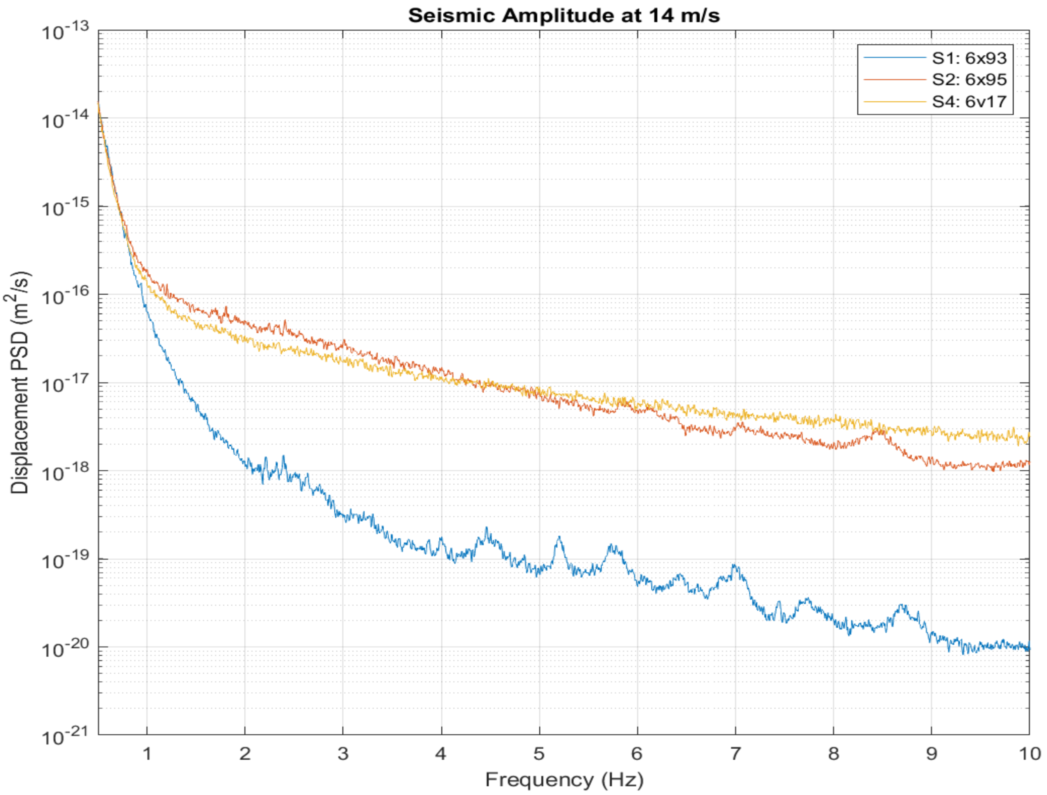

Seismic Amplitude at 10 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)


Seismic Amplitude at 11 m/s
Displacement PSD (m^2/s)
Frequency (Hz)
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17

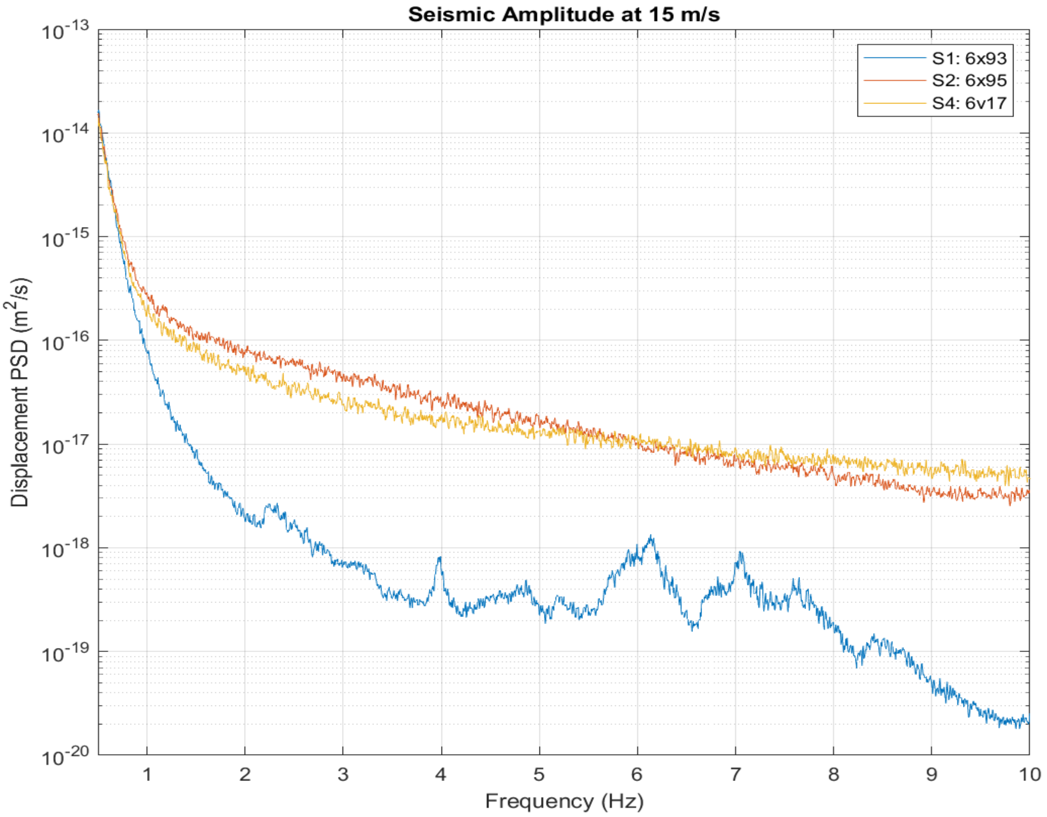

Seismic Amplitude at 12 m/s
Displacement PSD (m^2/s)
Frequency (Hz)
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17

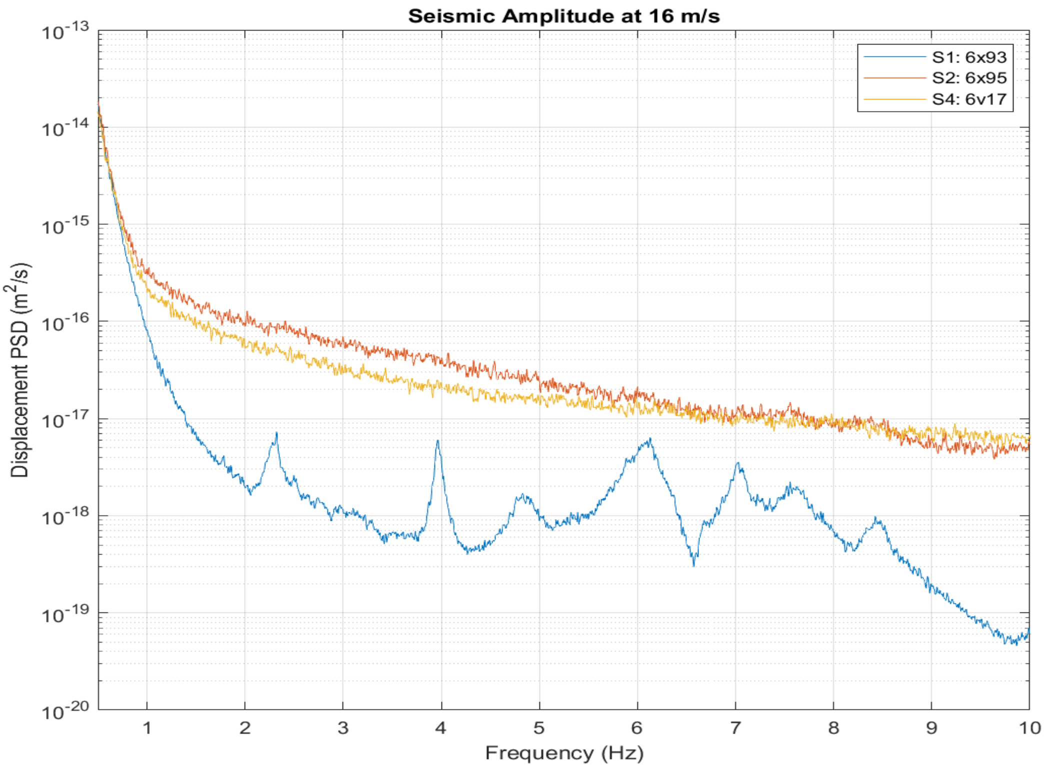


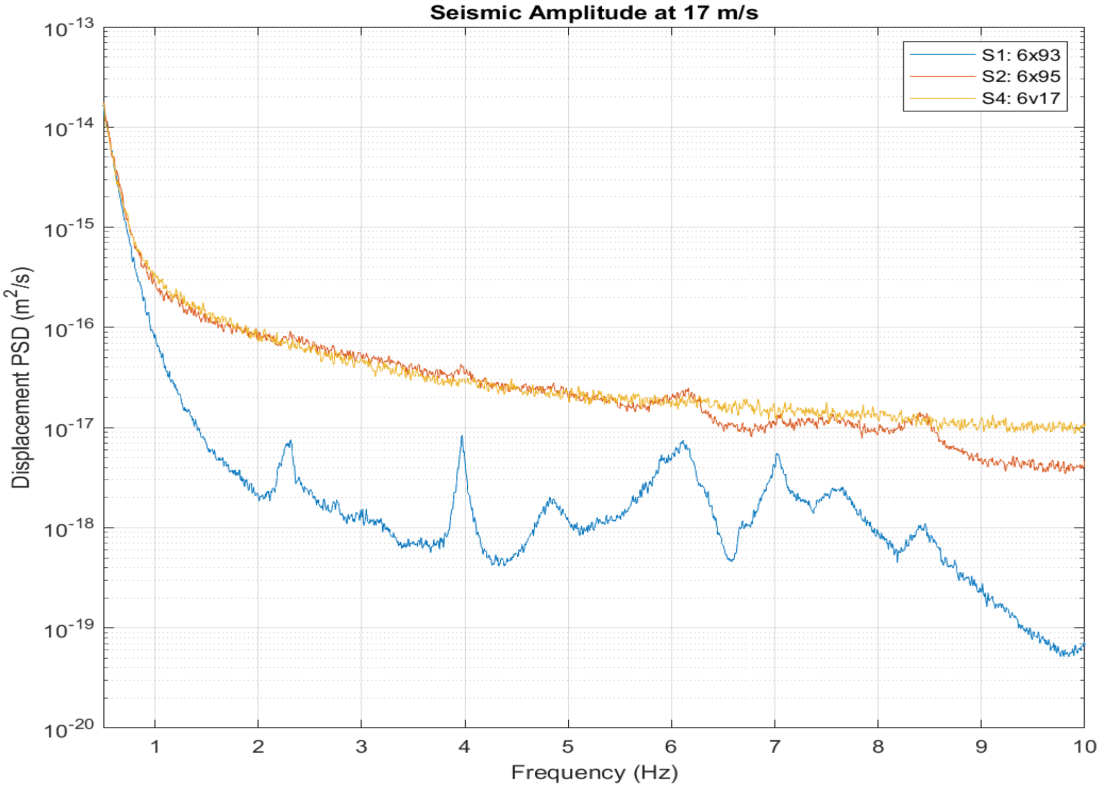
Seismic Amplitude at 13 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)



Seismic Amplitude at 14 m/s
S1: 6x93
S2: 6x95
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)


Seismic Amplitude at 15 m/s
S1: 6x93
S2: 6x95
S4: 6v17
Displacement PSD (m2/s)
Frequency (Hz)

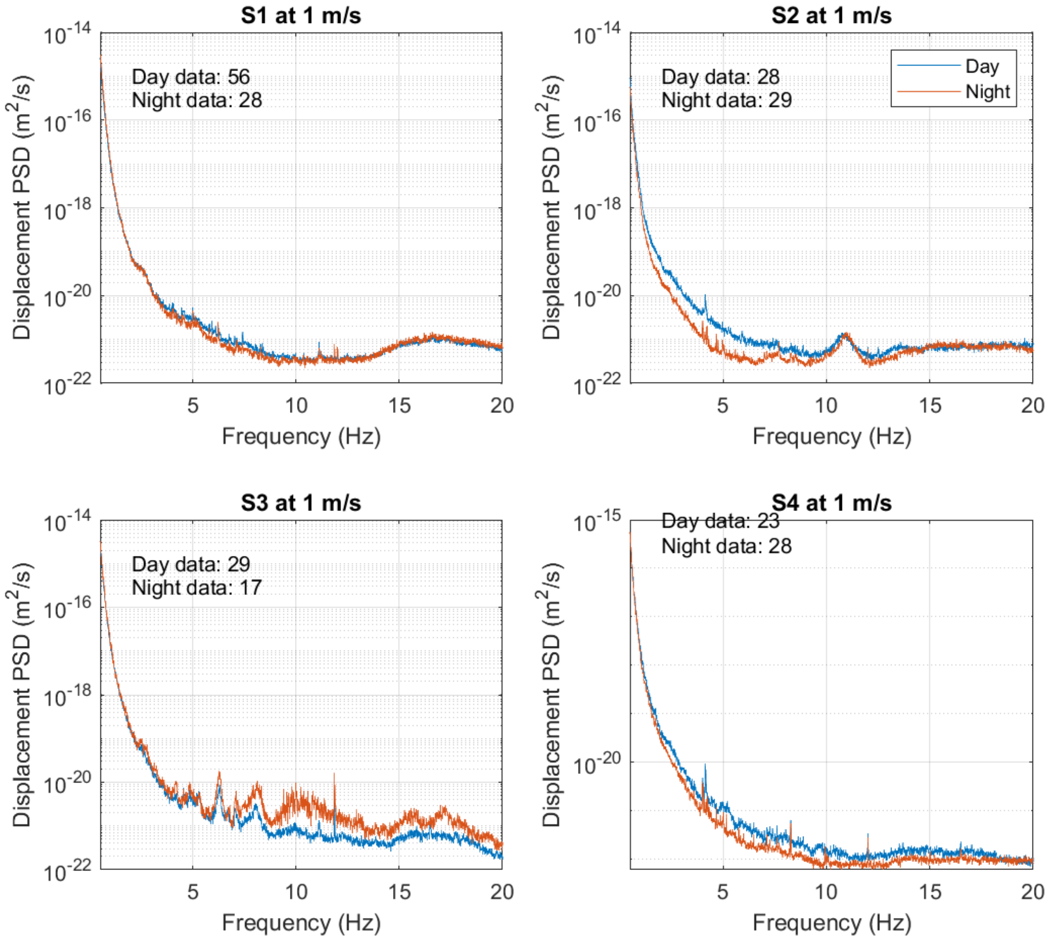

Seismic Amplitude at 16 m/s
S1: 6x93
S2: 6x95
S4: 6v17
Displacement PSD (m2/s)
Frequency (Hz)



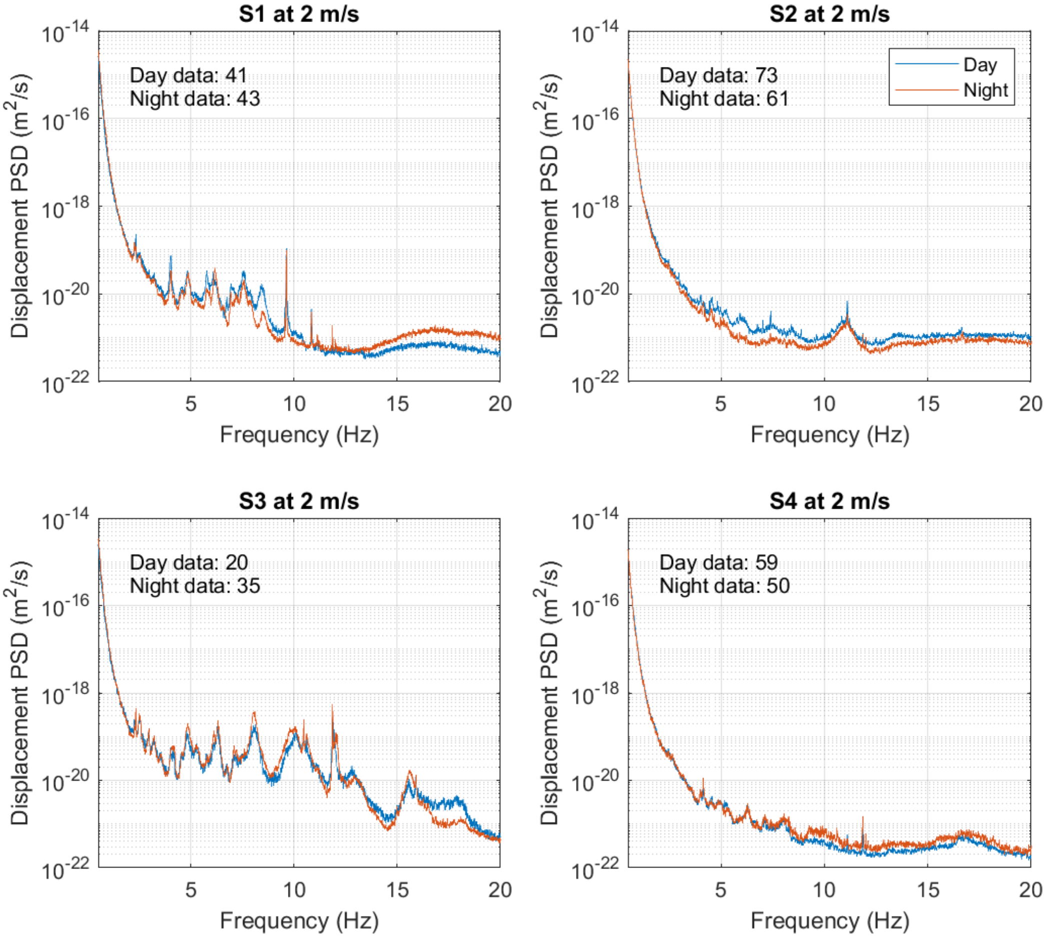
Seismic Amplitude at 17 m/s
S1: 6x93
S2: 6x95
S4: 6v17
Displacement PSD (m2/s)
Frequency (Hz)

12.8 Measurement Appendix C – Comparison of Diurnal variation

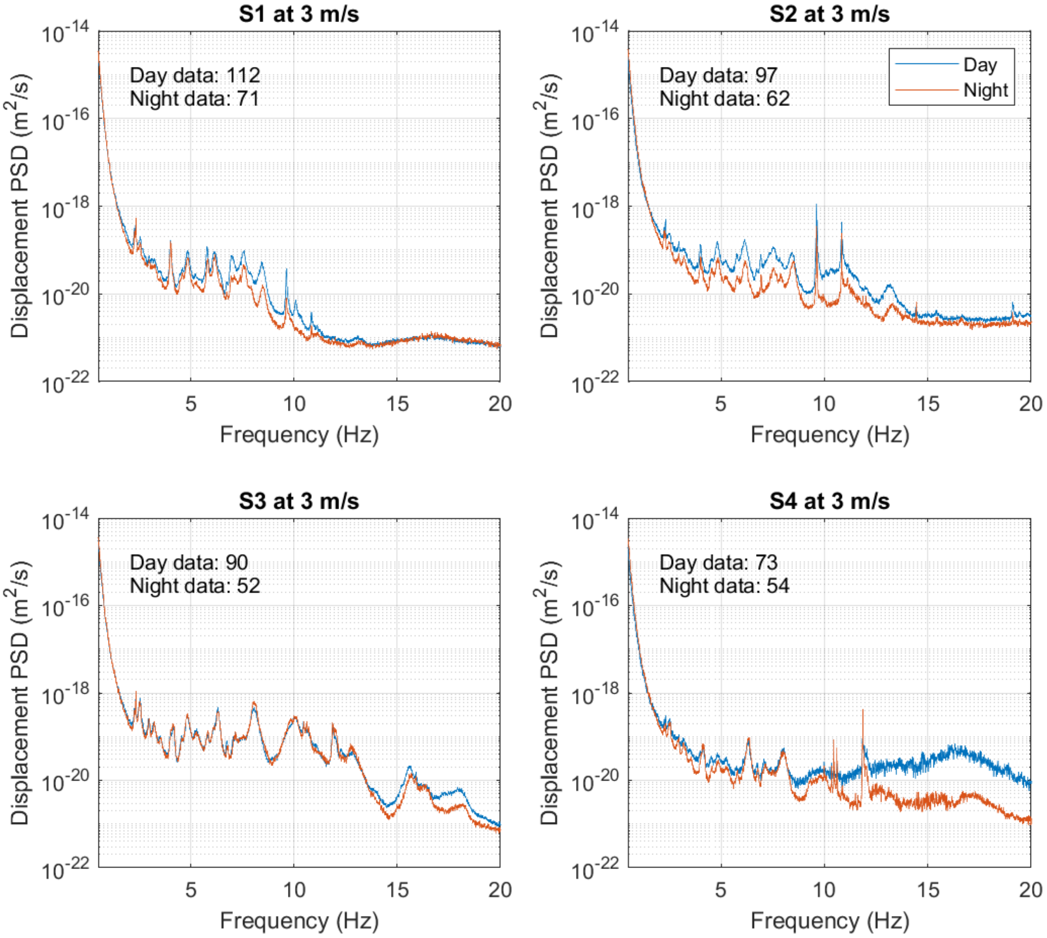
12.8.1 DIURNAL VARIATION AT WIND SPEED OF 1.0 M/S



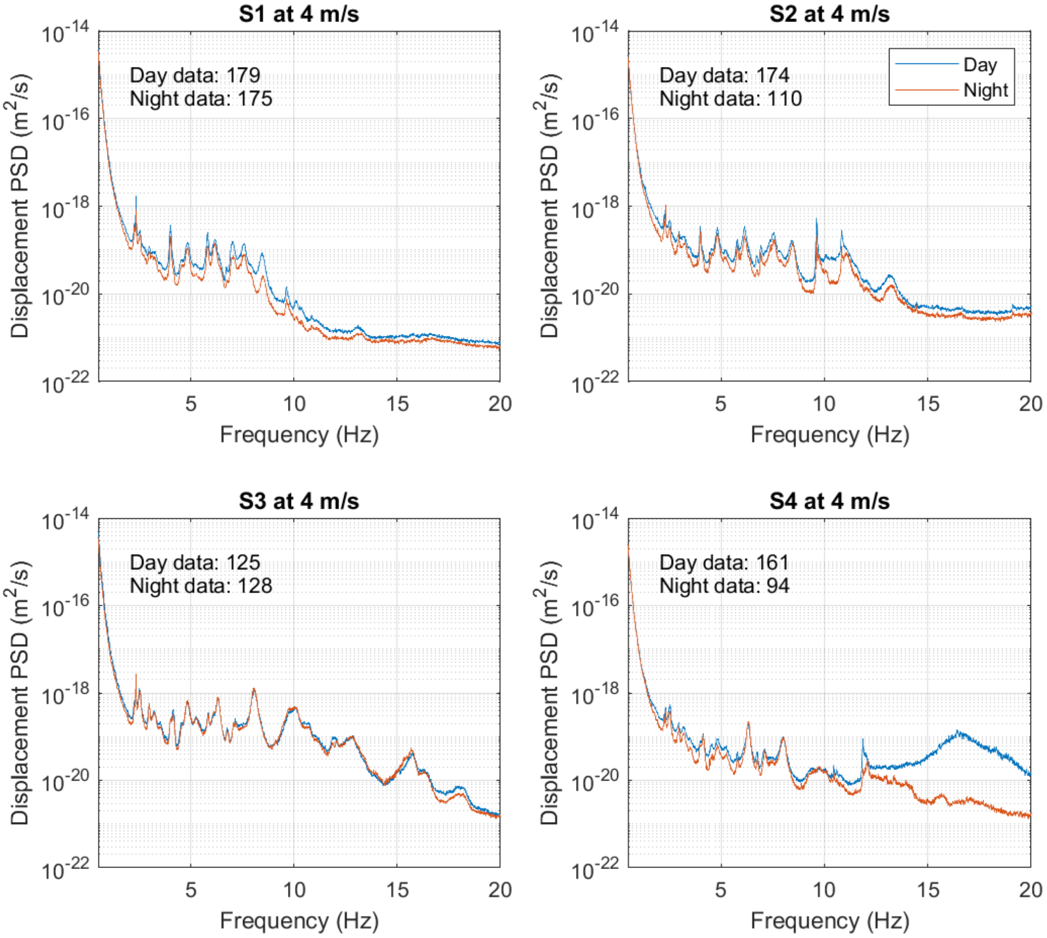
12.8.2 DIURNAL VARIATION AT WIND SPEED OF 2.0 M/S



