<u>Eskdalemuir Working Group Meeting – 29 July 2020</u>

<u>Introduction</u>

The Eskdalemuir Working Group (EWG) was reformed in 2018 with the view to consider options available to realise the full potential of the consultation zone covering the 50km area surrounding the Eskdalemuir Seismic Array.

In 2019, EWG considered proposals on the budget allocation policy and made a recommendation to the MoD. However, these proposals were not progressed at that time.

Given this exploration of a policy-based approach, Scottish Government considered an evidence-led process would be necessary to provide a long term solution to this issue. Scottish Government commissioned Xi Engineering to undertake a technical analysis of the budget calculation tool currently used by MoD. The purpose of this was used to investigate potential headroom within the assumed seismic contribution of existing sites within the area.

The results of the initial phases of this work was presented to EWG and views sought from members on the value of continuing this work.

<u>Presentation of Phase 1 and 2</u>

Dr Brett Marmo (Xi Engineering) presented '*Extrapolation of Potential Installed Capacity Based on Observed Seismic Output of Modern WTGs with Future Scenario Planning'* to the group. In this presentation he outlined that the standard EKA algorithm includes a safety factor and therefore over estimates the contribution of wind turbines. In phases 1 and 2, the algorithm was fitted with existing data from Craig and Clyde Windfarms in addition to new measurements from Middlemuir Windfarm.

The results of phase 1 and 2 of this technical assessment showed that there is an overestimation of budget allocation between 21-44%, which could mean a potential additional capacity in the area between 0.8-1.2GW. The amount of additional capacity is highly dependent on distance from the array and it was suggested that the headroom could be protected by increasing the exclusion zone.

These results were caveated on the basis that they assume Middlemuir are representative of other turbines within the consultation zone.

<u>Proposed Phase 3 and 4</u>

Dr Mark-Paul Buckingham (Xi Engineering) presented a follow up to Dr Marmo's presentation, looking specifically at the proposals for Phase 3 and 4. He highlighted that there could be potential additional budget gains by removing background noise, which requires pre and post build out measurements, drivers to ensure the 'quietest' turbines are installed, alongside other mitigation technologies and a potential revised buildable area.

For Phase 3, Xi would conduct a desk based audit of what has been built in the area, and what is in planning, breaking down by site make/model/size of turbines. This information will then be used to extrapolate the calculation used in phases 1 and 2, with the aim of establishing a more accurate picture of existing seismic contribution.

Using the data obtained in phase 3, phase 4 will involve on-site measurements of pre-existing turbines within the 50km zone, with these measurements being factored in to the calculation to give the most up to date cumulative seismic contribution possible.

<u>Summary of Group Discussions</u>

- The majority of EWG members agreed with the findings and welcomed the Phase 1 and Phase 2 reports.
- Concerns were raised regarding the constraints factored in to Xi's methodology - specifically the exclusion of known limitations such as wild land, aviation and topography. It was also highlighted that work conducted by RES in 2014 may better reflect the views of industry on the perceived constraints to development in this area.
- Xi clarified that they are aware there are many other factors affecting planning but the focus was to inform the group how distance plays a significant role. Xi confirmed that the calculations could be re-run with a more detailed constraints planning map.
- It was noted that some members are concerned that the process of establishing a constraints planning map would be time-consuming and, on balance, potentially causing unnecessary delays. Highlighting that across the board agreement on levels of protection for particular characteristics would be unlikely.
- Phase 1 and 2 of the report indicated that in order to make most efficient use of the finite noise budget resource, an increase of the 10km exclusion zone will have to be considered. This was met with mixed opinions by EWG members, and Scottish Government officials clarified that this remains an open discussion and a final decision will not be made until the further supporting evidence (Phase 3 and Phase 4) is available for consideration.
- It was noted that some members of EWG view this matter as having been considered fully already, and that further consultation would result in unnecessary delays. Scottish Government representatives reiterated that this work continues to add to the ongoing consideration of this matter.

EWG Members Poll on Phase 3 and Phase 4

A virtual poll was conducted to determine whether EWG members saw value in proceeding to Phases 3 and 4 of this work. This poll covered the 25 EWG members who were able to participate, of whom 24 agreed to proceeding, with one member abstaining.

Only those participating online using WebEx were able to cast a vote; the 5 members dialling into the meeting were unable to participate. These results therefore do not represent the views of the full EWG, though Scottish Government officials have welcomed further views to be shared post-meeting by those unable to fully participate.