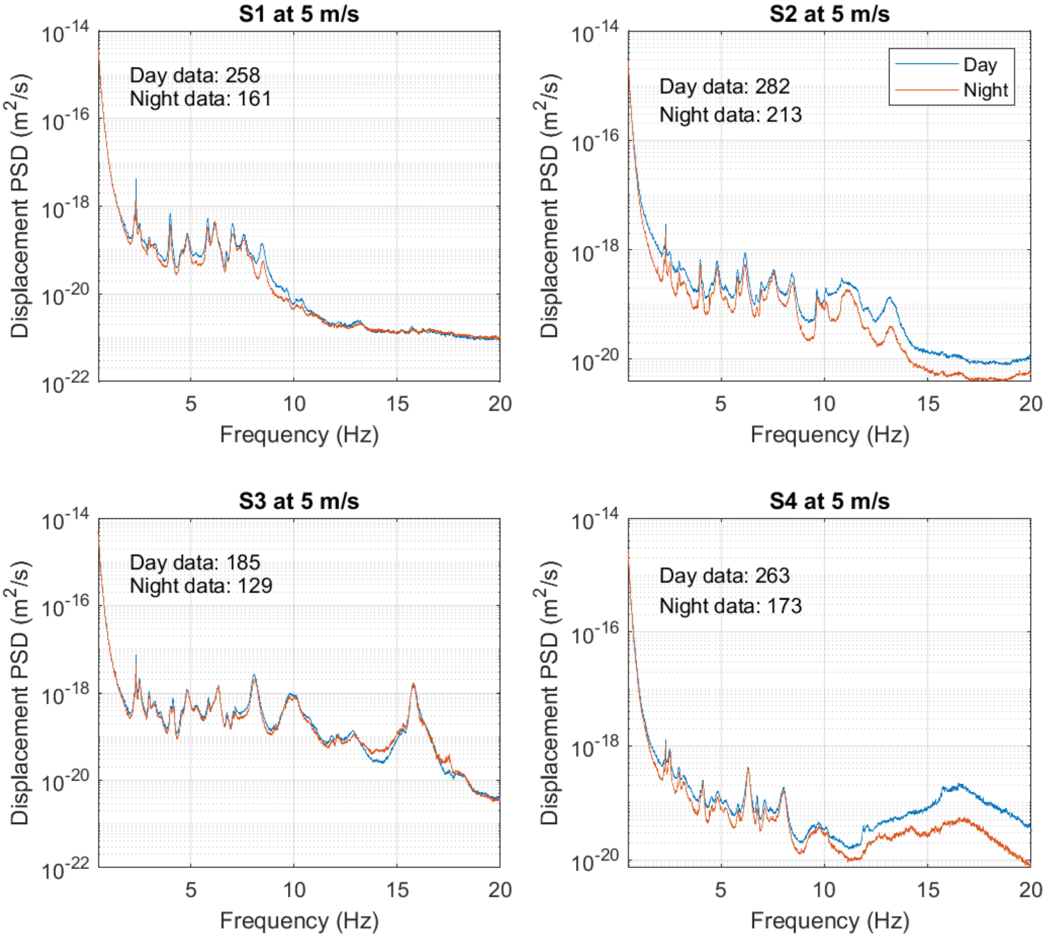
12.8.3 DIURNAL VARIATION AT WIND SPEED OF 3.0 M/S



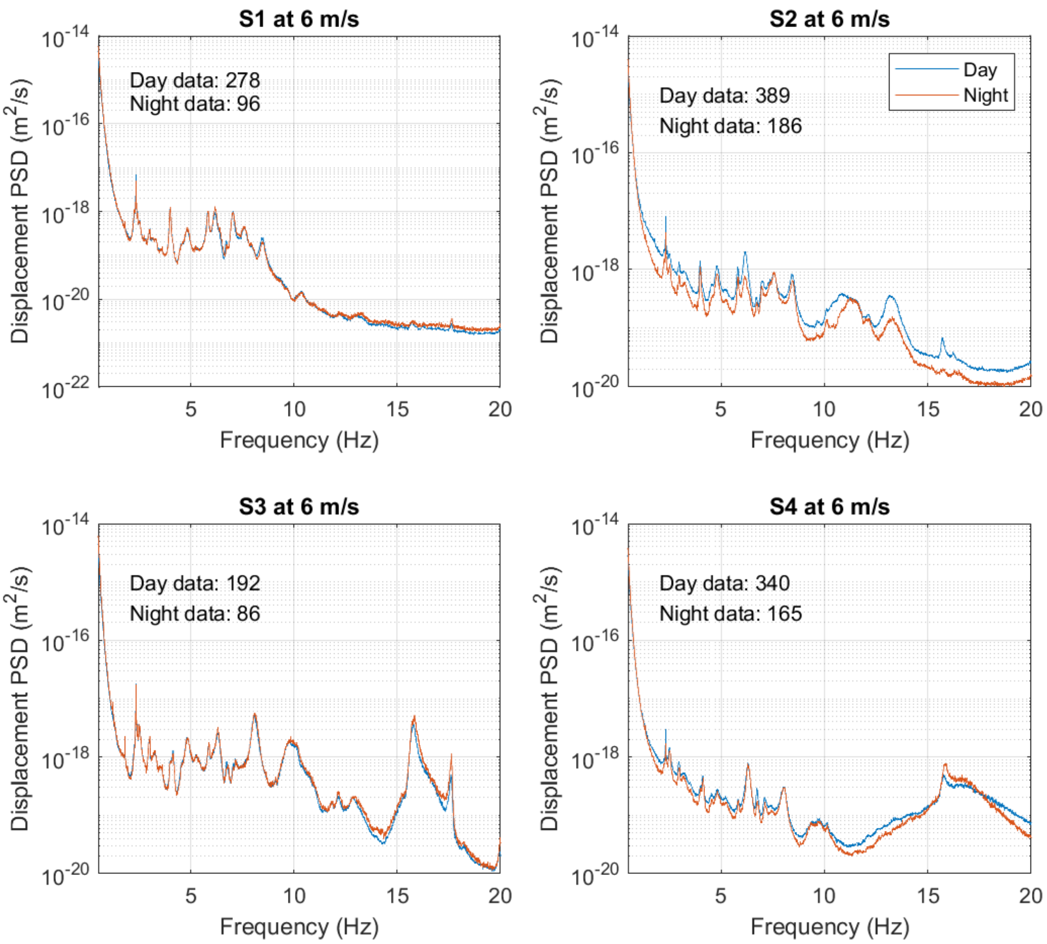
12.8.4 DIURNAL VARIATION AT WIND SPEED OF 4.0 M/S



12.8.5 DIURNAL VARIATION AT WIND SPEED OF 5.0 M/S



12.8.6 DIURNAL VARIATION AT WIND SPEED OF 6.0 M/S



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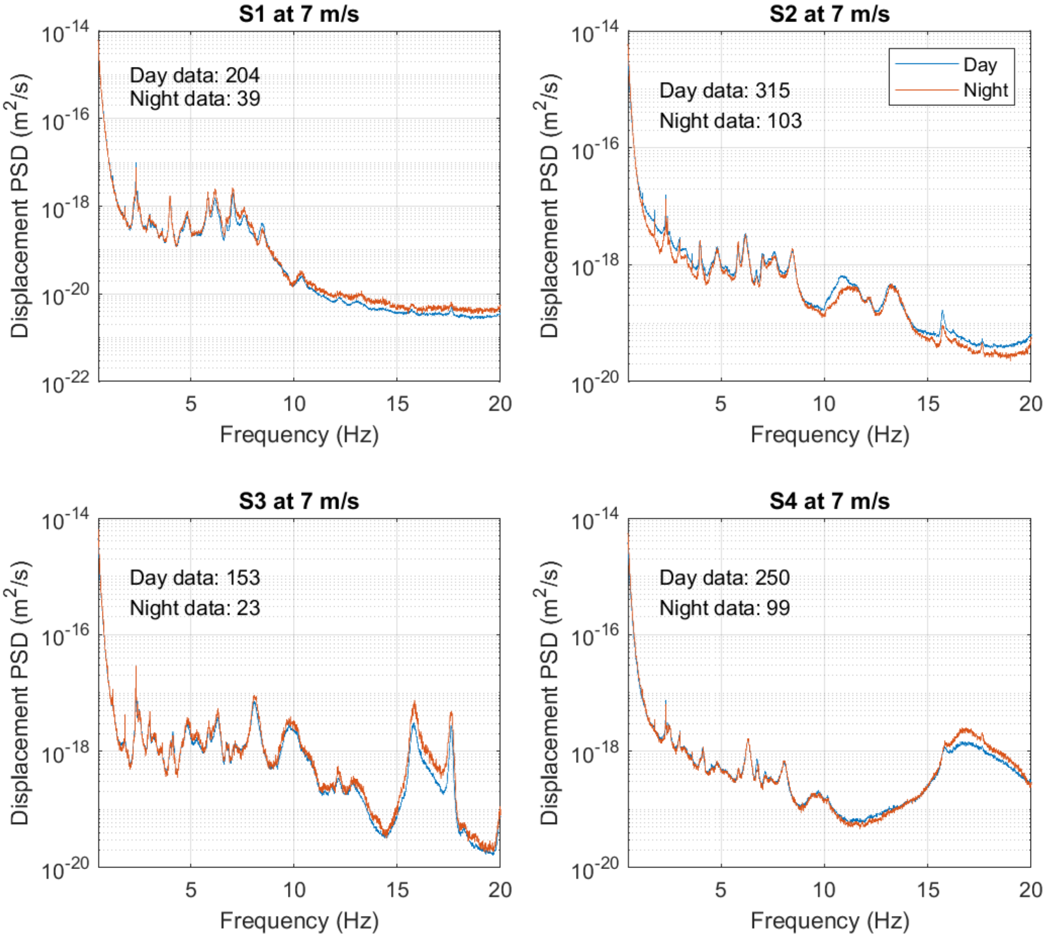
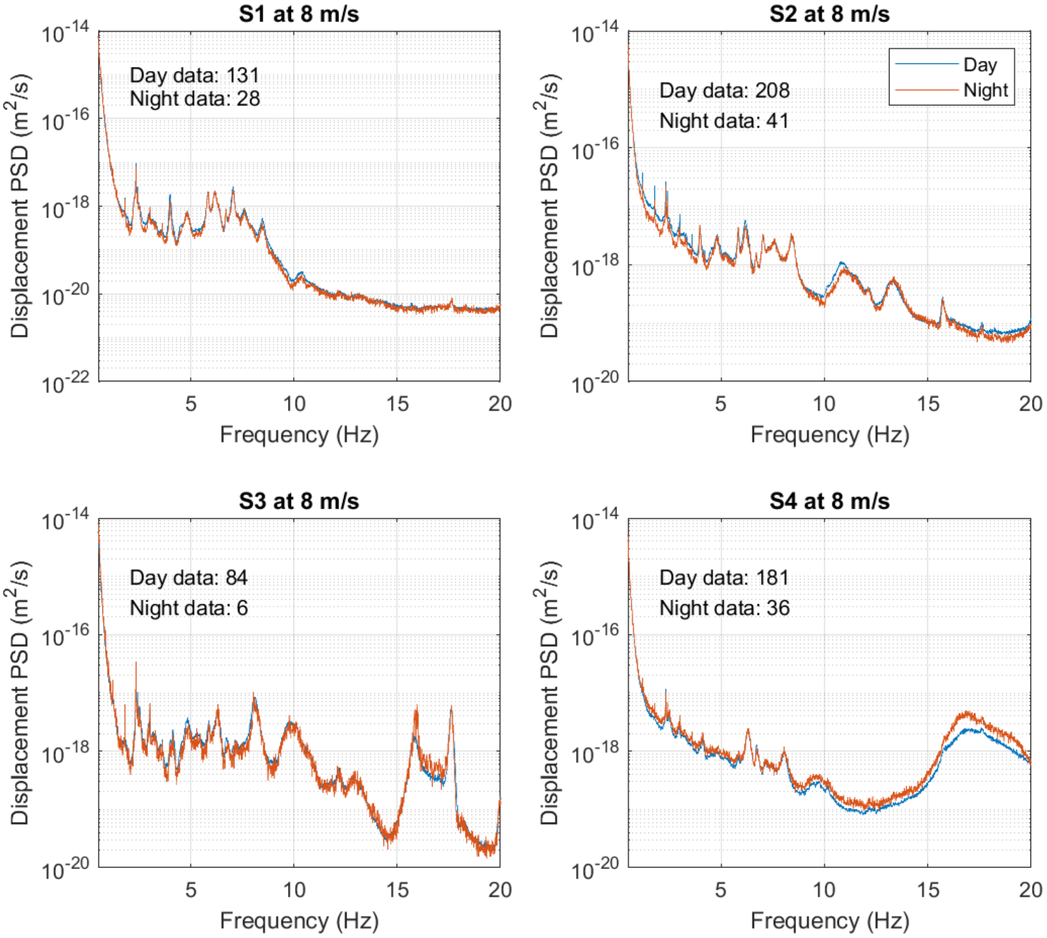
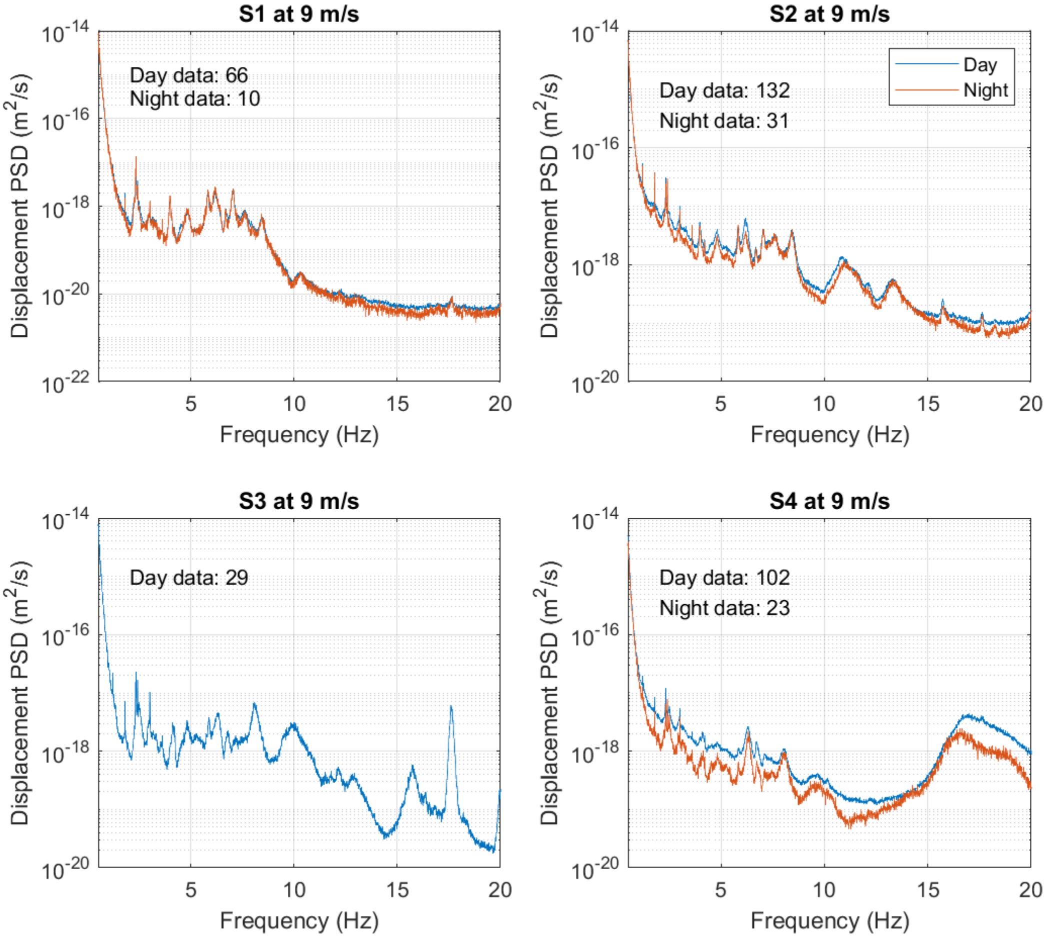
12.8.7 DIURNAL VARIATION AT WIND SPEED OF 7.0 M/S



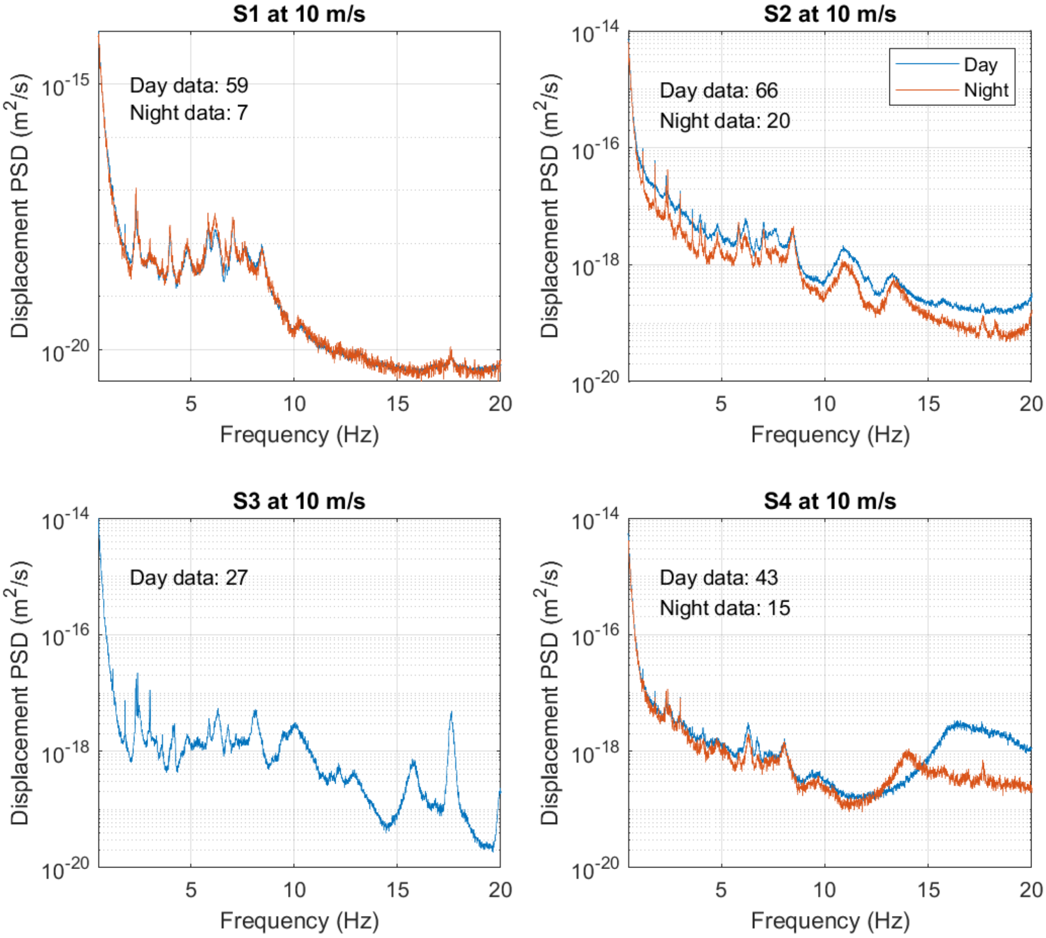
12.8.8 DIURNAL VARIATION AT WIND SPEED OF 8.0 M/S



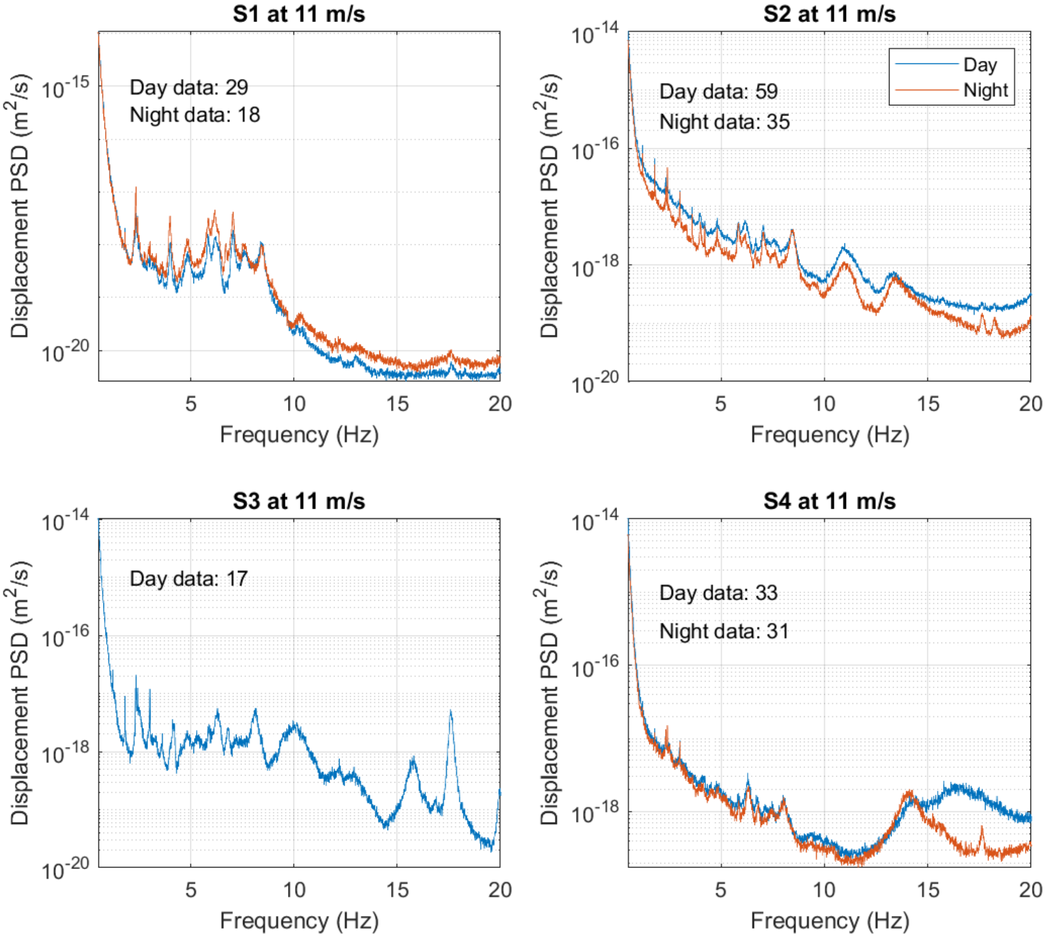
12.8.9 DIURNAL VARIATION AT WIND SPEED OF 9.0 M/S



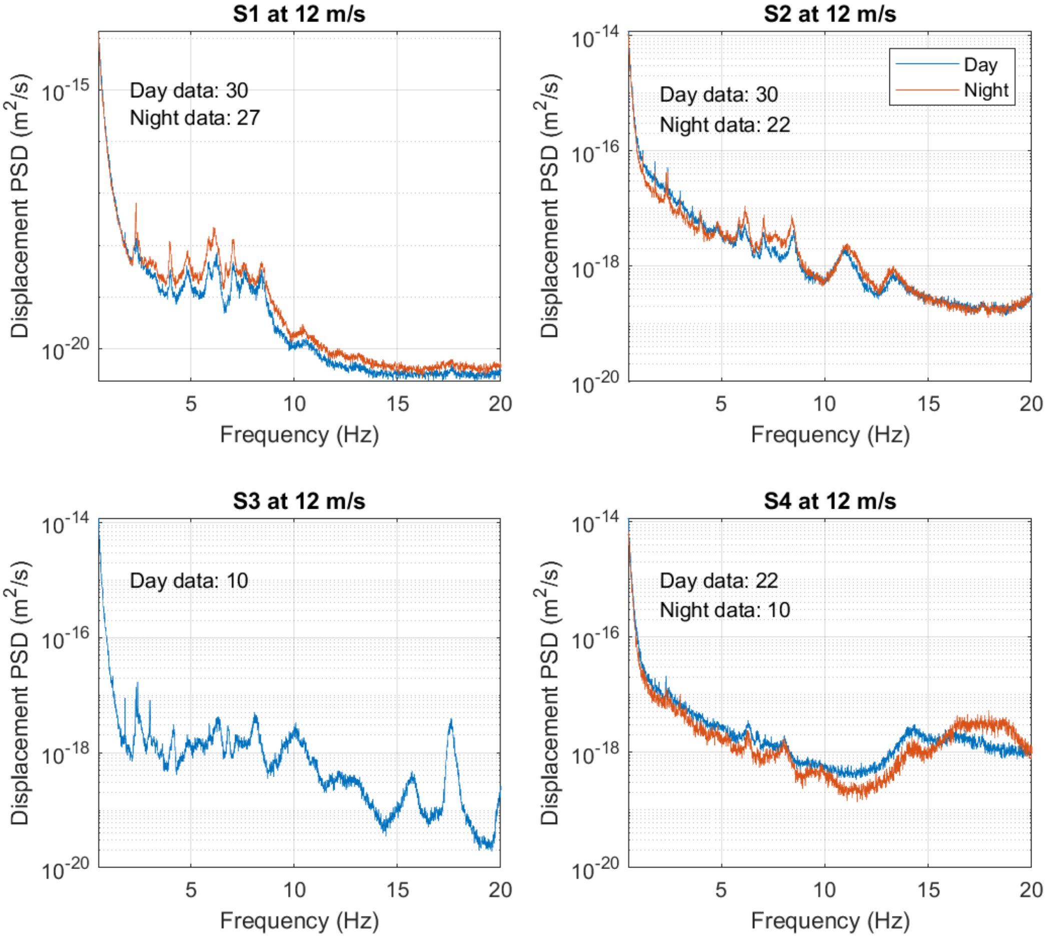
12.8.10 DIURNAL VARIATION AT WIND SPEED OF 10.0 M/S



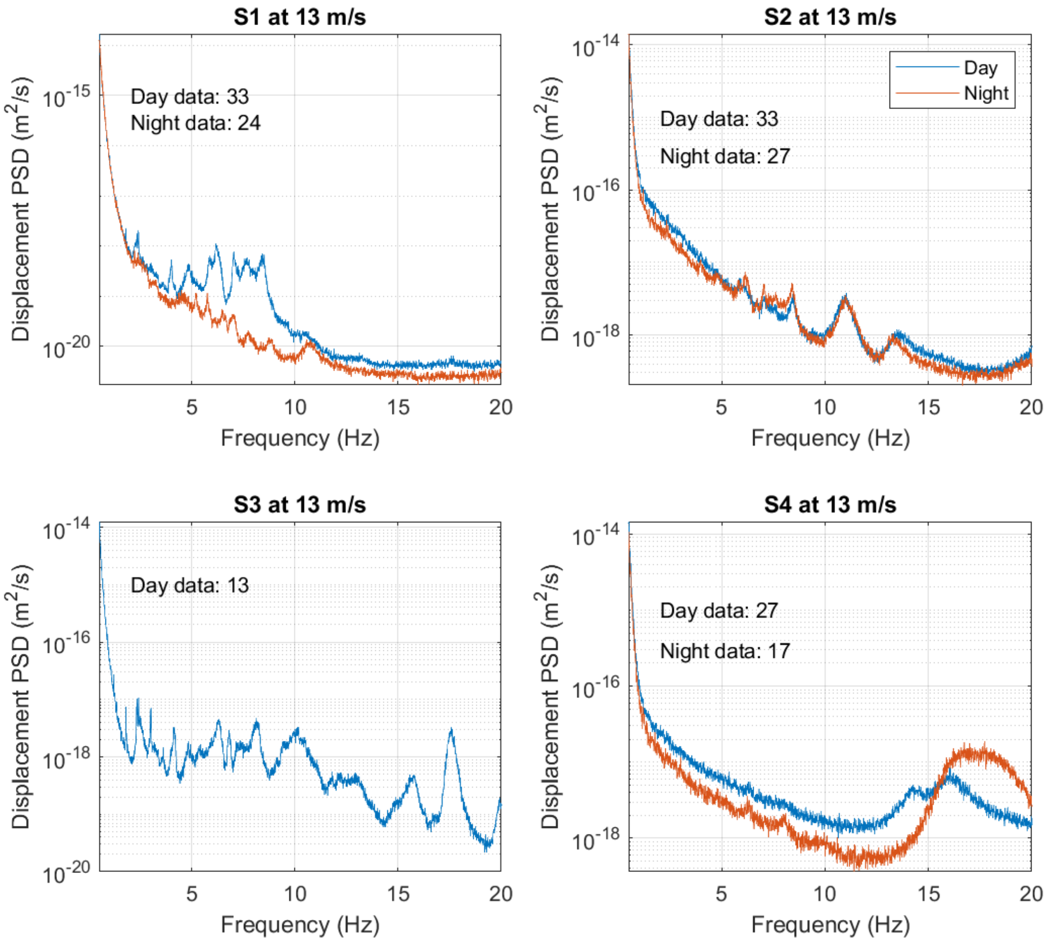
12.8.11 DIURNAL VARIATION AT WIND SPEED OF 11.0 M/S



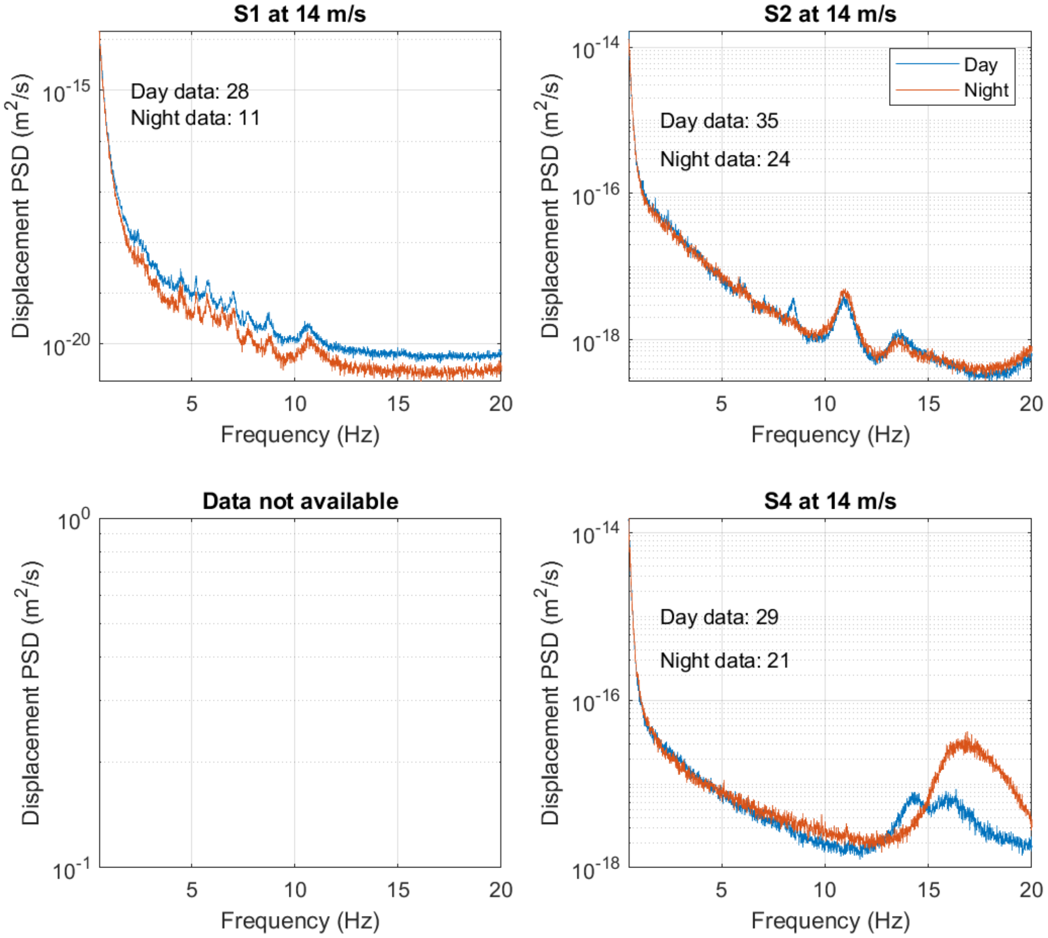
12.8.12 DIURNAL VARIATION AT WIND SPEED OF 12.0 M/S



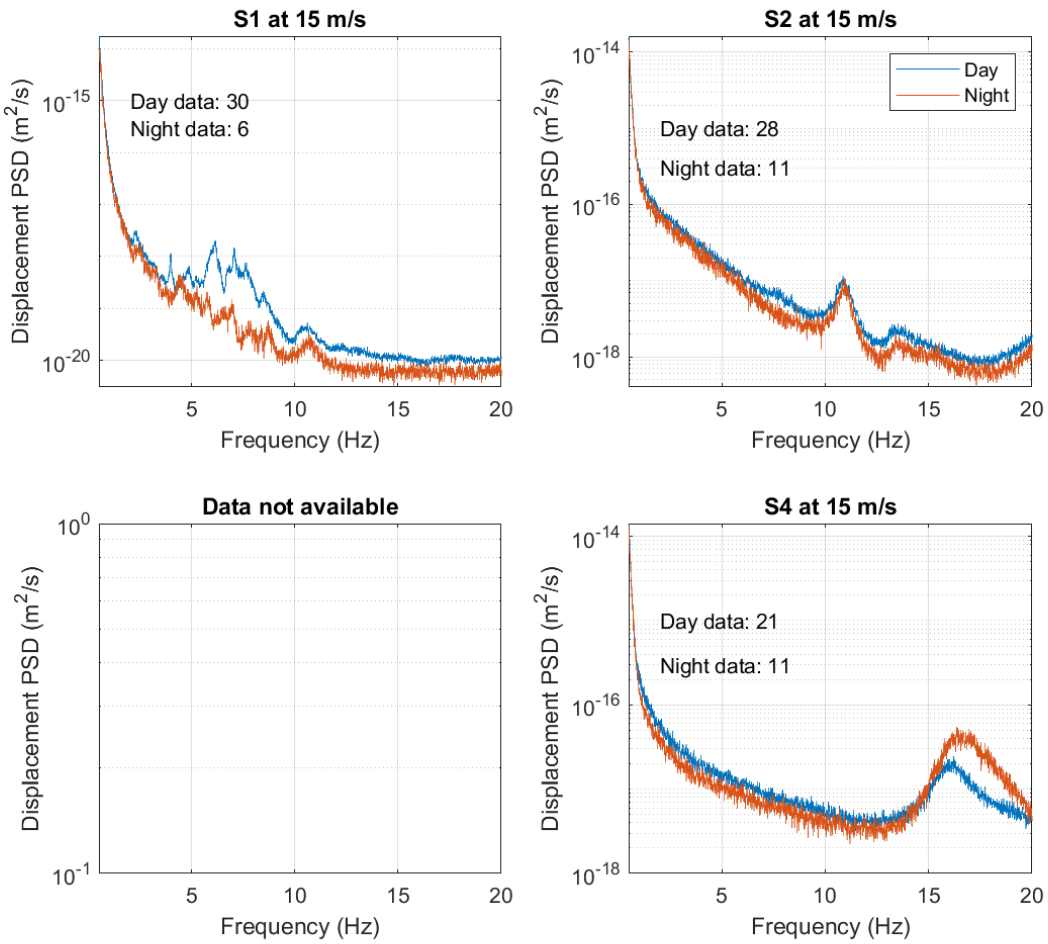
12.8.13 DIURNAL VARIATION AT WIND SPEED OF 13.0 M/S



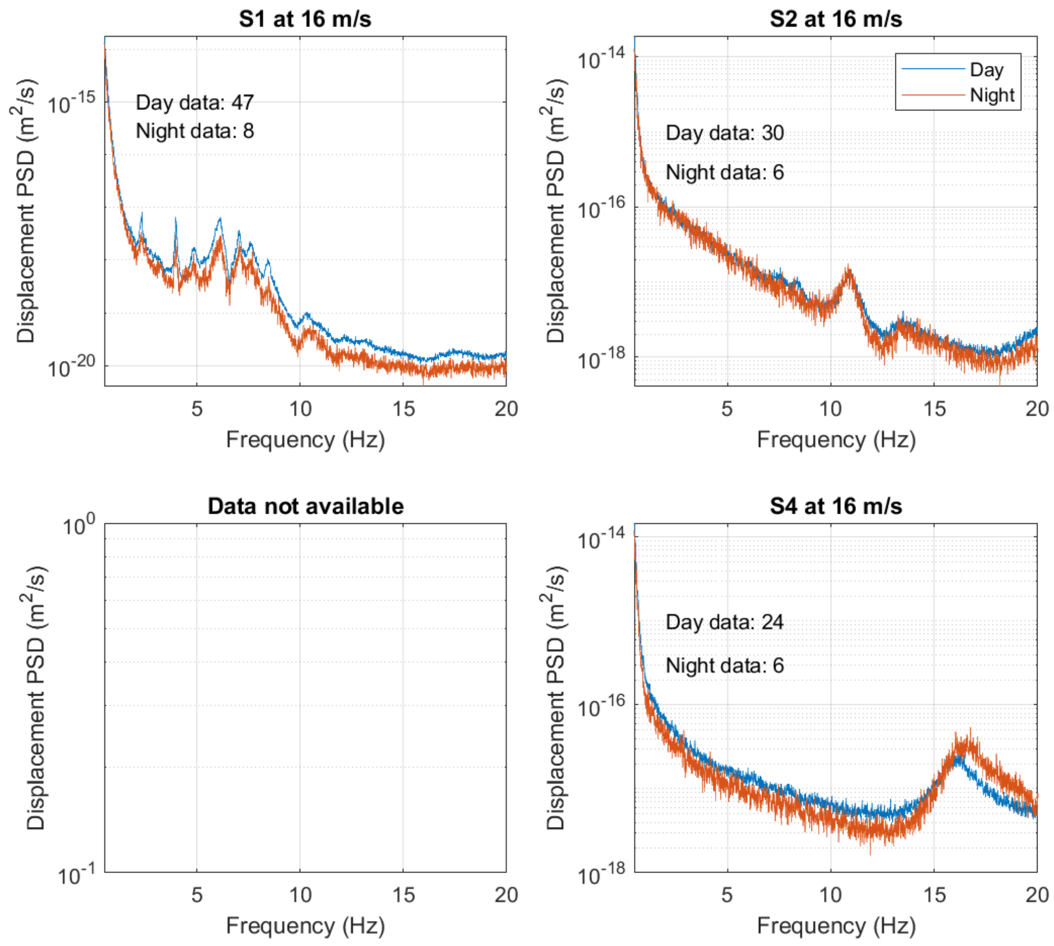
12.8.14 DIURNAL VARIATION AT WIND SPEED OF 14.0 M/S



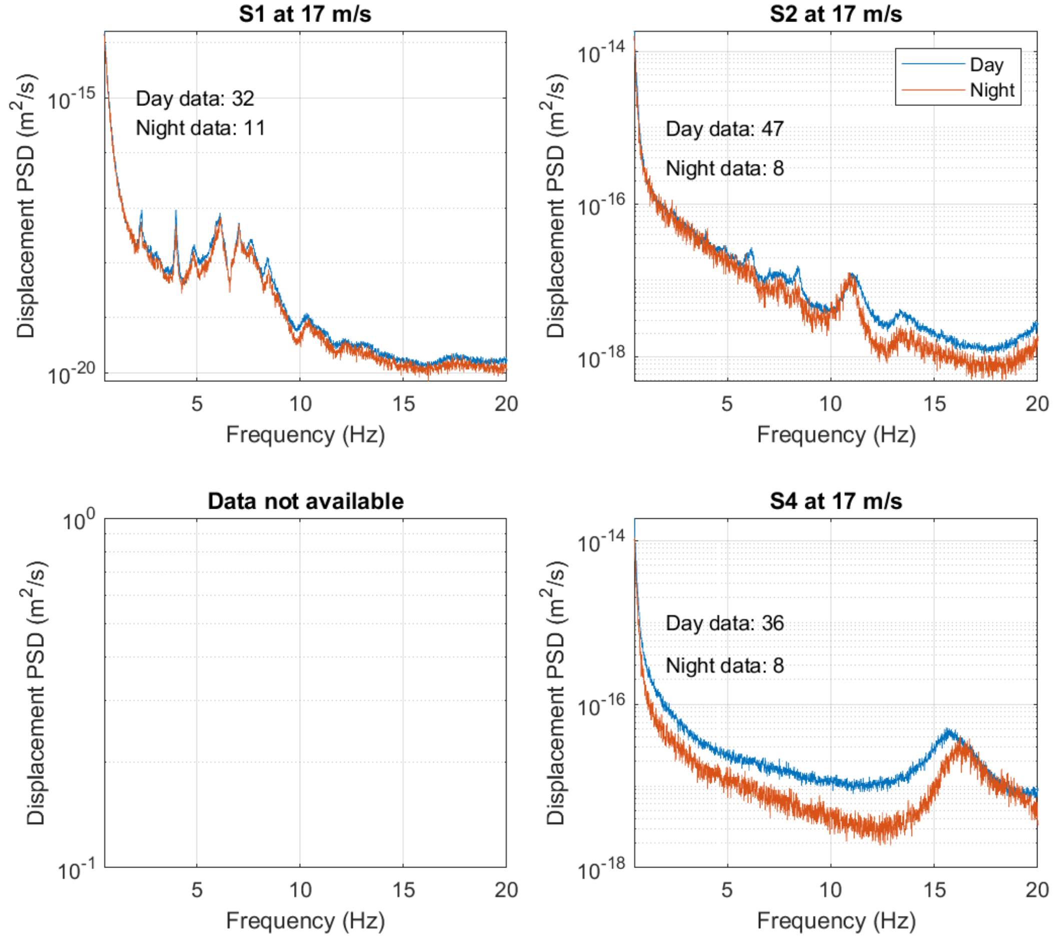
12.8.15 DIURNAL VARIATION AT WIND SPEED OF 15.0 M/S



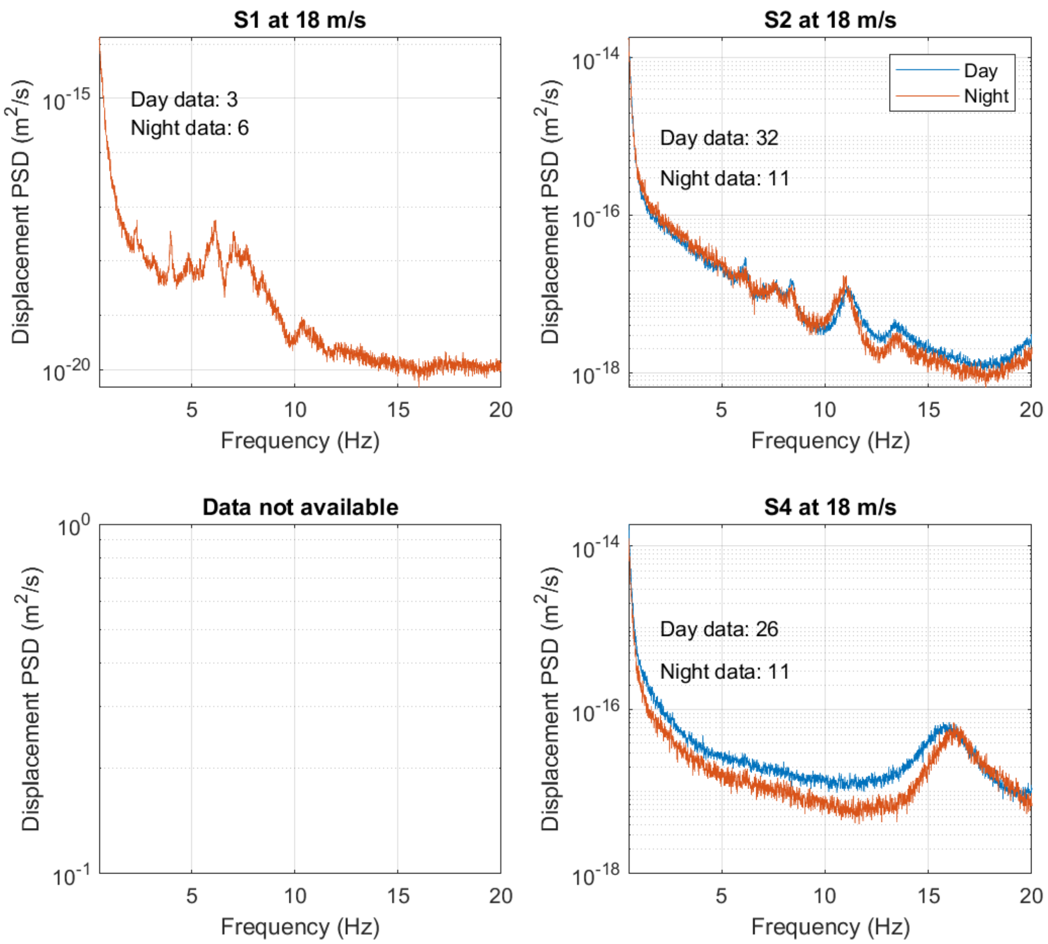
12.8.16 DIURNAL VARIATION AT WIND SPEED OF 16.0 M/S



12.8.17 DIURNAL VARIATION AT WIND SPEED OF 17.0 M/S



12.8.18 DIURNAL VARIATION AT WIND SPEED OF 18.0 M/S



Xi Engineering Consultants

Desktop Audit of EKA Budget Sheet

Work to determine scale of measurement requirements

Presented to The Scottish Government

Issue Date: 20/11/2020
Document No: SGV_203_Tech_Report_v12

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Document Summary

This document assumes a knowledge of the previous two studies by Xi Engineering Consultants for the Scottish Government – documents; *Xi Headroom Analysis Report Final (Phase1).pdf* and *Xi Headroom Analysis Report Final (Phase2).pdf.* It is recommended that these reports are read in order to fully understand the work covered in this document.

The detection capabilities of the Eskdalemuir seismic array (EKA) are protected from seismic vibration and the MoD manage a budget spreadsheet which allows data to be collected up to the point at which the seismic budget of 0.336nm is reached.

Having reached this point, further work is necessary to audit the full queue and asses the likely consumed budget based on the current worst-case turbine algorithm and measured actual data.

Several scenarios have been assessed to determine the likely actual seismic budget consumed, should the sites be measured to provide quantitative data for the MoD. Recommendations are made for proposed site measurements and are made based on this desktop audit, in order to release budget through delivery of quantified empirical data.