Agreed Actions

- Scottish Government to share presentation slides from Xi Engineering
- Scottish Government to send on EKA audit sheet
- EWG members to complete and return EKA audit sheet for **all** relevant sites by 14 August 2020. EWG also to indicate whether they would allow site access for future measurements
- Community Wind Power to share their research relevant to this technical work, including their planning constraints map, when it becomes available
- Scottish Government to consider a timeline and subgroup for phases 3 and 4 and provide an outline of this to EWG in due course
- Scottish Government to consider an suggest a suitable date for EWG to meet again, before the end of 2020
- EWG to suggest agenda points they wish to be included in this further meeting
- Scottish Government to follow up with RUK to consider constraints and realistic planning factors

Eskdalemuir Wind Turbine Seismic Vibration

Assessment of Headroom

Presented to The Scottish Government

Issue Date: 24/02/2020

Document No: SGV_201_Tech_Report_v04

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

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

Matters relating to this document should be directed to:

Brett Marmo — E: brettmarmo@xiengineering.com
Technical Director — T: 0131 290 2249

Mark-Paul Buckingham — E: mp@xiengineering.com
Managing Director — T: 0131 290 2257
M: 07747 038 764

Principal contacts at client's organisation

Temeeka Linton — E: temeeka.linton@gov.scot
Onshore Wind Policy Manager — T: 0300 244 1243 (ext. 41243)

Lesley McNeil — E: Lesley.McNeil@gov.scot
Head of Wind Energy Policy and Development — T: 0300 244 1243(ext. 41243)
M: 07973 879888

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).

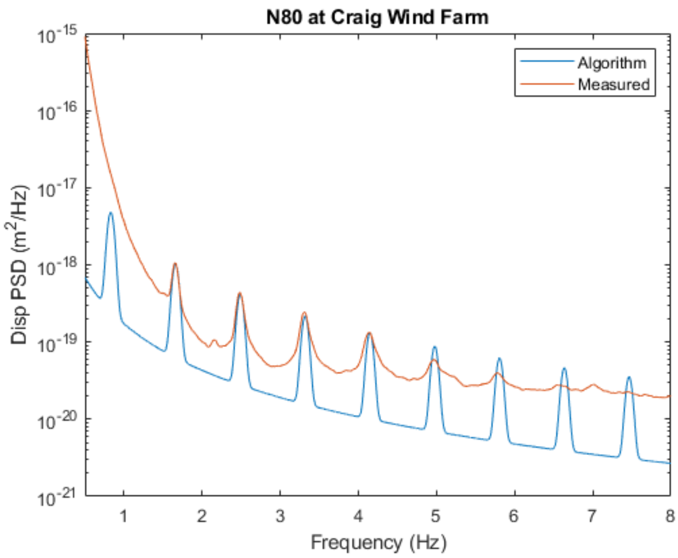


Figure 1 – Algorithm fitted to blade-pass dominated spectra measured at Craig wind farm. Please note the noise floor (level of troughs between peaks) was not fitted to Craig data in the 2014 Report, but rather the Clyde data set.

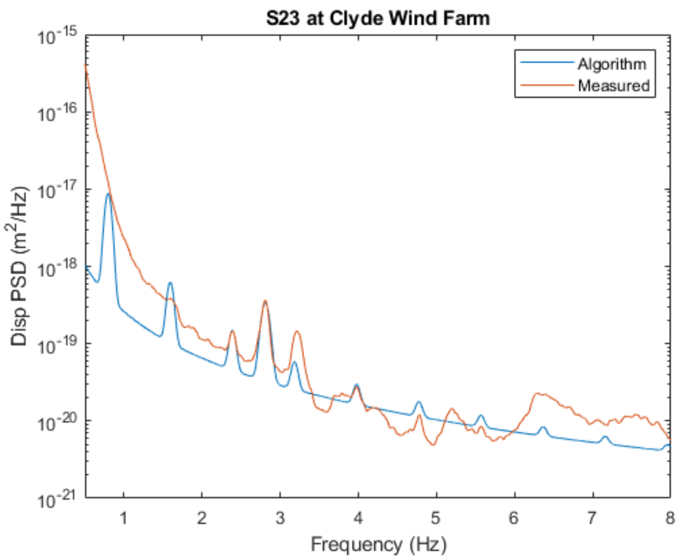


Figure 2 Algorithm fitted to structural resonance dominated spectra measured at Clyde wind farm.

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.

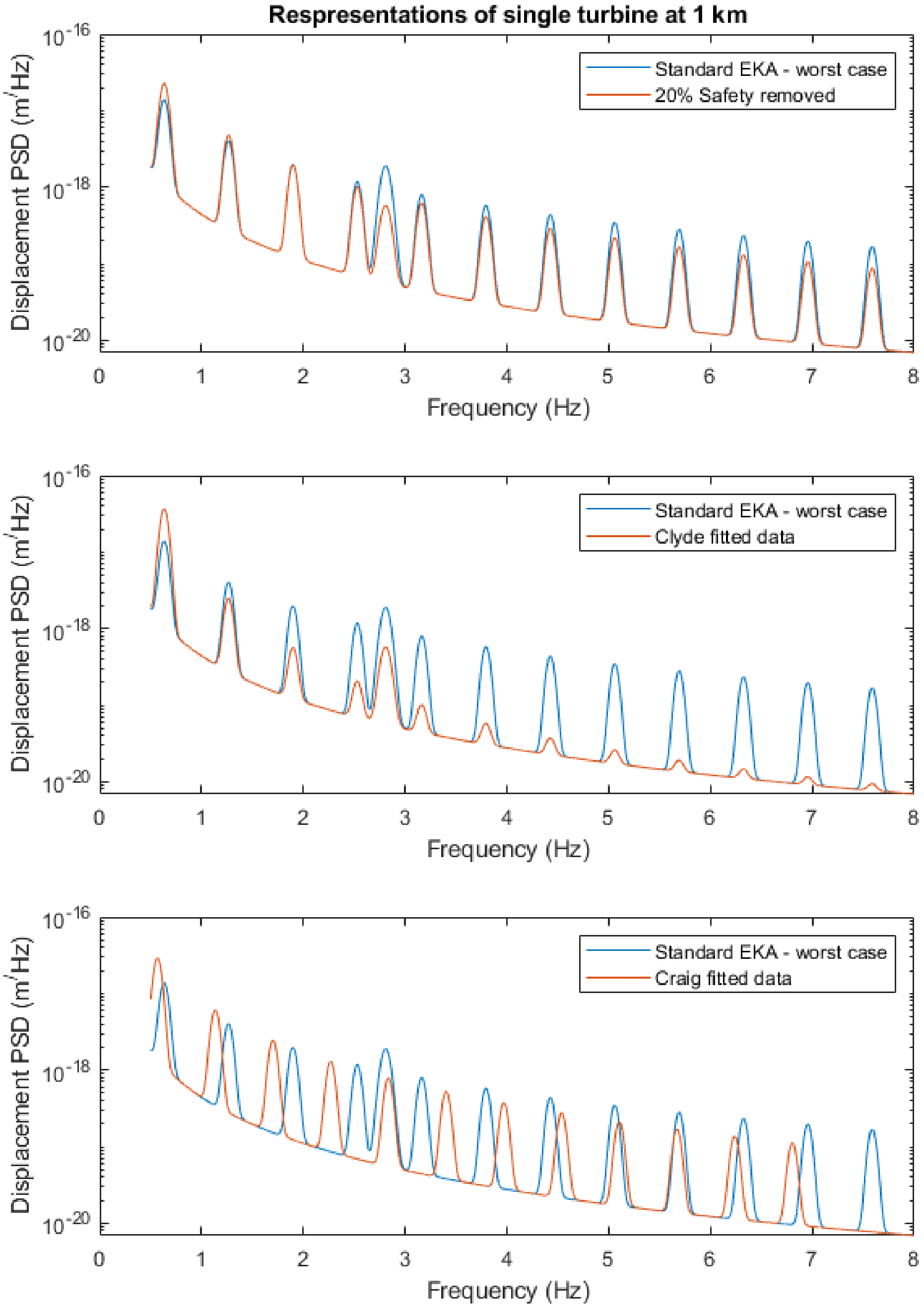


Figure 3 – Comparison of the spectra for the four different ways to represent the seismic output of turbines when applied to a turbine with rotor diameter of 93.5 m and a hub height of 117 m.

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

Issue Date: 23/07/2020
Document No: SGV_202_Tech_Report_v07

COMSOL Certified Consultant
renewableUK Company Member
PRINCE2 PRACTITIONER
bsi. ISO 9001 Quality Management
UVDB empowered by Achilles Registered
The Scottish Green Energy Awards Winner

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

Xi

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

Matters relating to this document should be directed to:

Brett Marmo — E: brettmarmo@xiengineering.com
Technical Director — T: 0131 290 2249

Mark-Paul Buckingham — E: mp@xiengineering.com
Managing Director — T: 0131 290 2257
M: 07747 038 764

Principal contacts at client's organisation

Temeeka Linton — E: temeeka.linton@gov.scot
Onshore Wind Policy Manager — T: 0300 244 1243 (ext. 41243)

Lesley McNeil — E: Lesley.McNeil@gov.scot
Head of Wind Energy Policy and Development — T: 0300 244 1243(ext. 41243)
M: 07973 879888

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.