		Date	Version	Amendment
Originator	Dr MP Buckingham	15/10/2020	v1	Issue
Review	Rebecca Horton	16/10/2020	v2	Review
Review	Dr M P Buckingham	27/10/2020	v3-4	Additional data
Review	Rebecca Horton	29/10/2020	v5-7	Review
Review	Dr M P Buckingham	29/10/2020	V8-9	Final Issue
Review	Dr M P Buckingham	16/11/2020	V10	Issue following EWG feedback
Review	Rebecca Horton	16/11/2020	V11	Review
Review	Dr M P Buckingham	17/11/2020	V12	Review

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M: 07973 879888

1 INTRODUCTION

In order to better assess the current position regarding the Seismic Budget status and likely measurements needed to release budget, this desk-based exercise has been conducted by Xi Engineering. Fundamentally, this desktop audit has been to verify what has been built within a 50km radius of Eskdalemuir Seismic Array (EKA) (as opposed to what had been planned prior to deployment) and what is currently in planning within the area. The output of this exercise is to both understand the current budget position, estimate the additional budget likely to be released if proposed sites are measured, and make recommendations with regards to measurement locations.

The aim of this desk-based study is three-fold:

- Update the Budget Spreadsheet to confirm the current number of turbines built and in planning
- Analyse the updated spreadsheet and use it to confirm the need for a series of measurements to be undertaken in order to release more headroom from the budget. Several scenarios will be assessed in order to robustly demonstrate the need for a field audit of existing sites to progress the re-assessment of the budget while ensuring the protection of the EKA.
- Use the updated spreadsheet to recommend the minimum number and location of measurement sites required to be able to justify the release of further budget

Since the data is collated and held on lengthy Spreadsheets with well over 100 lines of data it is extremely difficult to include these within a word document. This document includes summary tables, and often just the budget including and post Fawside wind farm only. However, several spreadsheets accompany this report for the various scenarios assessed.

2 METHODOLOGY

2.1 Desktop Audit Process

Best endeavours have been used to gather and collate data from members of the Eskdalmuir Working Group (EWG), and developers and owner operators who are not members of the EWG. Both Xi Engineering and the Scottish Government are grateful for the industry's engagement in this process.

The foundation of this desktop Audit has been the MoD's spreadsheet up to and including Fawside Wind farm. Subsequent wind farms have been added based on date of submission order in line with current MoD practises.

This desktop study has produced a revised budget sheet with the following inputs and assumptions;

- As built information – size (rotor diameter & hub height), make, model, number of turbines and locations
- Additional sites in planning have been added to the queue using the submission date and the current 'first come first served' approach adopted by the MoD

2.1.1 SCENARIOS ASSESSED

With a view to demonstrating the definite need for a measurement of existing sites in order to release budget headroom, several scenarios have been assessed using the now updated budget. These scenarios will show, in different ways, either the point where the budget is consumed or the amount of headroom that could be released if different and more accurate input data is used. It is expected that all scenarios will show that, with more empirical data, it is very likely that budget will be released. They will also help to determine which measurements should take place. These scenarios are not intended to propose alternative methods of managing the queue, solely to show how much budget becomes available on a 'what if' basis. Most scenarios assessed contain both initial sites and resubmitted sites, each calculated as an independent site. This is intentional.

The scenarios modelled are as follows;

A. Current budget with sites added to queue. i.e. past the consumption of the budget based on planning information received- Using current 'worst case' algorithm for 'as built' turbines and those in queue
B. Using a mixed model with 'worst case' and measured data where possible (i.e. Siemens 2.3 for Clyde, Senvion data for Middle Muir data etc)
C. Using Middle Muir data to represent all turbines in queue
D. Scenarios B with sites with turbines located within 15km of the array excluded
E. Scenario C with sites with turbines located within 15km of the array excluded
F. Same as E except all sites post original budget consumption at Fawside using Middle Muir with background levels mathematically removed. (see note on background removal)
G. Same as F except initial submissions for sites that have been resubmitted have been excluded to prevent duplication (this is a mathematical approach to prevent duplication and is in no way intended to suggest reordering of sites)

2.1.2 BACKGROUND NOISE REMOVAL

Seismic measurements of wind turbines include ambient seismic noise. This noise is not attributed to the wind turbines themselves, rather it is produced by a combination of natural and anthropogenic sources. The ambient noise may, however, mask lower amplitude wind turbine seismicity (i.e. there may be some component of wind turbine noise, but it may be just below the background noise level so it wasn't detected). For this reason, the EKA algorithm includes a noise floor based on the measurements of Clyde wind farm.

It has been proposed that a background noise measurement could be conducted before wind farms are built and then a subsequent measurement be conducted once the farm is operational. The background noise could then be subtracted from the operational noise giving a truer value of the contribution of the wind farm to seismicity. This approach is common in acoustic measurements of wind farms. To illustrate the affect that such a measurement campaign may have, tables have been provided where the noise floor has been removed from the algorithms such that the seismic contribution of the wind turbines only come from blade pass and structural resonances. This is very much a best-case scenario and is provided for illustrative purposes only. The authors note that the approach of removing all background noise from the algorithm is contrary to the precautionary approach used to design the worst-case EKA algorithm and that it is likely that some turbines generate noise which exists below the noise floor. Working through real world empirical assessments of this will further understanding of how close to this best-case scenario results will be.

2.2 Analysis of Scenarios

The final calculations to determine which sites should be measured are based on both nm per turbine and make model and size. To better understand the seismic signature of different turbines we need to capture all manufacturers and ensure we are not using a single data point for those that have already been measured.

2.3 Measurement Audit Recommendations

Following the analysis of the scenarios, measurement recommendations will be made. These will take into consideration: location, manufacturer, size of budget allocation, whether the site has already been measured, proportion of turbines across the entirety of the EKA and corresponding representation in the audit, accessibility and alternatives.

3 RESULTS

3.1 Scenario Results

NOTE – for all the scenarios the following windfarms have been removed from the list as they can no longer obtain planning for the original application lodged;

1. Birneyknowe Windfarm submitted 14th May 2014, 15 turbines
2. Harryburn Windfarm submitted 8th June 2016, 17 turbines
3. Barrelaw Windfarm submitted 14th September, 7 turbines

NOTE – all small wind turbines under 1MW have NOT been audited with respect to location or size due to the difficulty of contacting owners and their minimal contribution to the budget.

NOTE – Scenarios A through F contain both initial sites and resubmitted sites, each calculated as an independent site. This is intentional as there is significant variation in the route these sites have reached planning and ultimately the queuing system. Scenario G shows what the impact would be on the cumulative budget assuming that there is no replication of sites and that the resubmissions are included as per this audit.

3.1.1 SCENARIO A – WORST CASE ALGORITHM/CURRENT BUDGET

Current budget with sites added to queue. i.e. past the consumption of the budget based on planning information received – all using standard 'Worst Case algorithm'

Site #	Wind_Farm	Operator/Developer	Date of submission	Number_of_ Turbines	Manufacturer	MW rating	Total MW	Size	StandardEKA	Selection	Budget Standard (nm)	Cum Total Scenario Model (nm)
114	Cliffhope	Community Windpower	29/92017	46	unknown	7.00	322.0	125/150	0.06528	StandardEKA	0.27619	0.21852
115	Faw Side	Community Windpower	11/01/2018	45	unknown	7.00	315.0	125/150	0.65524	StandardEKA	0.71107	0.69072
116	Little Heart Fell	Energiekontor	1/2/2018	9	Nordex	5.70	51.3	105/149	0.15546	Craig	0.72787	0.70184
117	Twentyshilling hill revised	Statkraft	14/2/2018	9	Vestas	4.20	37.8	81.5/117	0.00397	StandardEKA	0.72788	0.70185
118	Daer	RWE	11/12/2018	15	unknown	5.80	87.0	102.5/155	0.05827	StandardEKA	0.73021	0.70426
119	Scoop Hill	Community Windpower	8/5/2019	78	unknown	7.00	546.0	125/150	0.85383	StandardEKA	1.12349	1.10680
120	Callisterhall	Epower	4/10/2019	13	Vestas	6.00	78.0	155/150	0.10932	StandardEKA	1.12880	1.11219
121	Priestgill resub	Muirhall Energy	2/12/2019	7	Vestas	5.60	39.2	125/150	0.01434	StandardEKA	1.12889	1.11228
122	Westerkirk	Oakridge Energy	7/1/2020	20	unknown	4.00	80.0	120/136	0.47780	StandardEKA	1.22584	1.21056
123	Loganhead resub	Muirhall Energy	23/3/2020	8	Nordex	4.80	38.4	113.4/133	0.09898	Craig	1.22983	1.21310
124	Hopsrig resub	Muirhall Energy	23/3/2020	12	Vestas	4.15	49.8	125/150	0.19493	StandardEKA	1.24518	1.22866
125	Harestaines South	Scottish Power	3/04/2020	8	unknown	5.50	44.0	125/150	0.04141	StandardEKA	1.24587	1.22936
126	Greystone Knowe	Coriolis	15/5/2020	15	unknown	4.50	67.5	105/150	0.00853	StandardEKA	1.24590	1.22939
127	Whitelaw resub	Baywa	22/6/2020	12	unknown	4.20	50.4	136.5/117	0.05914	StandardEKA	1.24730	1.23081
128	Scawd Law	Fred Olsen	31/07/2020	12	unknown	4.20	50.4	120/180	0.01272	StandardEKA	1.24736	1.23088
129	Grayside	ARCUS	24/8/2020	25	unknown	6.60	165.0	122.5/155	0.04621	StandardEKA	1.24822	1.23175

Figure 1 Final rows of Scenario A and B cumulative budget nm

3.1.2 SCENARIO B – REPRESENTATIVE TURBINE/MIXED MODEL

This scenario uses a mixed model to predict the budget levels. It uses measured data where the data is available for the same manufacturer type i.e. Siemens 2.3 from Clyde for any Siemens machine - Senvion data from Middle Muir data for Senvion or Nordex from Craig data. For manufacturers without data (GE, Enercon, Vestas Games, SGRE or EWT) the worst-case algorithm is used. **NOTE** – it has not been shown from measurements that this approach is representative as there is only a single point of data for each manufacturer.

3.1.3 SCENARIO C - ALL TURBINES INCLUDING <1MW ASSUMED RECENT DATA AS PER MIDDLEMUIR

All sites and small turbines <1MW in the region have been assumed to have the same seismic levels as the data gathered from Middlemuir as this represents the most recent installation within the region and the seismic levels lie between the measured data of the siemens at Clyde and the Nordex at Craig. .

Site #	Wind_Farm	Operator/Developer	Date of submission	Number_of_ Turbines	Manufacturer	MW rating	Total MW	Size	StandardEKA	Selection	Budget Standard (nm)	Cum Total Scenario Model (nm)
114	Cliffhope	Community Windpower	29/92017	46	unknown	7.00	322.0	125/150	0.06528	Middlemuir	0.27619	0.19889
115	Faw Side	Community Windpower	11/01/2018	45	unknown	7.00	315.0	125/150	0.65524	Middlemuir	0.71107	0.51305
116	Little Heart Fell	Energiekontor	1/2/2018	9	Nordex	5.70	51.3	105/149	0.15546	Middlemuir	0.72787	0.52466
117	Twentyshilling hill revised	Statkraft	14/2/2018	9	Vestas	4.20	37.8	81.5/117	0.00397	Middlemuir	0.72788	0.52467
118	Daer	RWE	11/12/2018	15	unknown	5.80	87.0	102.5/155	0.05827	Middlemuir	0.73021	0.52626
119	Scoop Hill	Community Windpower	8/5/2019	78	unknown	7.00	546.0	125/150	0.85383	Middlemuir	1.12349	0.81003
120	Callisterhall	Epower	4/10/2019	13	Vestas	6.00	78.0	155/150	0.10932	Middlemuir	1.12880	0.81361
121	Priestgill resub	Muirhall Energy	2/12/2019	7	Vestas	5.60	39.2	125/150	0.01434	Middlemuir	1.12889	0.81368
122	Westerkirk	Oakridge Energy	7/1/2020	20	unknown	4.00	80.0	120/136	0.47780	Middlemuir	1.22584	0.88625
123	Loganhead resub	Muirhall Energy	23/3/2020	8	Nordex	4.80	38.4	113.4/133	0.09898	Middlemuir	1.22983	0.88902
124	Hopsrig resub	Muirhall Energy	23/3/2020	12	Vestas	4.15	49.8	125/150	0.19493	Middlemuir	1.24518	0.89962
125	Harestaines South	Scottish Power	3/04/2020	8	unknown	5.50	44.0	125/150	0.04141	Middlemuir	1.24587	0.90009
126	Greystone Knowe	Coriolis	15/5/2020	15	unknown	4.50	67.5	105/150	0.00853	Middlemuir	1.24590	0.90012
127	Whitelaw resub	Baywa	22/6/2020	12	unknown	4.20	50.4	136.5/117	0.05914	Middlemuir	1.24730	0.90109
128	Scawd Law	Fred Olsen	31/07/2020	12	unknown	4.20	50.4	120/180	0.01272	Middlemuir	1.24736	0.90114
129	Grayside	ARCUS	24/8/2020	25	unknown	6.60	165.0	122.5/155	0.04621	Middlemuir	1.24822	0.90174

Figure 2 Final rows of Scenario A and C cumulative budget nm

3.1.4 SCENARIO D – 15KM EXCLUSION ZONE/MIXED MODEL

This scenario excludes sites with turbines within 15Km of the array and uses a mixed model to predict the budget levels. It uses measured data where the data is available for the same manufacturer type i.e. Siemens 2.3 from Clyde for any Siemens machine - Senvion data from Middle Muir data for Senvion or Nordex from Craig data. For manufacturers without data (GE, Enercon, Vestas Games, SGRE or EWT) the worst-case algorithm is used.

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Site #	Wind_Farm	Operator/Developer	Date of submission	Number_of_ Turbines	Manufacturer	MW rating	Total MW	Size	StandardEKA	Selection	Cum Total Budget Standard (nm)	Cum Total Scenario Model (nm)
114	Cliffhope	Community Windpower	29/92017	46	unknown	7.00	322.0	125/150	0.06528	StandardEKA	0.27619	0.21852
115	Faw Side	Community Windpower	11/01/2018	45	unknown	7.00	315.0	125/150	0.65524	Excluded	0.71107	0.21852
116	Little Heart Fell	Energiekontor	1/2/2018	9	Nordex	5.70	51.3	105/149	0.15546	Craig	0.72787	0.25146
117	Twentyshilling hill revised	Statkraft	14/2/2018	9	Vestas	4.20	37.8	81.5/117	0.00397	StandardEKA	0.72788	0.25149
118	Daer	RWE	11/12/2018	15	unknown	5.80	87.0	102.5/155	0.05827	StandardEKA	0.73021	0.25815
119	Scoop Hill	Community Windpower	8/5/2019	78	unknown	7.00	546.0	125/150	0.85383	Excluded	1.12349	0.25815
120	Callisterhall	Epower	4/10/2019	13	Vestas	6.00	78.0	155/150	0.10932	StandardEKA	1.12880	0.28034
121	Priestgill resub	Muirhall Energy	2/12/2019	7	Vestas	5.60	39.2	125/150	0.01434	StandardEKA	1.12889	0.28071
122	Westerkirk	Oakridge Energy	7/1/2020	20	unknown	4.00	80.0	120/136	0.47780	Excluded	1.22584	0.28071
123	Loganhead resub	Muirhall Energy	23/3/2020	8	Nordex	4.80	38.4	113.4/133	0.09898	Craig	1.22983	0.29147
124	Hopsrig resub	Muirhall Energy	23/3/2020	12	Vestas	4.15	49.8	125/150	0.19493	StandardEKA	1.24518	0.35065
125	Harestaines South	Scottish Power	3/04/2020	8	unknown	5.50	44.0	125/150	0.04141	StandardEKA	1.24587	0.35308
126	Greystone Knowe	Coriolis	15/5/2020	15	unknown	4.50	67.5	105/150	0.00853	StandardEKA	1.24590	0.35319
127	Whitelaw resub	Baywa	22/6/2020	12	unknown	4.20	50.4	136.5/117	0.05914	StandardEKA	1.24730	0.35810
128	Scawd Law	Fred Olsen	31/07/2020	12	unknown	4.20	50.4	120/180	0.01272	StandardEKA	1.24736	0.35833
129	Grayside	ARCUS	24/8/2020	25	unknown	6.60	165.0	122.5/155	0.04621	StandardEKA	1.24822	0.36130

Figure 3 Final rows of Scenario A and D cumulative budget nm

3.1.5 SCENARIO E - 15KM EXCLUSION ZONE/ ASSUMPTIONS USING MIDDLE MUIR DATA

This scenario excludes sites with turbines within 15Km. All sites and small turbines <1MW in the region have been assumed to have the same seismic levels as the data gathered from Middlemuir as this represents the most recent installation within the region and the seismic levels lie between the measured data of the siemens at Clyde and the Nordex at Craig. .

Site #	Wind_Farm	Operator/Developer	Date of submission	Number_of_ Turbines	Manufacturer	MW rating	Total MW	Size	StandardEKA	Selection	Cum Total Budget Standard (nm)	Cum Total Scenario Model (nm)
114	Cliffhope	Community Windpower	29/92017	46	unknown	7.00	322.0	125/150	0.06528	Middlemuir	0.27619	0.19889
115	Faw Side	Community Windpower	11/01/2018	45	unknown	7.00	315.0	125/150	0.65524	Excluded	0.71107	0.19889
116	Little Heart Fell	Energiekontor	1/2/2018	9	Nordex	5.70	51.3	105/149	0.15546	Middlemuir	0.72787	0.22716
117	Twentyshilling hill revised	Statkraft	14/2/2018	9	Vestas	4.20	37.8	81.5/117	0.00397	Middlemuir	0.72788	0.22718
118	Daer	RWE	11/12/2018	15	unknown	5.80	87.0	102.5/155	0.05827	Middlemuir	0.73021	0.23083
119	Scoop Hill	Community Windpower	8/5/2019	78	unknown	7.00	546.0	125/150	0.85383	Excluded	1.12349	0.23083
120	Callisterhall	Epower	4/10/2019	13	Vestas	6.00	78.0	155/150	0.10932	Middlemuir	1.12880	0.24310
121	Priestgill resub	Muirhall Energy	2/12/2019	7	Vestas	5.60	39.2	125/150	0.01434	Middlemuir	1.12889	0.24333
122	Westerkirk	Oakridge Energy	7/1/2020	20	unknown	4.00	80.0	120/136	0.47780	Excluded	1.22584	0.24333
123	Loganhead resub	Muirhall Energy	23/3/2020	8	Nordex	4.80	38.4	113.4/133	0.09898	Middlemuir	1.22983	0.25322
124	Hopsrig resub	Muirhall Energy	23/3/2020	12	Vestas	4.15	49.8	125/150	0.19493	Middlemuir	1.24518	0.28827
125	Harestaines South	Scottish Power	3/04/2020	8	unknown	5.50	44.0	125/150	0.04141	Middlemuir	1.24587	0.28973
126	Greystone Knowe	Coriolis	15/5/2020	15	unknown	4.50	67.5	105/150	0.00853	Middlemuir	1.24590	0.28981
127	Whitelaw resub	Baywa	22/6/2020	12	unknown	4.20	50.4	136.5/117	0.05914	Middlemuir	1.24730	0.29280
128	Scawd Law	Fred Olsen	31/07/2020	12	unknown	4.20	50.4	120/180	0.01272	Middlemuir	1.24736	0.29295
129	Grayside	ARCUS	24/8/2020	25	unknown	6.60	165.0	122.5/155	0.04621	Middlemuir	1.24822	0.29481

Figure 4 Final Rows of Scenarios A and E nm

3.1.6 SCENARIO F - 15KM EXCLUSION ZONE/ MIDDLE MUIR ASSUMPTIONS WITHOUT BACKGROUND

This scenario excludes sites with turbines within 15Km. All sites post original budget consumption at Fawside have the same seismic levels as the data gathered from Middlemuir without background. There is potential for further budget if all sites not actually constructed conducted before and after measurements, however, this is likely offset by the 'best-case' nature of the background noise removal.

Site #	Wind_Farm	Operator/Developer	Date of submission	Number_of_ Turbines	Manufacturer	MW rating	Total MW	Size	StandardEKA	Selection	Cum Total Budget Standard (nm)	Cum Total Scenario Model (nm)
114	Cliffhope	Community Windpower	29/92017	46	unknown	7.00	322.0	125/150	0.06528	Middlemuir	0.27619	0.19889
115	Faw Side	Community Windpower	11/01/2018	45	unknown	7.00	315.0	125/150	0.65524	Excluded	0.71107	0.19889
116	Little Heart Fell	Energiekontor	1/2/2018	9	Nordex	5.70	51.3	105/149	0.15546	MM NB	0.72787	0.21274
117	Twentyshilling hill revised	Statkraft	14/2/2018	9	Vestas	4.20	37.8	81.5/117	0.00397	MM NB	0.72788	0.21275
118	Daer	RWE	11/12/2018	15	unknown	5.80	87.0	102.5/155	0.05827	MM NB	0.73021	0.21472
119	Scoop Hill	Community Windpower	8/5/2019	78	unknown	7.00	546.0	125/150	0.85383	Excluded	1.12349	0.21472
120	Callisterhall	Epower	4/10/2019	13	Vestas	6.00	78.0	155/150	0.10932	MM NB	1.12880	0.22114
121	Priestgill resub	Muirhall Energy	2/12/2019	7	Vestas	5.60	39.2	125/150	0.01434	MM NB	1.12889	0.22128
122	Westerkirk	Oakridge Energy	7/1/2020	20	unknown	4.00	80.0	120/136	0.47780	Excluded	1.22584	0.22128
123	Loganhead resub	Muirhall Energy	23/3/2020	8	Nordex	4.80	38.4	113.4/133	0.09898	MM NB	1.22983	0.23211
124	Hopsrig resub	Muirhall Energy	23/3/2020	12	Vestas	4.15	49.8	125/150	0.19493	MM NB	1.24518	0.25075
125	Harestaines South	Scottish Power	3/04/2020	8	unknown	5.50	44.0	125/150	0.04141	MM NB	1.24587	0.25158
126	Greystone Knowe	Coriolis	15/5/2020	15	unknown	4.50	67.5	105/150	0.00853	MM NB	1.24590	0.25163
127	Whitelaw resub	Baywa	22/6/2020	12	unknown	4.20	50.4	136.5/117	0.05914	MM NB	1.24730	0.25313
128	Scawd Law	Fred Olsen	31/07/2020	12	unknown	4.20	50.4	120/180	0.01272	MM NB	1.24736	0.25321
129	Grayside	ARCUS	24/8/2020	25	unknown	6.60	165.0	122.5/155	0.04621	MM NB	1.24822	0.25433

Figure 5 Final Rows of Scenarios A and F nm

3.1.7 SCENARIO G - 15KM EXCLUSION ZONE/ MIDDLE MUIR ASSUMPTIONS WITHOUT BACKGROUND AND EXCLUSION OF INITIAL SITES THAT HAVE BEEN RESUBMITTED

This scenario excludes sites with turbines within 15Km. All sites not built in the region have been assumed to have the same seismic levels as the data gathered from Middlemuir without background. There is potential for further budget if all sites not actually constructed conducted before and after measurements, however, this is likely offset by the 'best-case' nature of the background noise removal. Sites which have been resubmitted have had the initial submission excluded. This is solely to optimise the mathematical output and is in no way intended to suggest a reordering of the list or loss of place in the budget queue.