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 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).

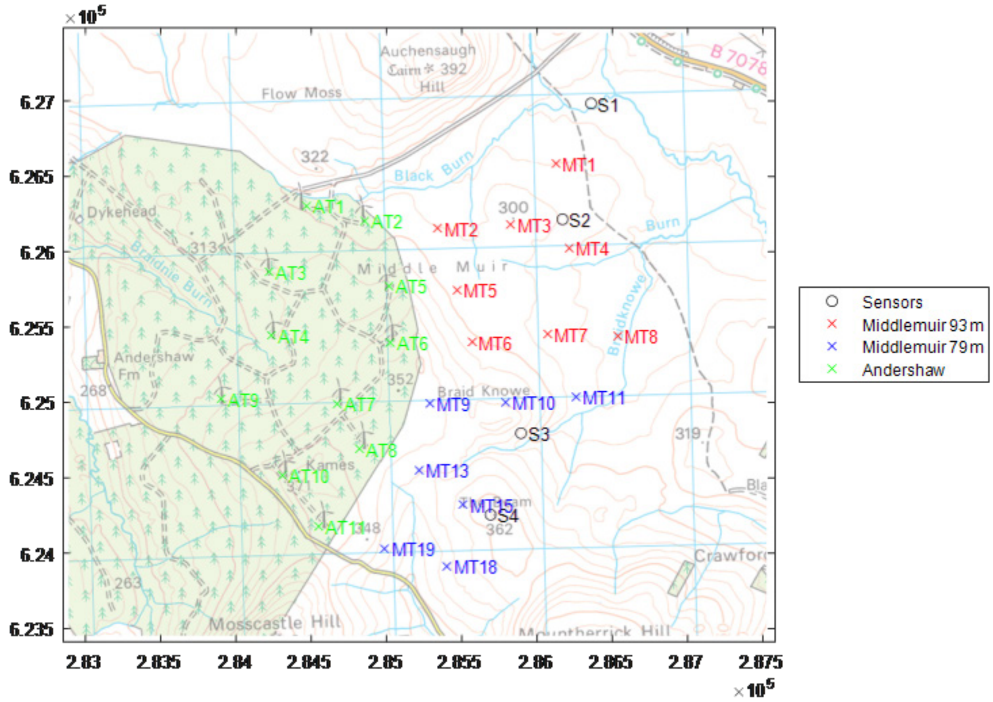


Figure 1 – Location map of seismic sensors and the wind turbines in the Middle Muir and Andershaw wind farms. The different hub heights of the Middle Muir turbines are also shown.