Site #	Wind_Farm	Operator/Developer	Date of submission	Number_of_ Turbines	Manufacturer	MW rating	Total MW	Size	StandardEKA	Selection	Cum Total Budget Standard (nm)	Cum Total Scenario Model (nm)
114	Cliffhope	Community Windpower	29/92017	46	unknown	7.00	322.0	125/150	0.06528	Middlemuir	0.27619	0.16785
115	Faw Side	Community Windpower	11/01/2018	45	unknown	7.00	315.0	125/150	0.65524	Excluded	0.71107	0.16785
116	Little Heart Fell	Energiekontor	1/2/2018	9	Nordex	5.70	51.3	105/149	0.15546	MM NB	0.72787	0.18405
117	Twentyshilling hill revised	Statkraft	14/2/2018	9	Vestas	4.20	37.8	81.5/117	0.00397	MM NB	0.72788	0.18407
118	Daer	RWE	11/12/2018	15	unknown	5.80	87.0	102.5/155	0.05827	MM NB	0.73021	0.18634
119	Scoop Hill	Community Windpower	8/5/2019	78	unknown	7.00	546.0	125/150	0.85383	Excluded	1.12349	0.18634
120	Callisterhall	Epower	4/10/2019	13	Vestas	6.00	78.0	155/150	0.10932	MM NB	1.12880	0.19370
121	Priestgill resub	Muirhall Energy	2/12/2019	7	Vestas	5.60	39.2	125/150	0.01434	MM NB	1.12889	0.19386
122	Westerkirk	Oakridge Energy	7/1/2020	20	unknown	4.00	80.0	120/136	0.47780	Excluded	1.22584	0.19386
123	Loganhead resub	Muirhall Energy	23/3/2020	8	Nordex	4.80	38.4	113.4/133	0.09898	MM NB	1.22983	0.20614
124	Hopsrig resub	Muirhall Energy	23/3/2020	12	Vestas	4.15	49.8	125/150	0.19493	MM NB	1.24518	0.22692
125	Harestaines South	Scottish Power	3/04/2020	8	unknown	5.50	44.0	125/150	0.04141	MM NB	1.24587	0.22784
126	Greystone Knowe	Coriolis	15/5/2020	15	unknown	4.50	67.5	105/150	0.00853	MM NB	1.24590	0.22789
127	Whitelaw resub	Baywa	22/6/2020	12	unknown	4.20	50.4	136.5/117	0.05914	MM NB	1.24730	0.22955
128	Scawd Law	Fred Olsen	31/07/2020	12	unknown	4.20	50.4	120/180	0.01272	MM NB	1.24736	0.22964
129	Grayside	ARCUS	24/8/2020	25	unknown	6.60	165.0	122.5/155	0.04621	MM NB	1.24822	0.23087

Figure 6 Final Rows of Scenarios A and G nm

Scenario	Scenario Detail	Total Cumulative Budget (nm)
A	Worst Case algorithm/current Budget	**1.24822**
B	Representative turbine/Mixed Model	**1.23175**
C	All turbines assumed Middlemuir	**0.90174**
D	15km/Mixed Model	**0.36130**
E	15km Assuming Middlemuir	0.29481
F	15km assuming Middlemuir no background	0.25433
G	As per F without resubmission duplication	0.23087

Table 1 Scenario Summary total nm (red text denotes budget exceeded)

Having considered the above seven scenarios, it is clear that, with more information input into the budget spreadsheet, it is very likely that further headroom could be released. In order to input more information into the budget spreadsheet, a measurement campaign is recommended to better determine the actual seismic output of existing sites in the EKA. It is also recommended that in order to avoid any future over or under estimations that subsequent developments are measured both pre and post deployment to maximise deployment potential.

3.2 Analysis of Budget Spreadsheet and Turbines

3.2.1 SITES BY BUDGET REQUIREMENT

In order to assess what type of measurement should take place, the sites should be considered initially in order of budget size. This assessment will help to determine the which sited should be measured as well as the number. This is particularly key, as the sites with the largest budget allocation, if following the logic of the above scenarios, will have the most budget headroom to contribute. This allows the assessment to consider which sites could be the most impactful in terms of budget re-assessment.

The following are the all sites with a budget requirement over 0.01nm starting from largest to smallest nm requirement.

Budget ordered by nm	Site #	Wind_Farm	Number_of_ Turbines	Total MW	Size	StandardEKA
1	119	Scoop Hill	78	546.0	125/150	0.85383
2	115	Faw Side	45	315.0	125/150	0.65524
3	122	Westerkirk	20	80.0	120/136	0.47780
4	126	Hopsrig resub	12	49.8	125/150	0.19493
5	103	Crossdykes	10	48.0	110/133	0.14086
6	110	Hopsrig	12	42.0	89.5/101	0.11239
7	120	Callisterhall	13	78.0	155/150	0.10932
8	125	Loganhead resub	8	38.4	113.4/133	0.09898
9	10	Ewe Hill	22	50.6	63.3/93	0.08858
10	105	Loganhead	8	25.6	75/120	0.08008
11	5	Clyde	152	349.6	82/93	0.07399
12	114	Cliffhope	46	322.0	125/150	0.06528
13	127	Whitelaw resub	12	50.4	136.5/117	0.05914
14	118	Daer	15	87.0	102.5/155	0.05827
15	6	Harestanes	68	136.0	78/87	0.05714
16	92	Whitelaw Brae	14	58.8	133.5/117	0.04898
17	52	Clyde Extension	54	162.0	89.5/74.5	0.04801
18	128	Grayside	25	165.0	122.5/155	0.04621
19	108	Wauchope & Newcastleton Forests	90	306.0	80/104	0.04199
20	123	Harestaines South	8	44.0	125/150	0.04141
21	4	Langhope Rig	10	15.0	80/82.5	0.04029
22	56	Solwaybank	15	30.0	76.5/100	0.03748
23	81	Windy Edge	9	202.5		0.03572
24	8	Minsca	16	36.8	80/82.4	0.03364
25	18	Minnygap	10	20.0	75/99.8	0.03168
26	2	Carlesgill	5	12.5	59/70	0.03136
27	111	Pines Burn	12	39.6		0.03108
28	12	Middle Hill - Glenkerie	11	22.0	78/80	0.01621
29	19	Carlesgill Ext	1	2.5	59/82	0.01572
30	78	Lion Hill	4	9.2	70.5/112	0.01472
31	121	Priestgill resub	7	39.2	125/150	0.01434
32	109	North Lowther	30	150.0	149/133	0.01347
33	129	Scawd Law	12	50.4	120/4180	0.01272
34	80	Crookedstane Farm	4	9.2	70.5/112	0.01182
35	76	Glenkerie Extension	6	15.0	59/82	0.01142
36	7	Dalswinton	15	30.0	80/82	0.01026
37	112	Priestgill	7	22.4		0.01015

Table 2 Sites by most budget requirement for all above 0.001nm

3.2.2 SITES MW PER NANOMETER MW/NM

A further analysis to determine which sites should be considered takes into account not only the budget allocation, but the budget allocation order in nm/MW. This analysis gives another view on which types of sites could be most impactful in terms of budget re-assessment.

The following is the top 36 sites from Table 2 ordered by nm requirement per MW. This table should be viewed with caution as at the planning stage multiple sites are predicting extremely large capacity turbines at relatively small sizes which offsets some of the sites' position in the table.

Budget ordered by nm	Site #	Wind_Farm	Total MW	StandardEKA	nm/MW
1	19	Carlesgill Ext	2.5	0.01572	0.006288
2	122	Westerkirk	80.0	0.47780	0.005972
3	126	Hopsrig resub	49.8	0.19493	0.003914
4	105	Loganhead	25.6	0.08008	0.003128
5	103	Crossdykes	48.0	0.14086	0.002935
6	4	Langhope Rig	15.0	0.04029	0.002686
7	110	Hopsrig	42.0	0.11239	0.002676
8	125	Loganhead resub	38.4	0.09898	0.002578
9	2	Carlesgill	12.5	0.03136	0.002509
10	115	Faw Side	315.0	0.65524	0.00208
11	10	Ewe Hill	50.6	0.08858	0.001751
12	78	Lion Hill	9.2	0.01472	0.0016
13	18	Minnygap	20.0	0.03168	0.001584
14	119	Scoop Hill	546.0	0.85383	0.001564
15	120	Callisterhall	78.0	0.10932	0.001402
16	80	Crookedstane Farm	9.2	0.01182	0.001285
17	56	Solwaybank	30.0	0.03748	0.001249
18	127	Whitelaw resub	50.4	0.05914	0.001173
19	123	Harestaines South	44.0	0.04141	0.000941
20	8	Minsca	36.8	0.03364	0.000914
21	92	Whitelaw Brae	58.8	0.04898	0.000833
22	111	Pines Burn	39.6	0.03108	0.000785
23	76	Glenkerie Extension	15.0	0.01142	0.000761
24	12	Middle Hill - Glenkerie	22.0	0.01621	0.000737
25	118	Daer	87.0	0.05827	0.00067
26	112	Priestgill	22.4	0.01015	0.000453
27	6	Harestanes	136.0	0.05714	0.00042
28	121	Priestgill resub	39.2	0.01434	0.000366
29	7	Dalswinton	30.0	0.01026	0.000342
30	52	Clyde Extension	162.0	0.04801	0.000296
31	128	Grayside	165.0	0.04621	0.00028
32	129	Scawd Law	50.4	0.01272	0.000252
33	5	Clyde	349.6	0.07399	0.000212
34	114	Cliffhope	322.0	0.06528	0.000203
35	81	Windy Edge	202.5	0.03572	0.000176
36	108	Wauchope & Newcastleton Forests	306.0	0.04199	0.000137
37	109	North Lowther	150.0	0.01347	8.98E-05

Table 3 Sites ordered nm per MW

3.2.3 TURBINE TYPE AND SIZE

Turbine type and size also need to be considered when determining sites for measurement.

The following is a breakdown of the manufacturer MW output and Sum of MW by manufacturer. It should be noted that a number of these turbines are in planning and not as yet erected.

Manufacturer	MW rating	Sum of Number_of_Turbines	Sum of Total MW
Siemens	3.00	54	162
	2.30	193	443.9
	3.50	12	42
Siemens Total		**259**	**647.9**
GE	3.20	15	48
	1.50	10	15
GE Total		**25**	**63**
Nordex	1.30	24	31.2
	2.50	5	12.5
	2.00	10	20
	3.30	12	39.6
	22.50	9	202.5
	4.80	30	144
	5.70	9	51.3
Nordex Total		**99**	**501.1**
Vestas	2.30	8	18.4
	2.00	26	52
	3.30	11	36.3
	2.20	6	13.2
	4.20	18	75.6
	3.45	9	31.05
	6.00	13	78
	5.60	7	39.2
	4.15	12	49.8
Vestas Total		**110**	**393.55**
Senvion	2.50	6	15
	2.00	34	68
	3.40	15	51
Senvion Total		**55**	**134**
Gamesa	2.00	68	136
Gamesa Total		**68**	**136**
unknown		500	2211.0397
Enercon	2.50	1	2.5
Enercon Total		**1**	**2.5**
EWT	0.50	1	0.5
EWT Total		**1**	**0.5**
(blank)	(blank)		
(blank) Total			
Grand Total		**1118**	**4089.5897**

Table 4 Breakdown of manufacturer and MW within the region

3.3 Measurement Audit Recommendations

Care has been taken to assess the sites within the region and the aim of this work is to determine how to measure the minimum number of sites whilst freeing up as much budget as possible. Whilst this is not an exact science the following assumptions have been made to determine how many sites require measurement;

- Only the sites that are currently installed are considered, future sites should likely have both a before and after measurement.
- It is necessary to capture data from all manufacturer machines
- Turbines with especially large budget allocation (again only built) must be measured to release the most budget.
- No replication of measurements for sites already measured (with the exception of Carlesgill (Craig) as it has had a further 2 machines installed, again which have not yet been measured).
- Obtaining more than one data set per manufacturer for the largest three by deployment number – Siemens, Nordex and Vestas respectively (some data is already available, through previous measurements, eg Middle Muir/Seimens).
- If access to sites is not possible alternatives could be sought

	Sites for measurement	Rationale	Manufacturer
1	Ewe Hill	Siemens are the most prolific turbine within the region and to not rely on a single data point Ewe Hill represents the largest budget allocation for a siemens machines.	Siemens
2	Carlesgil and extension	One of the largest nm/MW sites and has now had additional 2 Enercon machines added which have yet to be measured	Nordex/Enercon
3	Solwaybank	There is no publicly available data for Vestas currently and Solway Bank has the largest budget requirement for a Vestas machine	Vestas
4	Harestaines	No data available for Gamesa machine and this site has largest budget for Gamesa machines	Gamesa
5	Langhope rig	There is no data for GE turbines and this site has the largest allocation for any GE machine	GE
6	Middlehill	Vestas with second highest budget allocation	Vestas
7	MinnyGap	Nordex second data point second largest nm/Mw after Carelsgill	Nordex

Table 5 Proposed sites to conduct measurement audit

NOTE – This list of proposed measurement sites has not yet been discussed with the MoD and could be subject to change.

Though the number of recommended measurement site is short, due to the distribution of turbines and budget allocation, combined with the suggested new pre & post deployment methodology, the above list or an approved version of it should adequately represent the sites with turbines currently installed in the consultation zone.

4 DISCUSSION

This exercise has highlighted a few potential improvements that could be made to the management of wind turbine development within the region specifically (but not exhaustively);

- Ensuring developers issue data to the MoD (or the organisation managing the budget) post construction – data was found to be inconsistent between data recorded in the budget spreadsheet including number of turbines, location and size of machines. All of these are crucial to understanding the level of seismic vibration from a turbine.
- Having an appropriate tool for the management of the budget. The Excel spreadsheet currently used will not calculate or maintain windfarms post budget saturation. This is how the tool was designed; however, it is clear that a more advanced tool is necessary – especially when data verification, amendments to site planning and repowering is considered.
- The need for a system which has an auditable dual signoff is needed to prevent inaccurate data entry and verification.

It is clear from looking at sites with most budget allocated that the trend to deploy larger turbine sizes has a significant impact on the budget requirement as both the Standard EKA algorithm and measured data are normalised against the size of the turbines.

The effect of removing background noise (albeit on a best-case scenario for this exercise) is significant. As with noise measurements it is standard to measure both before and after in order to remove noise not attributable to the turbines. The budget calculations above clearly show a vast improvement if this process were to be followed, even if the reduction were even half the size it still represents a significant additional deployment in the region. As this process is yet to be conducted in practice with the MoD seismic experts (the principle of this approach is agreed) it is likely that the initial background measurements would take ~ 6 months duration to be sure of a statistically significant data set. However, the likelihood is, once several have been conducted it could be possible to shorten this period to a few months assuming suitable wind conditions on site. To maximise deployment in the area it is recommended that all sites that have yet to be built are measured pre construction. It is also possible to measure during construction phases BUT before towers are erected. Data during site activities (daytime) would be excluded from the data set but all times in which there is no site activity could be used as long as the towers have not been erected.

This practice of before and after measurement also presents a solution to repowering of sites with larger turbines. As measuring background can release in the region of 30% additional budget per site- if sites were to be measured post decommissioning and pre reinstatement – significant additional budget would be freed up for the site, potentially allowing a similar number of turbines at much larger rotor diameter and height.

5 CONCLUSIONS

- A desktop audit has been conducted of all sites built, consented and in planning within 50km of the Eskdalemuir seismic array and the budget spreadsheet brought up to date
- This audit has highlighted the need for developers to issue as built information for the safeguarding of the array. (Location micro siting and turbine number, heights and rotor diameter would be necessary)
- A series of spreadsheets accompany this report for the scenarios A through G, in order to show the need for more accurate data to inform the budget.
- Significant additional budget is released if a pre and post site measurement are conducted.
- It is proposed that 7 sites are to be measured to capture make, model and sizes to sufficiently reduce any risk of replacing the worst case, standard EKA algorithm. (note this will need to be assessed by MoD experts)
- Without an increased exclusion zone, the budget is rapidly consumed with minimal MW deployed.
- To prevent the budget being consumed even if the exclusion zone is extended there is a clear need for before and after measurements.
- A best-case noise removal method has been used to calculate the effect of background noise removal.

Eskdalemuir Wind Turbine Seismic Vibration

Phase 4: Field Audit of Selected sites within the EKA Consultation Zone to support Government Policy Decisions

Report presented to: Scottish Government and Eskdalemuir Working Group (EWG)

10/02/2022

Document number: SGV_204_Tech_Report_v12

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Document Summary

Seismic sensors were used to measure the amplitude of ground-waves produced by wind turbines at seven wind farms in the Eskdalemuir consultation zone. The data was normalised to produce conservative spectra that represent single wind turbines measured at a distance of 1 km. These spectra were used to fit curves that represent most of the major wind turbine manufacturers in the consultation zone; Nordex, Siemens, GE, Gamesa, Enercon, Vestas and Senvion (EWT was the only known turbine manufacturer not measured, of which there is a single turbine with a capacity of 500 kW). The cumulative amplitude estimated by the current budget algorithm that includes an appropriate safety factor for the data sets available at the time was compared to the curves fitted here. The current algorithm estimates that the cumulative amplitude of all wind turbines operational and in planning up to and including and Faw Side T2 is 0.3216 nm. When the same calculation is carried out using the measured data from this campaign and then is extrapolated to represent the different wind turbine manufacturers, the cumulative amplitude is 0.2054 nm. The algorithm therefore over-estimates the measured data by 36.1%. The over-estimate is consistent with initial estimates calculated in Phase 2 (between 21% and 43%), thus the conclusions made in Phase 2 with respect to headroom, installable capacity and exclusion zone remain unchanged. Whilst the measured data fitted still maintains conservatism, further budget could be released if an approach to removing background noise from measured data were agreed, and before and after measurements were made.

Action	Name	Date	Version	Amendment
Originator	Dr B Marmo	6th Dec 2021	V1	Issue
Checked by	Dr M P Buckingham	13th Dec 2021	V2	review
Revised by	Dr B Marmo	13th Dec 2021	V3	Revised Discussion
Checked by	R Horton	13th Dec 2021	V4	Review
Revised by	Dr B Marmo	14th Dec 2021	V5	Following internal review
Checked by	Dr D Crooks	14th Dec 2021	V6	Review
Revised by	Dr B Marmo	14th Dec 2021	V7	Following internal review
Review	Dr M P Buckingham	15th Dec 2021	V8	Draft Release
Revised by	R Horton	4th Feb 2022	V9	Revisions based on external feedback of v8
Revised by	Dr B. Marmo	8th Feb 2022	V10	Revisions based on external feedback of v8
Review	Dr M P Buckingham	9th Feb 2022	V11	Director Review
Review	R Horton	10th Feb 2022	V12	Review

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Contents

1. Introduction

With good wind conditions and proximity to population centres, southern Scotland has excellent potential for onshore wind generation. However, much of this region falls within the Eskdalemuir consultation zone and limits wind development. The zone is formed by a 50 km radius (representing nearly 10% of Scotland's total land area) surrounding the Eskdalemuir seismic measuring station (EKA) which is operated by the Ministry of Defence. To protect the EKA, wind turbines built in the area must operate within a seismic vibration budget of 0.336nm. Each turbine currently contributes to the budget based upon a worst-case hypothetical turbine. Using this hypothetical turbine, the vibration budget of 0.336nm has been reached. Currently no further wind turbine development in the region is possible, preventing access to this significant wind resource available in the area.

By design, the algorithm used to represent the worst-case turbine includes factors of safety appropriate to the data sample size available at the time, ensuring that the algorithm over-estimates the cumulative seismic vibrations produced by wind turbines and does not compromise the seismic array. The approach adopted here is to increase the available data set and reduce but not remove the safety factor appropriately. Directly measuring the seismic output of a greater number of turbines in the consultation zone, and reducing the safety factor applied, allows further wind capacity to be deployed within the region.

Due to the pressing nature of the Climate Crisis, to retrospectively measure every wind turbine site within the consultation zone is not viable due to both time constraints and number of turbines deployed within the region. Therefore, seven wind farms were chosen that contain a high proportion of wind turbine make and models in the consultation zone. The wind farms selection was informed by work presented in the report *Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements* (SGV_203_Tech_Report_v12). The wind farms measured in this phase of work were Craig Hill, Langhope Rig, Harestanes, Ewe Hill, Glenkerie, Minnygap and Solwaybank. The cumulative seismic amplitude of turbines that have been constructed and are operational at the time of measurement (i.e., not including those consented or in planning but not yet built) is 0.161 nm as estimated by the EKA budget. The wind turbine models at the wind farms reported here combined with those previously measured at Middle Muir and Clyde contribute a total of 0.153 nm of the 0.161nm when using the current algorithm, thus we have captured the vast majority of the budget contribution with these measurements.

The focus of the work presented here is to use measured data to reduce the level of uncertainty in calculating the contribution of wind turbines provided by the budget algorithm. When decisions on data handling are required, a conservative approach to ensure that the detection capabilities of the Eskdalemuir seismic array are protected.

The work presented here follows and builds upon the previous studies:

- Eskdalemuir Wind Turbine Seismic Vibration: Assessment of Headroom (SGV_201_Tech_Report_v04)
- Eskdalemuir Wind Turbine Seismic Vibration: Extrapolation of Potential Installed Capacity Based on Observed Seismic Output of Modern WTGs with future scenario planning (SGV_202_Tech_Report_v07)
- Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements (SGV_203_Tech_Report_v12)

2. Technical Background

Xi were commissioned by the Eskdalemuir Working Group (EWG) in 2013 to develop a robust physics-based approach to estimating the worst-case ground vibration produced by wind turbines. Xi developed an algorithm which is currently used by the Ministry of Defence (MoD) to calculate the worst-case cumulative effect of all wind turbines on the EKA; see "*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" (2014).

The physics-based approach uses an algorithm that creates a displacement spectrum (frequency vs seismic amplitude) that represents the seismic output measured at 1 km from any given turbine when the wind speed at a height of 80 m is 12 m/s. The premise behind the physics-based algorithm is that the wind energy that passes through a wind turbine can be considered to be portioned to electrical energy and lost energy. Losses will consist of energy converted to noise, frictional heat, seismic energy etc. Thus, some proportion of the energy passing through the rotor is converted to seismic vibration. The wind energy passing through the rotor is a function of wind speed and the swept area of the rotor. Thus, assuming that the proportion of wind energy that is lost to seismic vibration is constant, it is possible to scale the seismic vibration based on blade length (to give swept area) and hub height (giving wind speed relative 12 m/s at a height of 80 m). The input requirements for the algorithm are therefore hub height and rotor diameter which are commonly submitted with a planning application making the algorithm viable for the purpose of estimating seismic vibration at the planning stage of a wind farm's development.

The algorithm includes a Frequency Dependant Weighting Function (FDWF) which accounts for the variation in transmission of low and high frequencies, to determine what is detected at the array. This function would be used to design distant specific mitigation measures if required.

The algorithm variables were adjusted in order to best match or 'fit' the algorithm with the seismic data. The algorithm was fitted using seismic data from operational wind farms in southern Scotland which was collected in 2012. These wind farms were Craig wind farm consisting of four Nordex N80 turbines with a hub height of 60 m and rotor diameter of 80 m; Clyde wind farm consisting of 152 Siemens 2.3 MW turbines (at the time of measurement) with a hub height of 78.3 m and rotor diameter of 93 m and Dun Law wind farm 26 Vestas V47 turbines with a hub height of 40 m and a rotor diameter of 47 m. As of 2020 these machines represent an older generation of wind turbine.

A key observation from the measurement of these three wind farms was that the seismic spectra produced by wind farms either related to blade-pass (Craig and Dun Law), or structural resonances (Clyde). Due to the limited public data available on seismic emissions from wind turbines, a conservative 'worst-case' approach was adopted. This worst-case turbine algorithm assumes that any given turbine produces *both* forms of seismic vibration, i.e. blade-pass *and* structural resonance. Continuing this conservative approach, the algorithm includes a factor of safety by over-fitting the empirical data by ~20% to account for uncertainty in the seismic output of different makes and models of wind turbines.

"Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project" was reviewed by the Ministry of Defence Subject matter experts (Dr D Bowers) who subsequently presented to the CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization) and was ultimately accepted by the Scottish Government. Adopting the new algorithm opened up over 1GW of onshore wind power within the 50km Eskdalemuir zone compared to the MoD's earlier approach.

3. Summary of measurements

The seismic amplitude at seven wind farms were measured between 30/04/2021 and 24/11/2021. Table 1 lists the model and dimension of the turbines at each wind farm and the number of turbines. Table 1 also lists the turbines of previous measurements (conducted for the EWG and Scottish Government) at Clyde and Middle Muir wind farms. Based on *Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements* (SGV_203_Tech_Report_v12), all known manufacturers with turbines in the consultation zone with megawatt class turbines (≥1MW) have been measured.

Farm	OtherName	Manufacturer	Model	Number of Turbines	Hub Height	Rotor
Craig Hill	(Carlesgil and Extension)	Nordex	N80	4	70	80
		Enercon	E82	2	59	80
Glenkerie	(MiddleHill)	Vestas	V80	6	60	80
				5	78	80
Harestanes		Gamesa	G8x	67	78	87
				1	67	80
Langhope Rig		GE	GE 1.6	10	80	82.5
Minnygap		Nordex	N100	10	75	99.8
Solwaybank		Vestas	V100	15	76.5	100
Ewe Hill		Siemens	SWT2.3	23	63.3	93
Previous Measurements						
Clyde		Siemens	SWT2.3	152	82	93
Middle Muir		Senvion	3.4M114	7	92.9	114
				8	79	114

Table 1 Summary of the wind farms measured listing the models and the dimensions of the turbines

Full details of the measurement at each wind farm and the approach to post processing the data are detailed in Appendices D.1 to D.7. At each wind farm, Güralp 6TD medium-motion, three component, broadband seismometers were deployed at four locations to measure seismic noise. Multiple sensors were deployed to cover sensor failure and local site conditions. It is accepted practice that the sensor with lowest background noise be used to represent each site. Table 2 lists the sensor with the lowest background noise at each wind farm and data from these sensors are used in all subsequent calculations.

The seismic signal detected at each of the sensor locations listed in Table 2 were normalised to a single wind turbine for the given wind farm measured at a distance of 1 km following the normalisation process as described in Appendices D.1 to D.7 that is based on the method defined in "*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" (2014).

Amplitude and topology of the seismic spectra from the turbines measured at 12 m/s wind speed are broadly consistent with those previously measured at Craig, Clyde and Middle Muir wind farms (Figure 1 and Figure 2). Exceptions to this topological consistency in the measured data are those from Minnygap and Solwaybank (see below)

Wind Farm	Sensor with lowest background noise level
Craig Hill	SL3
Glenkerie	SL4
Harestanes	SL3
Langhope Rig	SL3
Minnygap	SL4
Solwaybank	SL3
Ewe Hill	SL3

Table 2 Sensor at each wind farm with the lowest background noise level. Data from these sensors are used to represent each wind farm in subsequent calculations

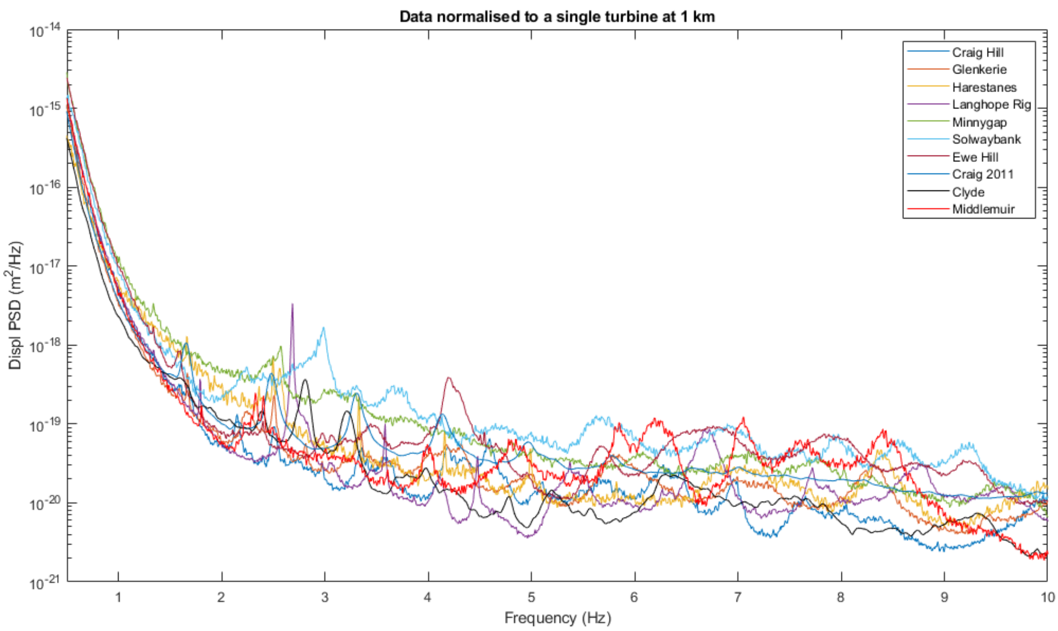


Figure 1 Seismic amplitude at each wind farm normalised to represent a single turbine measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m.

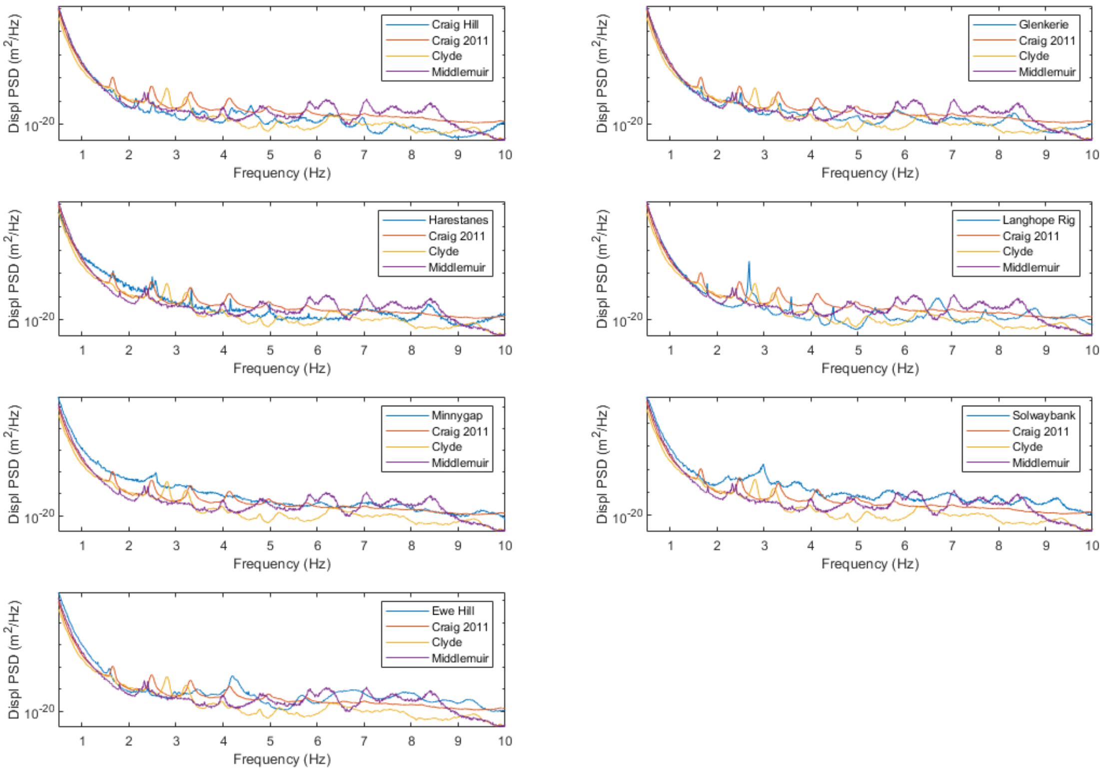


Figure 2 Seismic amplitude at each wind farm measured in the 2021 campaign compared to previously measured sites. The spectra have been normalised to represent a single turbine measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m.

3.1. Background noise at Solwaybank and Minnygap

The seismic signal recorded at each sensor includes background noise not generated by wind turbines. The background noise comes from natural sources or from localised human activities. A significant source of background noise is from wind interacting with the ground surface and other structures such as trees. The background noise increases with wind speed as these interactions become more vigorous. As the wind speed increases, the background noise level can mask ground vibration generated by wind turbines. This has been a common observation in previous wind turbine measurements and has confounded some surveys where it is not possible to detect wind turbine signals due to background noise induced by high winds in combination with other vibration sources.

At Minnygap peaks at 2.6 Hz and 3.3 Hz are visible in spectra measured up to wind speeds of 8 m/s (Figure 3). These peaks could be attributed to the Nordex N100 turbines at Minnygap, most likely due to the turbines' structural resonances. However, at 12 m/s these signals are masked by the wind induced background noise such that seismic power measured at this wind speed is attributed mostly to sources outwith the wind turbines (Figure 3).

At Solwaybank peaks at 2.1 Hz, 2.9 Hz, 3.6 Hz and 4.3 Hz are noted in the spectra measured up to 8 m/s wind speed (Figure 4). These peaks can be attributed to seismic vibration generated by blade pass of the Vestas V100 turbines; in the case of the peak at 2.9 Hz, there is likely an interaction with a structural resonance resulting in a peak with significant power. Like Minnygap, these peaks are masked at higher wind speeds such the majority of seismic power measured at 12 m/s wind speed is attributed to sources outwith the wind turbines (Figure 4).

Given that the 12 m/s spectra from Minnygap and Solwaybank do not reflect the ground vibration produce by wind farms, these measurements are excluded from the budget calculations below. For clarity, the spectra are compared in Figure 5 with Minnygap and Solwaybank excluded.

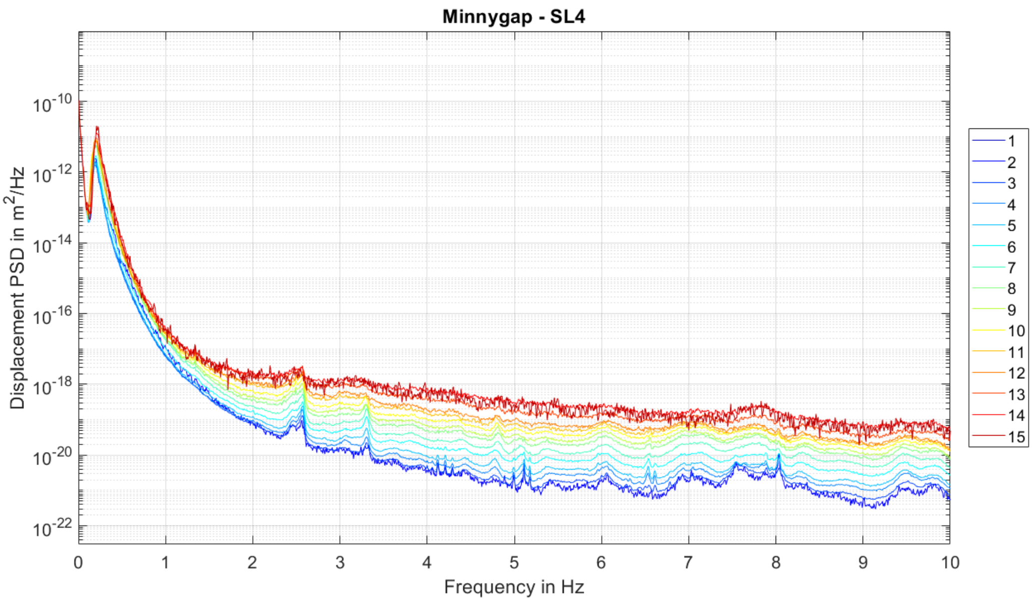


Figure 3 Variation of seismic amplitude with wind speed at Minnygap

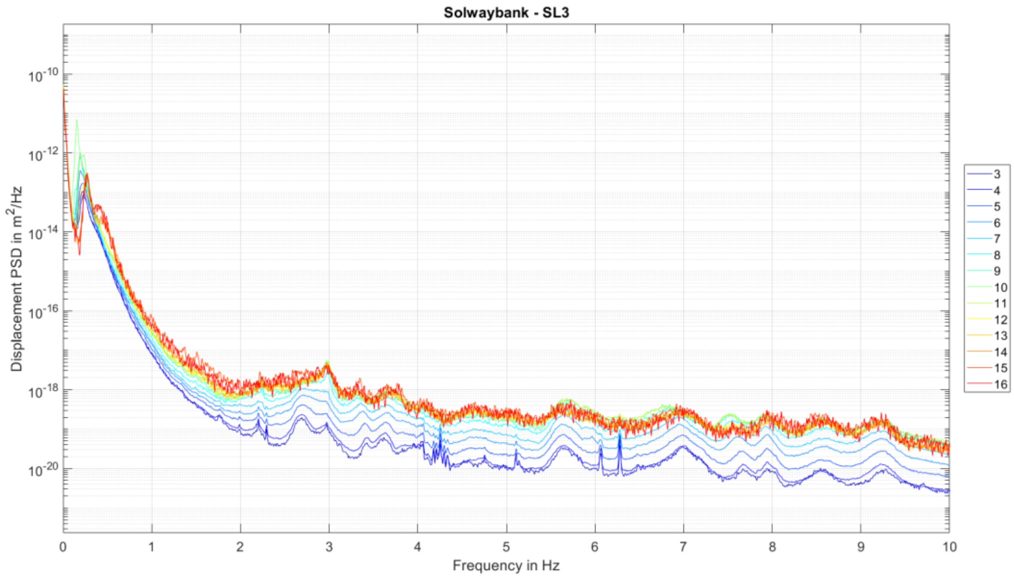


Figure 4 Variation of seismic amplitude with wind speed at Solwaybank

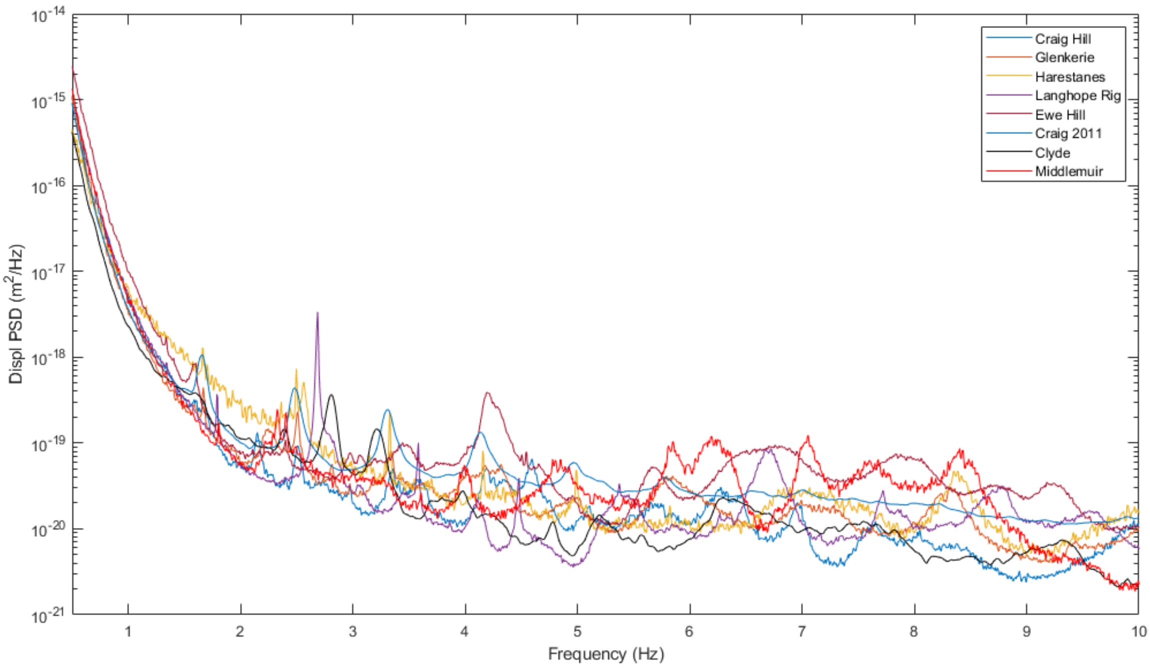


Figure 5 Seismic amplitude at each wind farm with Minnygap and Solwaybank excluded. The data are normalised to represent single turbines measured at a distance of 1 km at wind speed of 12 m/s at a reference height of 80 m.

3.2. Background noise and extrapolation at Harestanes

The Harestanes measurement also had high levels of background noise due to ground conditions at the site. As noted in Appendix D.4 low wind speeds over the summer of 2021 resulted in no data being collected in the 12 m/s wind speed bin. The high site background noise and extrapolation (see Appendix D.4) resulted in unrealistically high broadband noise levels measured at Harestanes. Unlike Minnygap and Solwaybank, spectra peaks attributed to wind turbines can be discerned at 11 m/s wind speeds (Figure 6) and the data has been used in the budget calculations below. However, it should be noted that it is likely that the amplitudes calculated for the Gamesa wind turbines are unrealistically high.

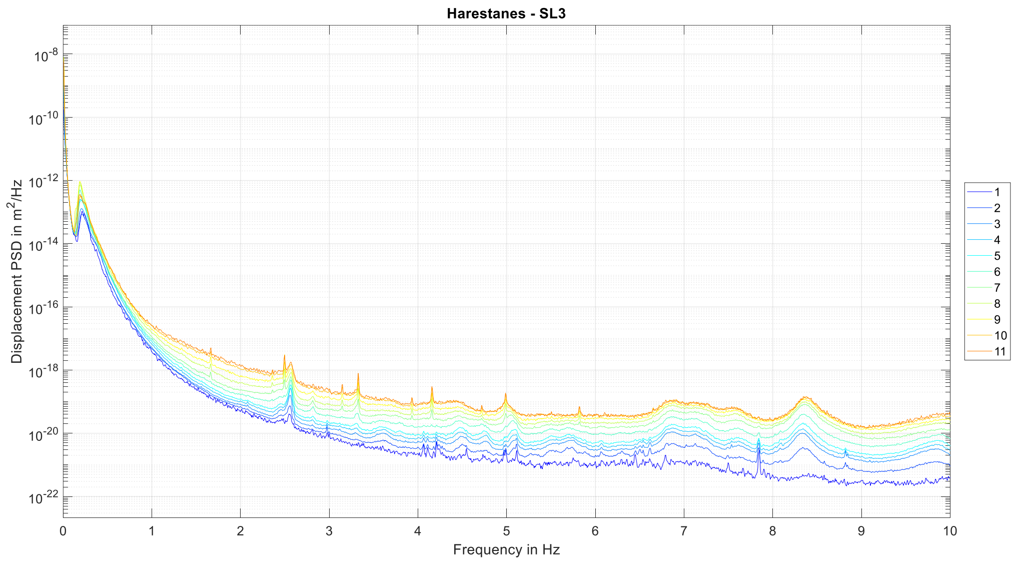


Figure 6 Variation of seismic amplitude with wind speed at Harestanes

4. Measured data compared to algorithm estimates

4.1. Results

The algorithm used to calculate the EKA budget uses a worst-case turbine to represent the spectra of any given wind turbine at a distance of 1 km (based on the turbines rotor diameter and hub height). This worst-case spectrum can be replaced by measured data at wind farms that have turbines with the same make and model as those measured here and previously. This approach considers that all seismic energy measured was generated by the given wind farm and is therefore an over-estimate as it includes background noise.

The impact of wind farms with makes and models that have been measured are listed in Table 3. These amplitudes consider the distance from EKA using the Frequency-Distance Weighting Function (FDWF), which is consistent with the budget calculations. Table 3 also lists the impact as calculated by the budget using a worst-case turbine. As noted above, the values for Harestanes are unrealistically high and have been included in Table 3 for completeness. The measured values are all lower than those estimated by the algorithm by between 23.1% and 42.7%. The cumulative measured impact for these wind turbines 31.1% lower than estimated by the budget.

Site	Farm	Number Of Turbines	Manufacturer	Model	Measured (nm)	Budget Algorithm (nm)	Over-estimate
2	Carlesgill (Craig)	5	Nordex	N80	0.0199	0.0314	36.7%
4	Langhope Rig	10	GE	GE1_6	0.0306	0.0403	24.1%
5	Clyde	152	Siemens	SWT2_3	0.0499	0.0740	32.5%
8	Minsca	16	Siemens	SWT2_3	0.0259	0.0336	23.1%
10	Ewe Hill	22	Siemens	SWT2_3	0.0602	0.0886	32.1%
12	Glenkerie	11	Vestas	V80	0.0115	0.0162	29.0%
19	Carlesgill (Craig) Ext	1	Enercon	E82	0.0100	0.0157	36.3%
58	Middle Muir	15	Senvion	M114	0.0036	0.0062	42.7%
Cumulative total					**0.0914**	**0.1326**	**31.1%**
6	Harestanes*	68	Gamesa	G8x	0.0662	0.0571	-15.88%

Table 3 Seismic impact of each wind farm based on measured data and considering the distance of each turbine from EKA using the FWDF curve. The estimate and the budget algorithm is also shown as is the ratio between the measured and algorithm-based values. *The Harestanes measurement included significant background noise due to ground conditions and low wind speeds required extrapolation 12 m/s, the results shown here include unrealistically high broadband noise levels.

5. Extrapolation to entire budget queue

The EKA Budget spread sheet *20118 EKA Audited Tables Final V4- BASE.xlsx* that was generated during the budget audit phase of work and issued to the Scottish government as part of "Desktop Audit of EKA Budget Sheet: Work to determine scale of measurement requirements (SGV_203_Tech_Report_v12)" is used here as the basis of budget calculations. The spreadsheet was the most up to date available to Xi at the time of writing. One modification has been made to the spreadsheet in that the planning stage for Solwaybank was moved from "In Construction" to "Operational". No sites have been removed or added to the table.

The spreadsheet contains wind turbine models that have not been measured and cannot therefore be represented with directly measured data. Instead, data from specific manufacturers (makes) have been extrapolated to different models based on their rotor diameter and hub height (e.g., Nordex N80 extrapolated to represent a Nordex N132). To extrapolate the data, the method used in *Eskdalemuir Wind Turbine Seismic Vibration: Assessment of Headroom (SGV_201_Tech_Report_v04)* and *Eskdalemuir Wind Turbine Seismic Vibration: Extrapolation of Potential Installed Capacity Based on Observed Seismic Output of Modern WTGs with future scenario planning (SGV_202_Tech_Report_v07)* is followed.

In *SGV_201_Tech_Report_v04* and *SGV_202_Tech_Report_v07* the algorithm used to represent wind turbines were tightly fitted to data from Craig, Clyde and Middle Muir wind farms. The coefficients used by the algorithm to represent wind turbines were adjusted and the algorithm iterated until a tight fit was achieved between data and algorithm. A similar approach is followed here, where the coefficients are fitted to Craig for Nordex and Enercon turbines, Langhope Rig for GE, Harestanes for Gamesa and Glenkerie for Vestas. The fitted coefficients from previous reports for Clyde represents Siemens turbines and for Middle Muir represents Senvion.

The algorithm used coefficients to represent spectra peaks related to blade pass and a single structural resonance. Here, two additional structural resonances have been included to better represent data from all wind farms. This is accomplished by adding two terms to equation 15 of *Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project*" (2014):

$$\boldsymbol{WCT}_{(\boldsymbol{f},\boldsymbol{vw},\boldsymbol{A},\boldsymbol{f}_{\boldsymbol{BP}})} = \boldsymbol{OBN}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}})} + \boldsymbol{BM1}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}},\boldsymbol{A})} + \boldsymbol{BM2}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}},\boldsymbol{A})} + \boldsymbol{BM3}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}},\boldsymbol{A})} + \boldsymbol{BP}_{(\boldsymbol{f},\boldsymbol{v}_{\boldsymbol{w}},\boldsymbol{A},\boldsymbol{f}_{\boldsymbol{BP}})}$$

where *WCT* is the synthetic spectra used to represent the turbine, *OBN* is the operational broadband noise, *BM1 BM2* and *BM3* are the three structural resonances (bending modes) and *BP* are peaks relating to blade pass. The variable f is frequency, A swept rotor area and v_w is wind speed. The coefficients used to represent the turbines produced by each manufacturer are listed in Appendix A with figures showing the fitting in Appendix B. The impact of the fitted data was assessed following the method detailed in Section 4.1 and Table 4 shows that there is good agreement between measured and fitted spectra.

Wind Farm	Impact based on directly measured spectra (nm)	Impact based on fitted spectra (nm)
Carlesgill (Craig)	0.0199	0.0227
Langhope Rig	0.0306	0.0268
Clyde	0.0499	0.0444
Harestanes	0.0662	0.0525
Ewe Hill	0.0602	0.0721
Middle Hill - Glenkerie	0.0115	0.0113
Carlesgill (Craig) Ext	0.0100	0.0118
Middle Muir	0.0036	0.0049
Cumulative total	0.1099	0.1070

Table 4 Comparison of impact of each wind farm when calculated directly for the measured spectra (Table 3) and when calculated using the spectra fitted with coefficients listed in Appendix A.

5.1.1. Two manufacturers at Craig wind farm

Craig wind farm now contains both Nordex and Enercon turbines. Craig wind farm was measured in 2011 with results presented in *Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project* (2014). In 2011 the wind farm contained only the four Nordex N80 turbines. The 2011 data was compared to data collected here to allow spectra peaks from the Nordex N80 to be discriminated from those related to the Enercon E82 turbines (Figure 7). The measured operational broadband noise is lower in the 2021 measurement likely due to a combination of improved sensor installation techniques developed over the subsequent decade and the mature wind farm having less activity related to installation and servicing than was the case when the then new farm was measured in 2011.

Once the spectral peaks related to the N80 and E82 turbines were discriminated from each other the normalised spectrum was used to fit coefficients to represent relevant turbines makes. To fit for each make, the amplitude of the normalised spectrum was adjusted to account for the numbers of turbines (i.e. 4 x Nordex N80 and 2 x Enercon E82). The fitting process assumes the operational broadband noise/background noise is produced by both the N80 turbines and the E82 turbines; this background noise is therefore double counted resulting in slightly higher spectrum representing the N80 and/or the E82. However, given that there is no way to discriminate the amount of broadband noise contributed by either turbine, a conservative approach is followed here, and the double counted values used.

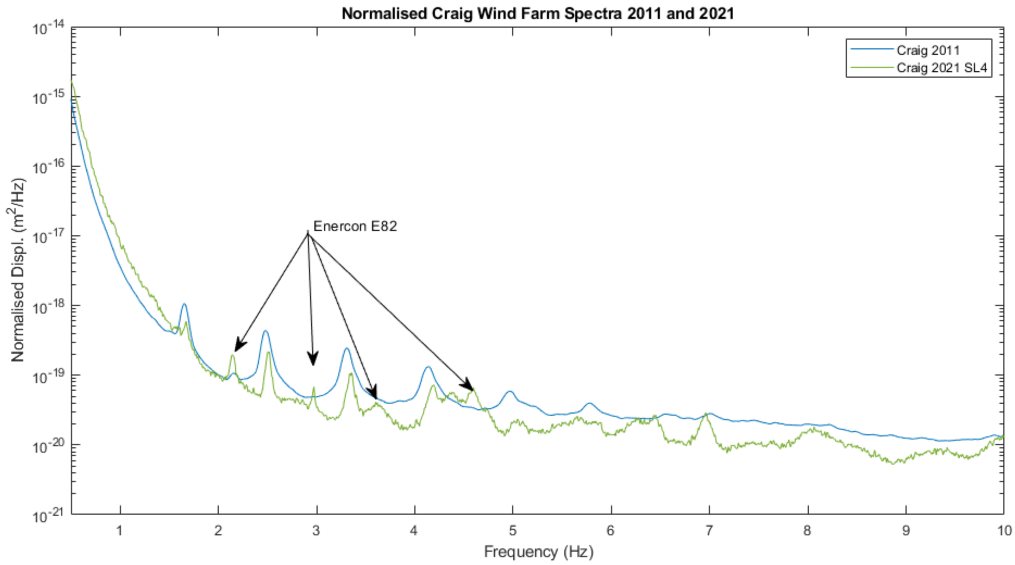


Figure 7 Comparison of data measured at Craig wind farm in 2011 when four Nordex N80 turbines were present compared to 2021 when the wind farm has an addition two Enercon E82 turbines.

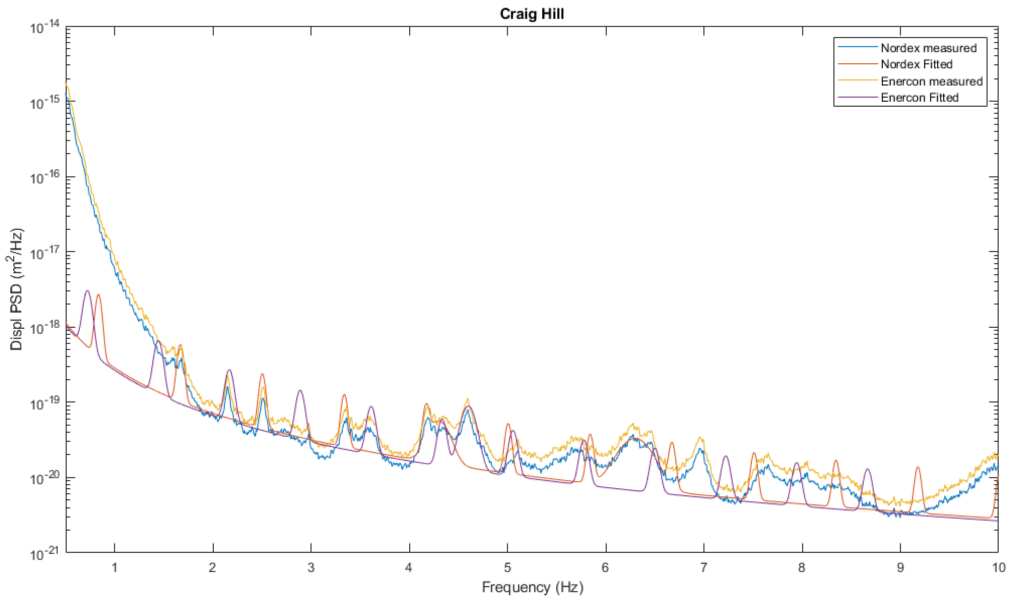


Figure 8 Fitting of coefficient to define the spectra used to extrapolate Nordex and Enercon turbines. The initial normalisation to a single turbine at 1 km was based on six turbines at Craig wind farm. The measured spectrum has been adjusted to account for there being two Enercon turbines and four Nordex, so that spectral peaks used for fitting have the correct amplitude.

5.1.2. Two hub heights at Glenkerie

The Glenkerie wind farm consists of eleven Vestas V80 wind turbines, of which six have hub heights of 60 m, and five have a hub heights of 78 m. Following a conservative approach, the coefficients were fitted such that it assumes that spectral peaks are produced by turbines with the 60 m hub height (see Appendix B).

5.1.3. Unknown and unmeasured turbines

Many wind farms in the budget queue are at the planning stage and have yet to determine which wind turbine will be installed at their proposed farm. Further, the single wind sub MW (500 kW) turbine listed as West of M6 Todhill was an operational EWT wind turbine for which there is no measured data. These wind farms required a fitted spectra to estimate their seismic contribution when extrapolating measured data to the entire queue.

The measurement of Langhope Rig had amplitudes closest to those estimated by the worst-case turbine in the budget algorithm (see Table 3) for turbines that are still in production and is a viable candidate for future sites in the consultation zone (Gamesa turbines at Harestanes are no longer in production). Following a conservative approach, the spectra representing GE wind turbines based on Langhope Rig has been used to estimate the contribution of all unknown turbines within the queue and the single sub MW class EWT.

5.1.4. Budget queue assumptions

The calculations provided below assume that the grid references, turbine dimensions and turbine manufacturers provided in the *20118 EKA Audited Tables Final V4- BASE.xlsx* are correct. To be consistent with the work detailed in Phase 2 (*SGV_202_Tech_Report_v07*) the budget is calculated for all turbines that are currently in the queue that do not breach the 0.336 nm threshold, i.e. all farms up to and including Cliffhope (submitted 29/09/2017) and the first two turbines (T1 and T2) from Faw Side (submitted 11/01/2018).

5.2. Results

The cumulative amplitude of all turbines in the budget queue was calculated up to and including Faw Side turbine T2. The current budget estimates that the cumulative impact of these turbines on EKA is 0.3216 nm. When measured seismic data is extrapolated using the approach detailed above, the cumulative impact is 0.2054 nm (Table 5). For clarity up to and including Cliffhope has been included in Table 4 as this is the final site which can be built out in full based on the current worst-case algorithm. The values based on the measurements presented here are 36.1% lower than the current budget estimate. Appendix C lists all wind farms in the queue as audited in Phase 3 (SGV_203_Tech_Report_v12) including those beyond Faw Side T2.

	Cumulative amplitude		Over-estimate
	Extrapolated from measurement (nm)	Standard EKA (nm)	
Queue to Cliffhope	0.1813	0.2762	34.4%
Queue to Faw Side T2	0.2054	0.3216	36.1%

Table 5 Comparison of cumulative impact on EKA based on measurement and the estimate provided by the current algorithmic approach. Values for the queue to Faw Side T2 is the point beyond which the 0.336 nm threshold is reached. Values up to Cliffhope (not including Faw Side turbines T1 and T2) are included for completeness.

6. Discussion

6.1. Uncertainties and assumptions

Measured data has been used here to better calculate the seismic contribution of wind turbines in the consultation zone. The seismic amplitude produced by a single wind turbine that is calculated by the budget algorithm was fitted to a relatively small dataset of just three wind farms that were available in 2014. Given the initially small dataset used to fit the algorithm in 2014, a safety factor was applied to ensure that the detection capabilities of EKA were not placed at risk. The data presented here show that the budget algorithm has not under-estimated the contribution of any wind farms measured and that the cumulative amplitude from installed and operating wind turbines has not endangered the capabilities of EKA.

The data presented here was used to calculate the actual installed capacity rather than estimated. However, it is not viable to retrospectively measure every wind turbine in the Eskdalemuir consultation zone, so a degree of extrapolation of data is required. In cases where decisions regarding data handling and extrapolation were required, a conservative worst-case approach was taken that was consistent with previous work for the Eskdalemuir Working Group. Thus, the spectra for a GE turbine based on Langhope Rig, which was the highest of the turbines measured that are still in production, was used to represent farms with “unknown” turbine manufactures and the EWT turbine for which there is no measured data. A worst-case approach was taken for separating the Nordex and Enercon turbines in that the broadband noise/background noise was effectively double counted. The worst-case approach was also taken when fitting data to the Glenkerie wind farm to represent Vestas turbines, whereby the smallest of the hub heights was used.

High background noise levels were measured at Minnygap and Solwaybank at 12 m/s such that the spectra do not reflect the ground vibration produced by wind farms and these measurements were excluded from the budget calculations below. The impact of Minnygap and Solwaybank on EKA was calculated using the fitted data for Nordex and Vestas machines respectively scaled for the given turbine’s rotor diameters and hub heights. Following the assumptions above, this scaling does not underestimate Minnygap and Solwaybank’s impact on EKA.

Due to low wind speeds over the summer of 2021 no data was recorded at Harestanes in the 12 m/s wind speed bin and data had to be extrapolated from lower wind speed bins to produce a 12 m/s spectrum. This process resulted in the broadband noise/background noise also being extrapolated to unrealistically high levels. The extrapolated 12 m/s wind speed bin was used to fit the coefficients that represent Gamesa turbines and, therefore, likely over-estimate the operational broadband noise level. Furthermore, Harestanes had notably high background noise levels due to ground conditions (see Appendix D4). In previous studies such as “*Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project”* (2014), high background noise levels at Craig wind farm were overcome by applying the operational broadband noise coefficient measured elsewhere. This approach could be followed to model the Gamesa turbine here. However, following a conservative approach, the contribution from Gamesa turbines were modelled using the operational broadband noise as measured and extrapolated from the Harestanes data.

6.2. Implications for head room and further capacity

Phase 2 of this work programme detailed in *Eskdalemuir Wind Turbine Seismic Vibration: Extrapolation of Potential Installed Capacity Based on Observed Seismic Output of Modern WTGs with future scenario planning* (SGV_202_Tech_Report_v07, see Appendix E – Summary of Results from Phase 2) used data from Craig, Clyde and Middle Muir to remove the safety factor from algorithm used to calculate the EKA budget and thereby assess potential head room. The conclusion of SGV_202_Tech_Report_v07 was that the algorithm over-estimated the impact by between 21% and 43%.

The work presented here follows a similar approach with a greatly increased data set. With the measurement provided here, combined with previous measurements, the dataset contains wind turbines that contribute 0.153 nm of the 0.161 nm currently installed and operating in the consultation zone. The method by which an over-estimate was assessed here is similar to that used in SGV_202_Tech_Report_v07. However, there is considerably less uncertainty in the over-estimate calculations given the very high proportion of turbines with which we now have seismic data. When measured data was extrapolated to the budget queue, an over-estimate of 36.1% was calculated (Table 5); this is in mid- to high-range concluded by SGV_202_Tech_Report_v07.

The Phase 2 work detailed in SGV_202_Tech_Report_v07 used a random population of the consultation zone to estimate how headroom in the budget provided by the removal of the safety factor in the budget algorithm with measured data might be converted to installable wind capacity. The report noted that conversion of budget headroom is very strongly dependent on the distribution of new wind turbines, where placing turbines preferentially further away from EKA resulted in higher installable capacity. Given a random distribution, SGV_202_Tech_Report_v07 estimated that the headroom would convert to between 480 MW and 1.2 GW. Given that the over-estimate calculated here falls in the mid- to high-range of that estimated in SGV_202_Tech_Report_v07, it follows that the installable capacity also lies between 480 MW and 1.2 GW (without additional measures to maximise deployment within the consultation zone, background removal or seismic mitigation). The installable capacity is highly dependent on the distribution of turbines and SGV_202_Tech_Report_v07 demonstrated skewing the random distribution toward 50km (away from 10 km would increase the conversion of headroom to installable capacity to between 860 MW and 2.1 GW. Again, given the similarity of results here it follows that the installable capacity based on the measurements here would be in the mid- to high-range for a similar distribution. These two analyses assume that two turbines at Faw Side consume budget and no further Faw Side turbines. Should the two Faw Side turbines not be built then the increase in headroom would result is significantly higher installable capacity than that noted above.

6.3. Implication of exclusion zone

The Phase 2 work detailed in SGV_202_Tech_Report_v07 modelled how the radius of the exclusion zone affects installable wind energy capacity. The report showed that increasing the radius of the exclusion zone from 10 km to 15 km could result in a three-fold increase in the conversion of headroom to installable capacity. Given that the results presented here are within the range of those used in SGV_202_Tech_Report_v07 it follows that the conclusions of the report with respect to the exclusion zone are unchanged.

6.4. Background noise levels

The measured data reported here and from previous reports include background noise which is not generated by wind turbines. The background noise comes from natural sources or from localised human activities. As all wind farm sites were not measured prior to installation; without pre-installation seismic data, background noise caused by non-turbine sources is not accurately able to be removed. Removing the background seismic energy to calculate the contribution just wind turbines make, would provide an additional increase in the available budget and increase deployment within the region. Available data shows that the seismic energy produced by the wind turbine increases with the cube of the wind speed, as would be expected as the energy content of the wind varies with the cube (the third power) of the average wind speed. However, the background noise increases at a greater rate than the third power which results in background masking the turbine signals at higher wind speeds. Conducting before and after installation measurements of sufficient length would allow quantification of background noise and provide a means of removing this energy from the calculations. Increased understanding of how the background noise scales at sites would potentially allow future measurements to be simplified and clarify methodology for background noise removal. Removal of background noise would effectively reduce the seismic levels of the turbines and further increase capacity in the region, while continuing to rigorously protect the EKA Seismic Array.

7. Conclusion

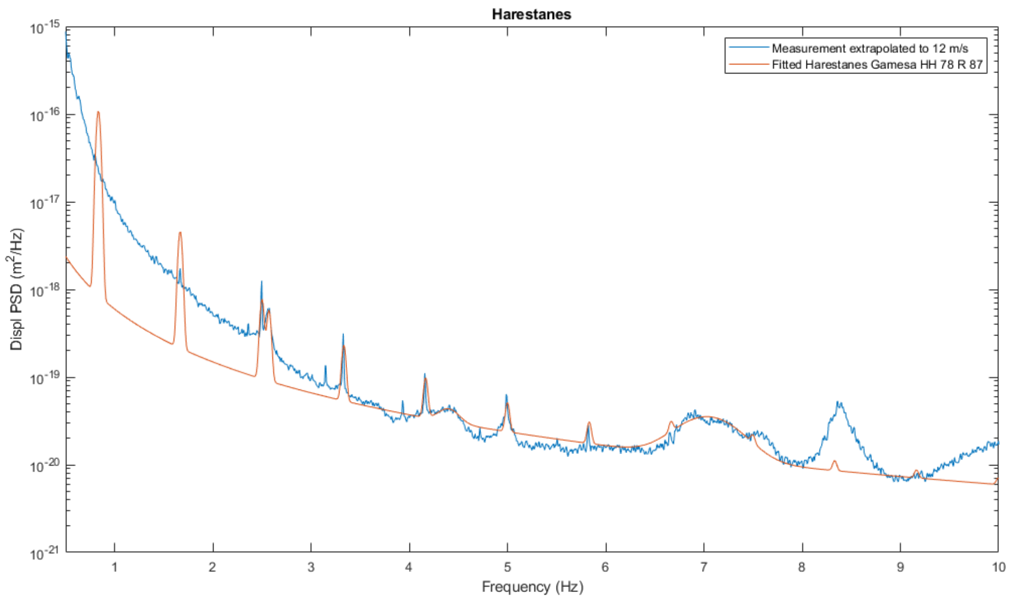
Data collected at seven wind farms combined with those from previous measurements allowed an assessment of the contribution of wind turbines to background seismic noise at Eskdalemuir Seismic Array. Currently, the seismic contribution is estimated using an algorithm based on the size of wind turbines and their distance to the EKA and includes a data set appropriate safety factor. The current algorithm estimates that the noise threshold of 0.336 nm will be breached by the third turbine at Faw Side (T3). The algorithm estimates that the contribution of all wind turbines in the budget queue up to and including Faw Side T2 is 0.3216 nm. Measured data was fitted to represent all the major turbine manufacturers in the consultation zone. Based on the extrapolation of data for each manufacturer (whilst maintaining conservatism) the contribution of all wind turbines in the budget queue up to and including Faw Side T2 is 0.2054nm. The algorithm therefore over-estimates the measured data by 36.1%. The over-estimate is consistent with initial estimates made with Phase 2 (between 21% and 43%), thus the conclusions made in Phase 2 with respect to headroom, installable capacity and exclusion zone are unchanged. Whilst the measured data fitted still maintains conservatism, further budget could be released if an approach to removing background noise from measured data were agreed, and before and after measurements were made.

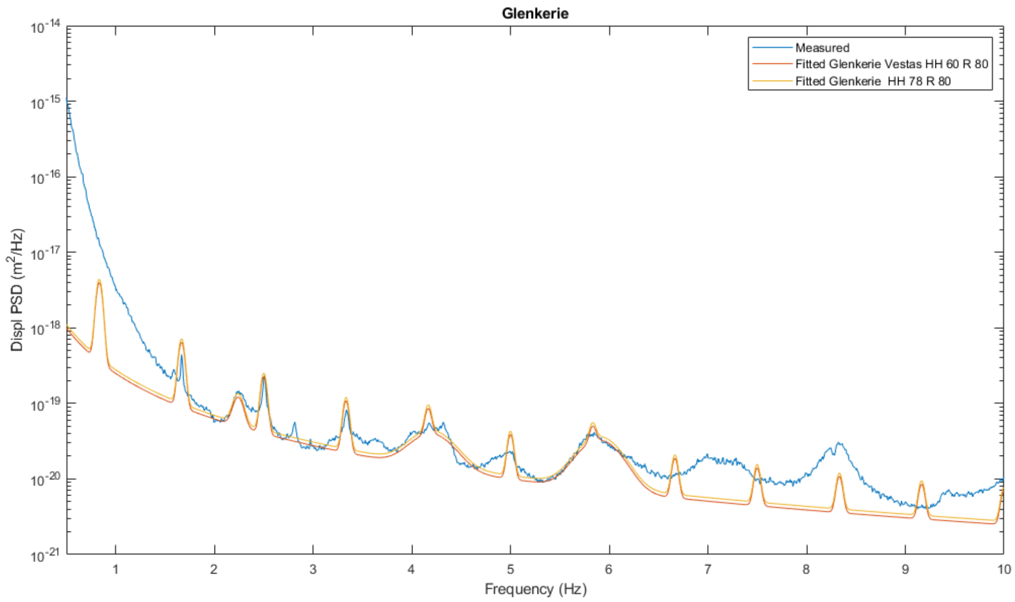
8. Appendix A – Coefficients used to represent turbines by manufacturers

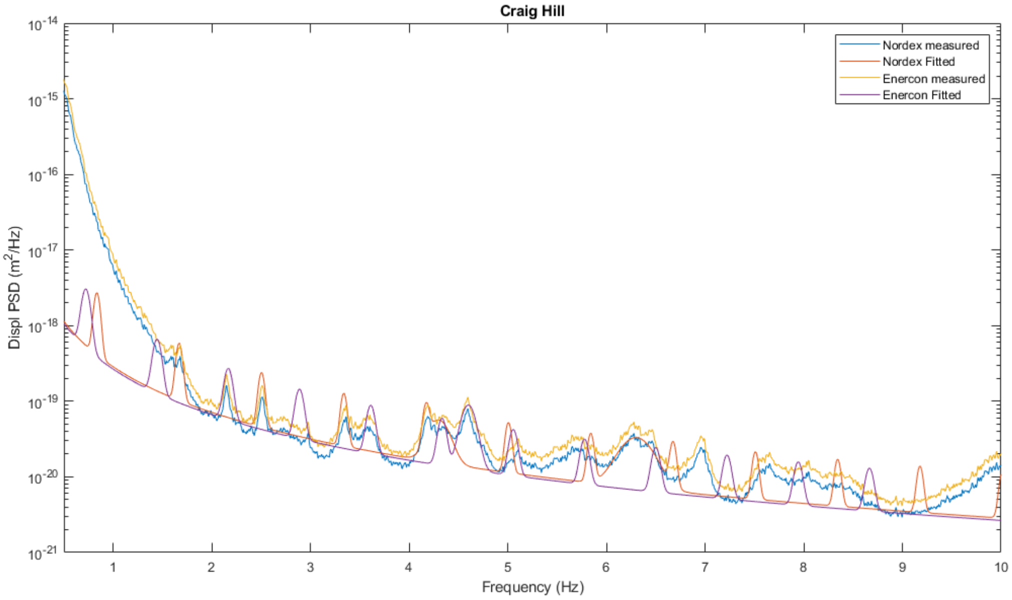
Coefficients	Standard EKA	Nordex	Siemens	Enercon	Vestas	Gamesa	GE	Senvion
Blade pass amplitude multiplier	2.8739E-25	1.87E-25	2.8739E-25	1.6e-25	2.87E-25	4.59E-24	2.69E-25	8E-25
Blade pass amplitude exponent	1.76	2.25	4	2.25	2.7	4.62	2.76	3.5
Blade pass shape parameter	0.04	0.03	0.04	0.04	0.03	0.02	0.02	0.03
Bending mode 1 amplitude multiplier	9.2303E-26	0	2.6152E-26	0	9.3E-27	4.85E-26	2.9E-25	8.1E-27
Frequency of bending mode 1	2.808	2.96	2.808	2.96	2.24	2.57	2.68	4.8
Bending mode 1 shape parameter	0.05	0.055	0.05	0.055	0.05	0.02	0.01	0.1
Bending mode 2 amplitude multiplier	0	5E-27	0	1e-26	3.3E-27	1.25E-27	1.8E-27	0
Frequency of bending mode 2	2.808	4.3	2.808	4.6	4.2	4.4	4.1	4.8
Bending mode 2 shape parameter	0.05	0.1	0.05	0.07	0.2	0.1	0.05	0.1
Bending mode 3 amplitude multiplier	0	3.15E-27	0	0	3.3E-27	2.30E-27	2.3E-27	0
Frequency of bending mode 3	2.808	6.3	2.808	5.7	5.9	7.04	5.4	4.8
Bending mode 3 shape parameter	0.05	0.16	0.05	0.23	0.2	0.3	0.14	0.1
Operational broadband noise multipliers	2.2282E-26	3.47e-26	2.2282E-26	3.47e-26	3.23E-26	5.85E-26	1.53E-26	3.5E-26
Tip Speed (m/s)	77.49	69.9	77.49	60.5	69.8	75.9	77.49	69.5