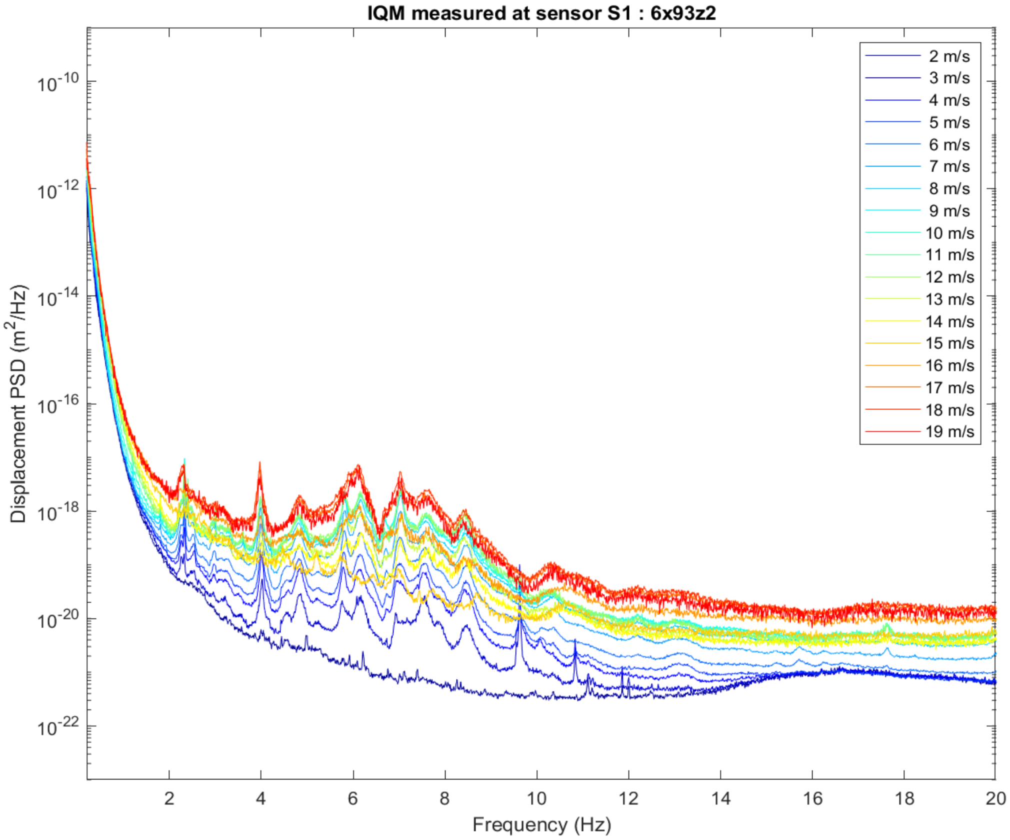


Figure 2 - Frequency spectra recorded by S1 with respect to different wind speeds on the range from 1 to 19 m/s.

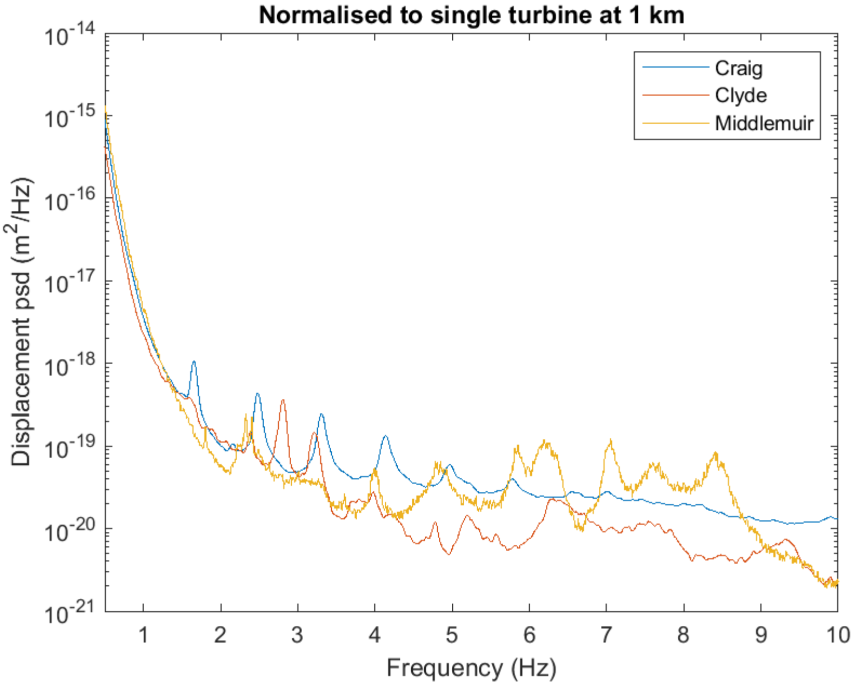


Figure 3 - Comparison of a Senvion turbine at Middle Muir normalised to 1km compared to Siemens S2.3 at Clyde and Nordex N80 at Craig.

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.

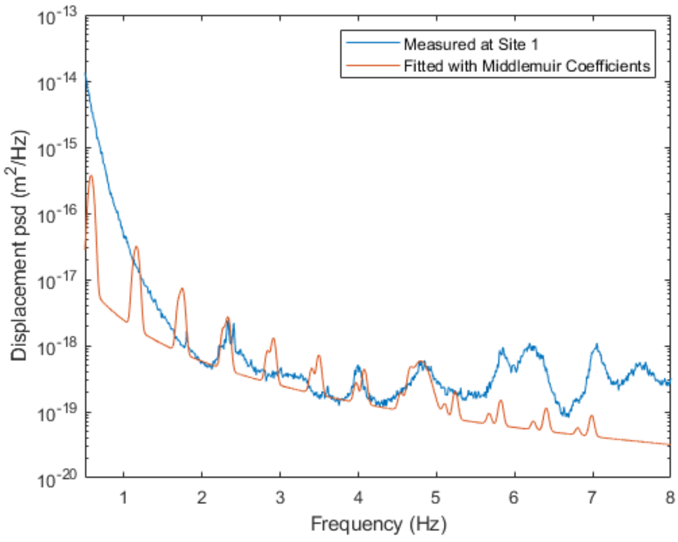


Figure 4 – Comparison of measured spectra at Middle Muir to algorithm with fitted coefficients