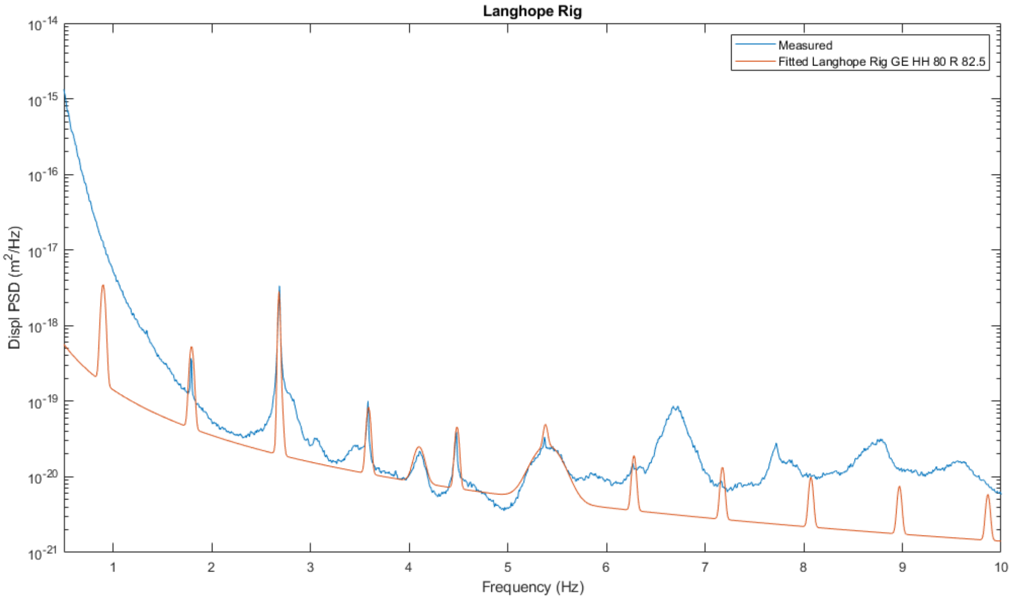
Coefficients used in the representations of seismic output of wind turbines manufacturers. The coefficients relate to those described in Section 8.2.1 of *Seismic Vibration produced by wind turbines in the Eskdalemuir region Release 2.0 of Substantial Research Project* with parameters representing two additional bending modes. The Standard EKA coefficients are those currently used by the budget algorithm and include a factor of safety.

9. Appendix B – Fitting of coefficients to represent different manufacturers






Craig Hill
Nordex measured
Nordex Fitted
Enercon measured
Enercon Fitted
Displ PSD (m^2/Hz)
Frequency (Hz)


Langhope Rig
Measured
Fitted Langhope Rig GE HH 80 R 82.5
Displ PSD (m^2/Hz)
Frequency (Hz)

Xi

10. Appendix C Assessment of budget queue

* Shaded cells show cumulative amplitude that exceed the 0.336 nm threshold

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
1	Bowbeat	24	1.3	31.2	Nordex	Nordex	0.00320	0.00442	0.0032	0.0044
2	Carlesgill	5	2.5	12.5	Nordex	Enercon	0.02268	0.03137	0.0229	0.0317
3	Halkburn - Longpark	19	2	38	Senvion	Senvion	0.00431	0.00560	0.0233	0.0322
4	Langhope Rig	10	1.5	15	GE	GE	0.02684	0.04029	0.0355	0.0516
5	Clyde	152	2.3	349.6	Siemens	Siemens	0.04443	0.07399	0.0569	0.0902
6	Harestanes	68	2	136	Gamesa	Gamesa	0.05248	0.05714	0.0774	0.1068
7	Dalswinton	15	2	30	Senvion	Senvion	0.00754	0.01026	0.0778	0.1073
8	Minsca	16	2.3	36.8	Siemens	Siemens	0.02035	0.03364	0.0804	0.1124
9	Carcant	3	2.3	6.9	Siemens	Siemens	0.00055	0.00079	0.0804	0.1124
10	Ewe Hill	22	2.3	50.6	Siemens	Siemens	0.05203	0.08858	0.0958	0.1431
11	Andershaw	11	3.3	36.3	Vestas	Vestas	0.00364	0.00498	0.0958	0.1432
12	Middle Hill - Glenkerie	11	2	22	Vestas	Vestas	0.01132	0.01621	0.0965	0.1441
13	Langshaw Farm	1	0.05	0.05	unknown	GE	0.00015	0.00018	0.0965	0.1441
14	Aikrigg Cottage	1	0.006	0.006	unknown	GE	0.00002	0.00002	0.0965	0.1441
15	Kingstown Ind Estate	1	0.015	0.015	unknown	GE	0.00003	0.00003	0.0965	0.1441
16	Lammerlaw Farm 7153	1	0.011	0.011	unknown	GE	0.00009	0.00010	0.0965	0.1441
17	Brunstock Close	1	0.006	0.006	unknown	GE	0.00002	0.00002	0.0965	0.1441
18	Minnygap	10	2	20	Nordex	Nordex	0.02168	0.03168	0.0989	0.1476
19	Carlesgill Ext	1	2.5	2.5	Enercon	Enercon	0.01179	0.01572	0.0996	0.1484

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
20	Land East of Braidwood	1	0.006	0.006	unknown	GE	0.00009	0.00011	0.0996	0.1484
21	Westmill Farm	1	0.11	0.11	unknown	GE	0.00006	0.00007	0.0996	0.1484
22	Windyknowe	1	0.006	0.006	unknown	GE	0.00004	0.00004	0.0996	0.1484
23	Land NW of Ferniehaugh	2	0.06	0.12	unknown	GE	0.00006	0.00007	0.0996	0.1484
24	Lochmailing	1	0.015	0.015	unknown	GE	0.00010	0.00012	0.0996	0.1484
25	Threepwood	1	0.015	0.015	unknown	GE	0.00007	0.00008	0.0996	0.1484
26	Lauder B	2	0.12	0.24	unknown	GE	0.00009	0.00011	0.0996	0.1484
27	Rennieston Edge	1	0.06	0.06	unknown	GE	0.00004	0.00005	0.0996	0.1484
28	Meadowside Cottage	1	0.02	0.02	unknown	GE	0.00009	0.00011	0.0996	0.1484
29	Mosshouses Farm	1	0.015	0.015	unknown	GE	0.00006	0.00008	0.0996	0.1484
30	Land SW of Larkhill	1	0.015	0.015	unknown	GE	0.00006	0.00008	0.0996	0.1484
31	Hall Burn	6	2.2	13.2	Vestas	Vestas	0.00393	0.00554	0.0997	0.1485
32	Muirlea Farm	2	0.04	0.08	unknown	GE	0.00014	0.00017	0.0997	0.1485
33	Whinney Rig	1	0.1	0.1	unknown	GE	0.00033	0.00041	0.0997	0.1485
34	Hillfield	1	0.005	0.005	unknown	GE	0.00002	0.00003	0.0997	0.1485
35	Cargo Farm Cottage	2	0.04	0.08	unknown	GE	0.00010	0.00012	0.0997	0.1485
36	Land NW of The Batts	1	0.0015	0.0015	unknown	GE	0.00005	0.00006	0.0997	0.1485
37	Burnhouse	1	0.0015	0.0015	unknown	GE	0.00006	0.00007	0.0997	0.1485
38	The Beeches	1	0.02	0.02	unknown	GE	0.00008	0.00009	0.0997	0.1485
39	Symington Mains Farm	1	0.02	0.02	unknown	GE	0.00007	0.00009	0.0997	0.1485
40	Midhill	1	0.015	0.015	unknown	GE	0.00009	0.00011	0.0997	0.1485
41	Newton of Wiston	1	0.015	0.015	unknown	GE	0.00006	0.00008	0.0997	0.1485
42	Newtonhead	1	0.06	0.06	unknown	GE	0.00011	0.00014	0.0997	0.1485

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
43	Gaups Mill	1	0.01	0.01	unknown	GE	0.00003	0.00004	0.0997	0.1485
44	South Melbourne Farm	1	0.006	0.006	unknown	GE	0.00004	0.00005	0.0997	0.1485
45	Walston Braehead Farm	3	0.06	0.18	unknown	GE	0.00014	0.00017	0.0997	0.1485
46	Easton Farm	1	0.02	0.02	unknown	GE	0.00007	0.00008	0.0997	0.1485
47	Pumro Fell	1	0.0015	0.0015	unknown	GE	0.00005	0.00006	0.0997	0.1485
48	Rivox	1	0.015	0.015	unknown	GE	0.00044	0.00055	0.0997	0.1485
49	Braco Farm	2	0.03	0.06	unknown	GE	0.00007	0.00008	0.0997	0.1485
50	Land at Arthurshiels	1	0.02	0.02	unknown	GE	0.00009	0.00010	0.0997	0.1485
51	Hyndshawland	1	0.02	0.02	unknown	GE	0.00009	0.00011	0.0997	0.1485
52	Clyde Extension	54	3	162	Siemens	Siemens	0.02853	0.04801	0.1037	0.1561
53	Glentaggart	5	3	15	unknown	GE	0.00176	0.00257	0.1037	0.1561
54	Kirkpatrick Hill	1	0.11	0.11	unknown	GE	0.00014	0.00017	0.1037	0.1561
55	East Millrig	1	0.015	0.015	unknown	GE	0.00011	0.00014	0.1037	0.1561
56	Solwaybank	15	2	30	Vestas	Vestas	0.02592	0.03748	0.1069	0.1605
57	Mallshill	1	0.005	0.005	unknown	GE	0.00006	0.00007	0.1069	0.1605
58	Middle Muir	15	3.4	51	Senvion	Senvion	0.00491	0.00623	0.1070	0.1606
59	Brockhouse	1	0.011	0.011	unknown	GE	0.00006	0.00007	0.1070	0.1606
60	Broomhills	1	0.01	0.01	unknown	GE	0.00006	0.00008	0.1070	0.1606
61	Land SW of Copland Farm	1	0.011	0.011	unknown	GE	0.00011	0.00013	0.1070	0.1606
62	Land N of Midtown Farm	1	0.05	0.05	unknown	GE	0.00010	0.00012	0.1070	0.1606
63	Birkenside Farmhouse	1	0.05	0.05	unknown	GE	0.00010	0.00012	0.1070	0.1606

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
64	Libberton Mains Farm	1	0.02	0.02	unknown	GE	0.00007	0.00008	0.1070	0.1606
65	Cloich Forest	12	4.8	57.6	Nordex	Nordex	0.00598	0.00868	0.1072	0.1609
66	Bankhouse	1	0.012	0.012	unknown	GE	0.00004	0.00005	0.1072	0.1609
67	Lammerlaw	2	0.022	0.044	unknown	GE	0.00012	0.00014	0.1072	0.1609
68	Cormiston Farm	1	0.02	0.02	unknown	GE	0.00012	0.00014	0.1072	0.1609
69	Hartsop	1	0.015	0.015	unknown	GE	0.00010	0.00012	0.1072	0.1609
70	Parkhouse Farm	2	0.02	0.04	unknown	GE	0.00010	0.00013	0.1072	0.1609
71	Shankfield Head	2	0.02	0.04	unknown	GE	0.00010	0.00012	0.1072	0.1609
72	Cambwell	1	0.011	0.011	unknown	GE	0.00013	0.00016	0.1072	0.1609
73	South of Hyndfordwells	3	0.18	0.54	unknown	GE	0.00014	0.00017	0.1072	0.1609
74	Rose Cottage	1	0.006	0.006	unknown	GE	0.00003	0.00004	0.1072	0.1609
75	Hillend Farm	1	0.011	0.011	unknown	GE	0.00013	0.00016	0.1072	0.1609
76	Glenkerie Extension	6	2.5	15	Senvion	Senvion	0.00820	0.01142	0.1075	0.1613
77	Deanfoot Farmhouse	1	0.05	0.05	unknown	GE	0.00009	0.00011	0.1075	0.1613
78	Lion Hill	4	2.3	9.2	Vestas	Vestas	0.01007	0.01472	0.1080	0.1620
79	West of Hyndfordwells Farm	1	0.02	0.02	unknown	GE	0.00006	0.00007	0.1080	0.1620
80	Crookedstane Farm	4	2.3	9.2	Vestas	Vestas	0.00811	0.01182	0.1083	0.1624
81	Windy Edge	9	22.5	202.5	Nordex	Nordex	0.02491	0.03572	0.1111	0.1663
82	Blackdyke	1	0.01	0.01	unknown	GE	0.00005	0.00006	0.1111	0.1663
83	Cottage Farmhouse	1	0.011	0.011	unknown	GE	0.00006	0.00007	0.1111	0.1663
84	Lampits Farm 2	1	0.25	0.25	unknown	GE	0.00016	0.00021	0.1111	0.1663
85	Land NW of West Morriston Farm	1	0.05	0.05	unknown	GE	0.00012	0.00015	0.1111	0.1663

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
86	Solway re-sub (Beckburn)	9	3.45	31.05	Vestas	Vestas	0.00565	0.00803	0.1112	0.1665
87	Land East of Mossbank	2	0.011	0.022	unknown	GE	0.00014	0.00017	0.1112	0.1665
88	Twentyshilling Hill	9	4.2	37.8	Vestas	Vestas	0.00191	0.00253	0.1112	0.1665
89	Townfoot	1	0.01	0.01	unknown	GE	0.00009	0.00011	0.1112	0.1665
90	South Slipperfield Farmhouse	1	0.011	0.011	unknown	GE	0.00009	0.00012	0.1112	0.1665
91	Rose Cottage (9812)	1	0.25	0.25	unknown	GE	0.00003	0.00004	0.1112	0.1665
92	Whitelaw Brae	14	4.2	58.8	unknown	GE	0.03175	0.04898	0.1157	0.1735
93	East of Newton of Covington	2	0.02	0.04	unknown	GE	0.00010	0.00012	0.1157	0.1735
94	Bailey Town Farm	1	0.01	0.01	unknown	GE	0.00015	0.00019	0.1157	0.1735
95	Kilravoch	1	0.0012	0.0012	unknown	GE	0.00002	0.00002	0.1157	0.1735
96	South Melbourne Farm 2	1	0.011	0.011	unknown	GE	0.00010	0.00012	0.1157	0.1735
97	SW of Kettleshill Farmhouse	1	0.012	0.012	unknown	GE	0.00003	0.00004	0.1157	0.1735
98	West of M6 Todhills	1	0.5	0.5	EWT	GE	0.00047	0.00063	0.1157	0.1735
99	Trough Head Farm	2	0.01	0.02	unknown	GE	0.00025	0.00030	0.1157	0.1735
100	72 Carlisle Road	2	0.085	0.17	unknown	GE	0.00025	0.00032	0.1157	0.1735
101	Clackmae Farm	1	0.1	0.1	unknown	GE	0.00016	0.00020	0.1157	0.1735
102	East of Whitslaid Farm	2	0.05	0.1	unknown	GE	0.00008	0.00010	0.1157	0.1735
103	Crossdykes	10	4.8	48	Nordex	Nordex	0.09860	0.14087	0.1520	0.2235
104	Whins Farm	1	0.085	0.085	unknown	GE	0.00050	0.00067	0.1520	0.2235
105	Loganhead	8	3.2	25.6	GE	GE	0.05001	0.08009	0.1600	0.2374

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
106	Jockstown Farm	1	0.1	0.1	unknown	GE	0.00046	0.00061	0.1600	0.2374
107	Burnswark Garage	1	0.5	0.5	unknown	GE	0.00063	0.00085	0.1600	0.2374
108	Wauchope & Newcastleton Forests	90	3.4	306	unknown	GE	0.02808	0.04199	0.1625	0.2411
109	North Lowther	30	5	150	unknown	GE	0.00889	0.01347	0.1627	0.2415
110	Hopsrig	12	3.5	42	Siemens	Siemens	0.06471	0.11242	0.1751	0.2664
111	Pines Burn	12	3.3	39.6	Nordex	Nordex	0.02100	0.03108	0.1764	0.2682
112	Priestgill	7	3.2	22.4	GE	GE	0.00672	0.01015	0.1765	0.2684
113	Land SE of Scotston Bank Farm	3	0.015	0.045	unknown	GE	0.00014	0.00017	0.1765	0.2684
114	Cliffhope	46	7	322	unknown	GE	0.04134	0.06528	0.1813	0.2762
115	Faw Side	45	7	315	unknown	GE	0.38546	0.65535	0.4260	0.7112
116	Little Heart Fell	9	5.7	51.3	Nordex	Nordex	0.10750	0.15547	0.4393	0.7280
117	Twentyshilling hill revised	9	4.2	37.8	Vestas	Vestas	0.00293	0.00397	0.4393	0.7280
118	Daer	15	5.8	87	unknown	GE	0.03632	0.05827	0.4408	0.7303
119	Scoop Hill	78	7	546	unknown	GE	0.50247	0.85396	0.6684	1.1237
120	Callisterhall	13	6	78	Vestas	Vestas	0.07393	0.10932	0.6725	1.1290
121	Priestgill resub	7	5.6	39.2	Vestas	Vestas	0.00982	0.01434	0.6726	1.1291
122	Westerkirk	20	4	80	unknown	GE	0.28381	0.47791	0.7300	1.2260
123	Loganhead resub	8	4.8	38.4	Nordex	Nordex	0.06845	0.09898	0.7332	1.2300
124	Hopsrig resub	12	4.15	49.8	Vestas	Vestas	0.13510	0.19494	0.7456	1.2454
125	Harestanes South	8	5.5	44	unknown	GE	0.02590	0.04141	0.7460	1.2461
126	Greystone Knowe	15	4.5	67.5	unknown	GE	0.00555	0.00853	0.7460	1.2461
127	Whitelaw resub	12	4.2	50.4	unknown	GE	0.03787	0.05914	0.7470	1.2475
128	Scawd Law	12	4.2	50.4	unknown	GE	0.00845	0.01272	0.7470	1.2476

							Wind Farm Amplitude (nm)		Cumulative Amplitude (nm)	
Site	Wind Farm	Number of Turbines	Power per turbine (MW)	Total Power (MW)	Manufacturer	Coefficients Used	Fitted to measurement	Standard EKA	Fitted to measurement	Standard EKA
129	Grayside	25	6.6	165	unknown	GE	0.02919	0.04621	0.7476	1.2484

11. Appendices D.1-D.7 – Measurement Reports for each Wind Farm

For full details of the measurement at each wind farm and the approach to post processing the data please see attached supplementary documents: Appendices D.1 to D.7

Appendix D.1 – Craig Hill

Appendix D.2 – Ewe Hill

Appendix D.3 - Glenkerie

Appendix D.4 - Harestanes

Appendix D.5 – Langhope Rig

Appendix D.6 - Minnygap

Appendix D.7 - Solwaybank

12. Appendix E – Summary of Results from Phase 2

The following text summarises the results of Phase 2 detailed in *SGV_202_Tech_Report_v07.pdf:*

> The amount of additional wind energy capacity that the head room may allow assuming an even spread of turbines through the consultation zone are listed in Table 6. The additional capacity and number of turbines listed in Table 6 are taken as the mean of 1000 simulations and the uncertainty is taken as one standard deviation. The additional capacity is dependent on the available head room, which in turn is dependent on the type of turbine used to calculate the head room. If the Senvion turbines at Middle Muir are representative of all turbines in the consultation zone resulting in head room of 0.097 nm, then 476±142 MW of additional capacity would likely result from the even distribution of ~141 3.4 MW turbines. Should the Siemens turbines at Clyde be representative then an additional 1.1±0.18 GW is likely and if the Nordex turbines at Craig are representative then the additional capacity would likely be 310±92 MW.
>
> The additional number of turbines and related capacity is strongly dependent on the distribution of those turbines. Table 7 lists how the head room converts to additional capacity when more turbines are built close to 50 km, while Table 8 lists how the head room converts to additional capacity when more turbines are placed close to 10 km. For the given weighting in the distribution there is a four-fold increase in additional capacity when the distribution is weighted towards 50km compared to 10 km (Table 9).

Scenario 3	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	26.3 ± 20.8	8.7 ± 6.2
Middle Muir	0.097	476.9 ± 142.2	141.3 ± 36.5
Clyde	0.149	1179.8 ± 180.5	348.0 ± 53.1
Craig	0.075	310.2 ± 87.4	92.2 ± 28.4

Table 6 – Consumption of head room by an even distribution of 3.4 MW turbines. Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Scenario 4	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	46.7 ± 36.0	14.7 ± 10.6
Middle Muir	0.097	872.5 ± 222.8	257.6 ± 65.5
Clyde	0.149	2147.6 ± 330.7	632.6 ± 97.3
Craig	0.075	558.0 ± 165.1	165.1 ± 52.5

Table 7 – Consumption of head room the distribution of 3.4 MW turbines that is weighted towards 50 km. Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Scenario 5	Head room nm	Additional Capacity MW	Number of turbines
Standard EKA	0.004	11.9 ± 11.2	4.3 ± 3.5
Middle Muir	0.097	216.9 ± 58.4	64.8 ± 17.2
Clyde	0.149	547.6 ± 89.7	162.1 ± 26.4
Craig	0.075	144.3 ± 43.8	43.4 ± 14.0

Table 8 – Consumption of head room the distribution of 3.4 MW turbines that is weighted towards 10 km. Estimates of additional capacity and number of turbines that the different levels of head room may allow. The levels of head room are based on the measured wind farm being representative of all turbines in the consultation zone. The levels show the mean of 1000 simulations and the uncertain level in one standard deviation.

Middle Muir - summary	Head room nm	Additional Capacity MW	Number of turbines
Scenario 3 – Linear Distribution	0.097	476.9	141.3
Scenario 4 – Weighted to 50 km	0.097	872.5	257.6
Scenario 5 – Weighted to 10 km	0.097	216.9	64.8

Table 9 – Summary of how the distribution of turbines affects the additional number of turbines and capacity before the threshold is breached. These values are when the simulation uses measured data from Middle Muir is used for each additional turbine.