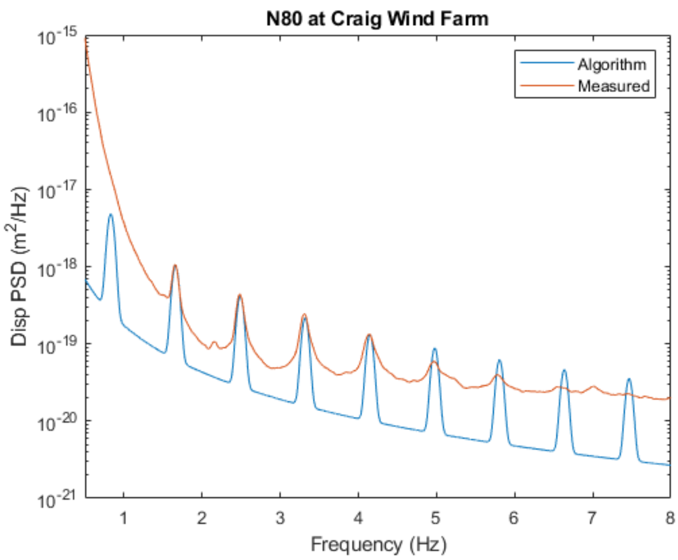


Figure 5 – Algorithm fitted to blade-pass dominated spectra measured at Craig wind farm. Please note the noise floor (level of troughs between peaks) was not fitted to Craig data in the 2014 Report, but rather the Clyde data set.

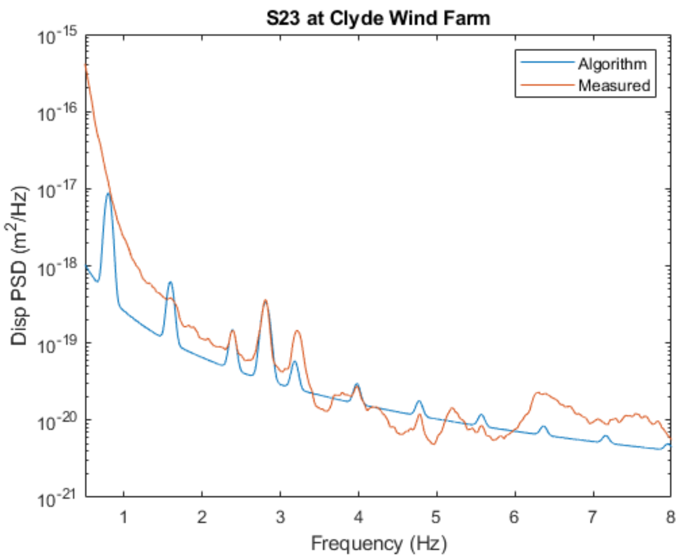


Figure 6 Algorithm fitted to structural resonance dominated spectra measured at Clyde wind farm.

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.

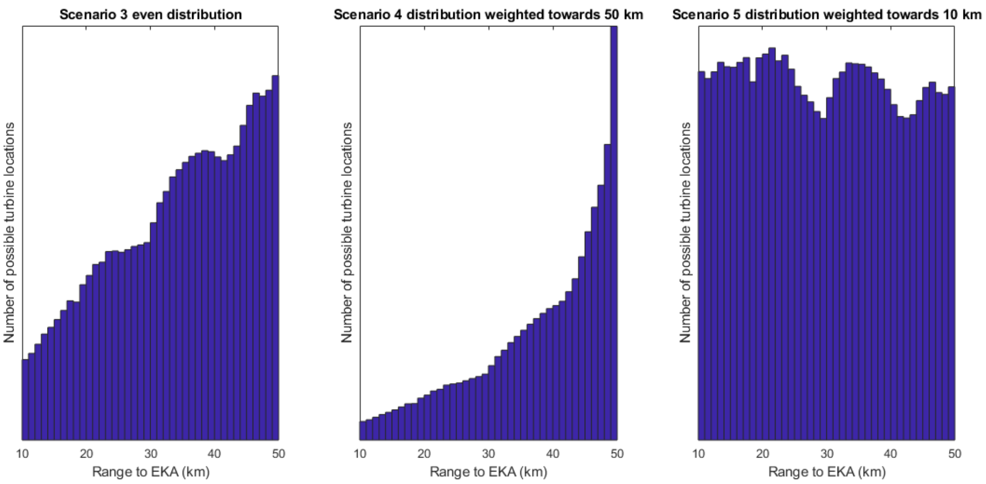


Figure 8 – Distribution of wind turbine additions for the three different scenarios; even; weighted towards 50 km; weighted towards 10 km. In each iteration of the simulation the turbines range is random and the simulation continuous until the budget threshold is breached. Therefore, number of turbines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

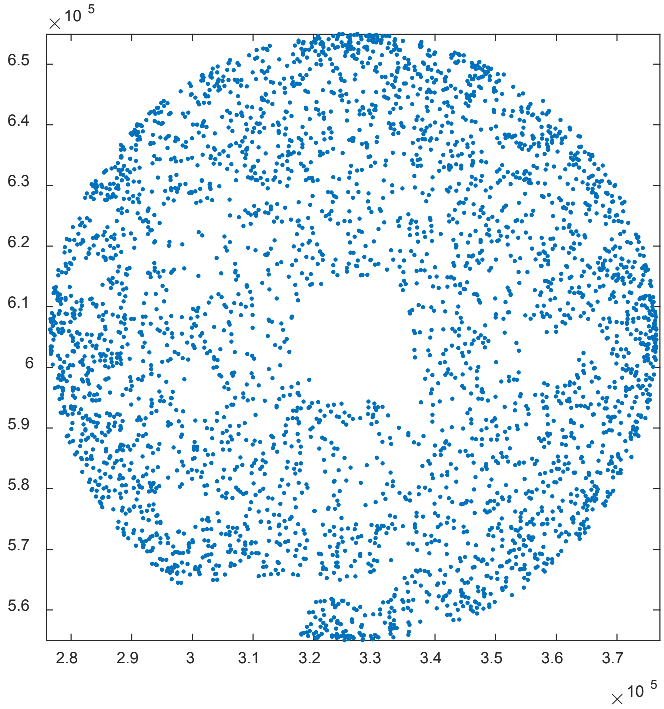


Figure 9 Location map of turbines distributed under scenario 4 – distribution weighted towards 50km

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.

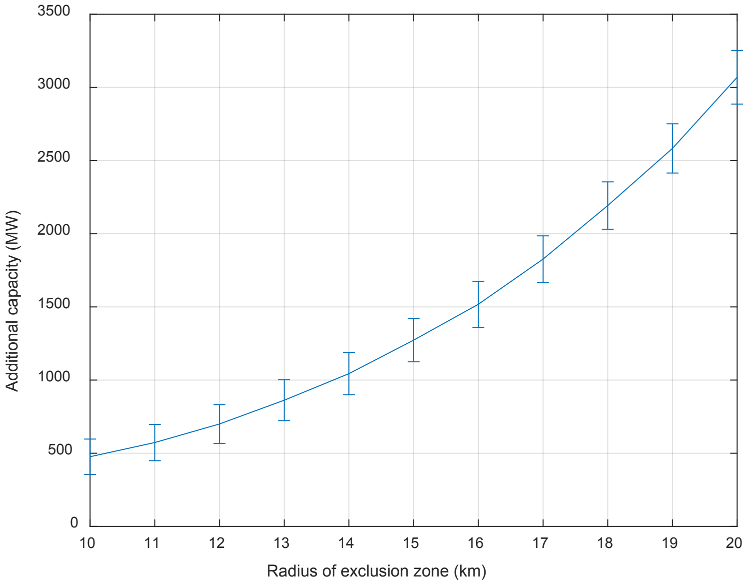


Figure 10 – Variation in additional capacity with the size of the exclusion zone based on Middle Muir measurements being representative and the consumable head room being 0.097 nm. An even distribution in the remaining consultation zone was assumed with some regions excluded due to cultural or geographic 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.

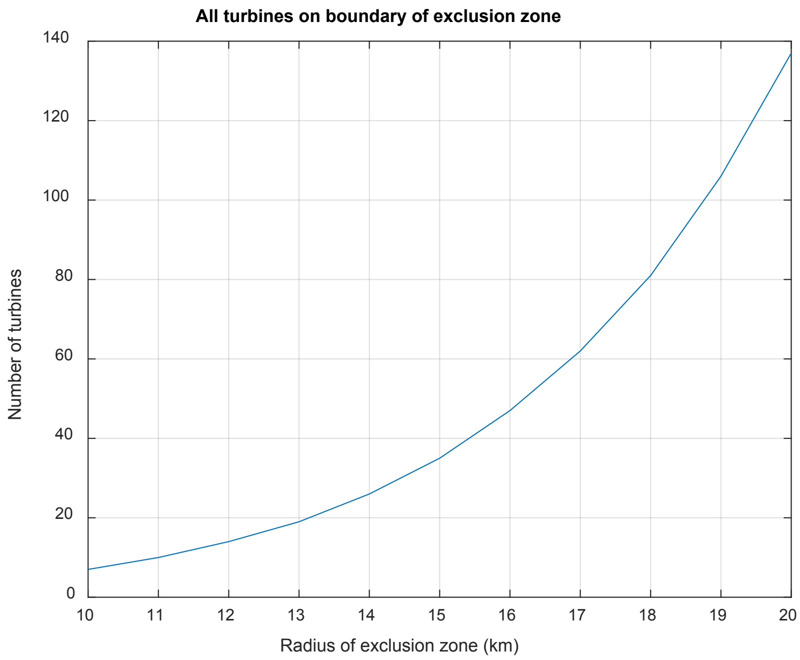


Figure 11 – Number of turbines that can be placed on the exclusion zones with different radii without breaching the budget threshold based on Middle Muir results.

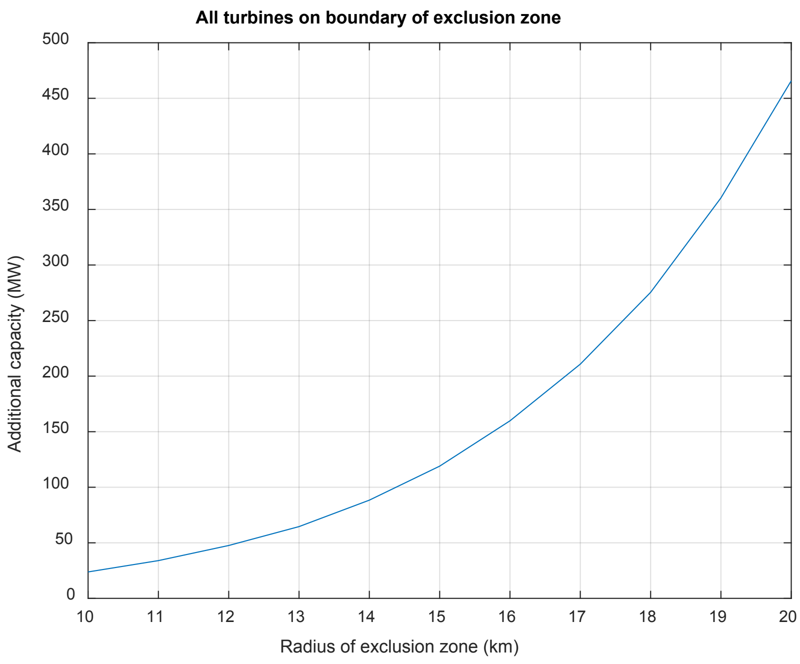


Figure 12 – Additional capacity related to 3.4 MW turbines placed on the exclusion zones with different radii without breaching the budget threshold based on Middle Muir results.

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

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).

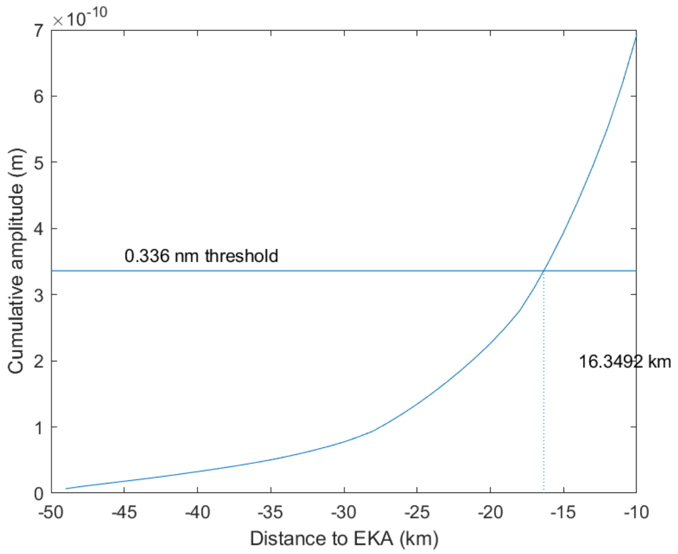


Figure 13 – Scenario 1 population from the outside towards the inside using the Standard EKA algorithm reaches the threshold at 16.35 km

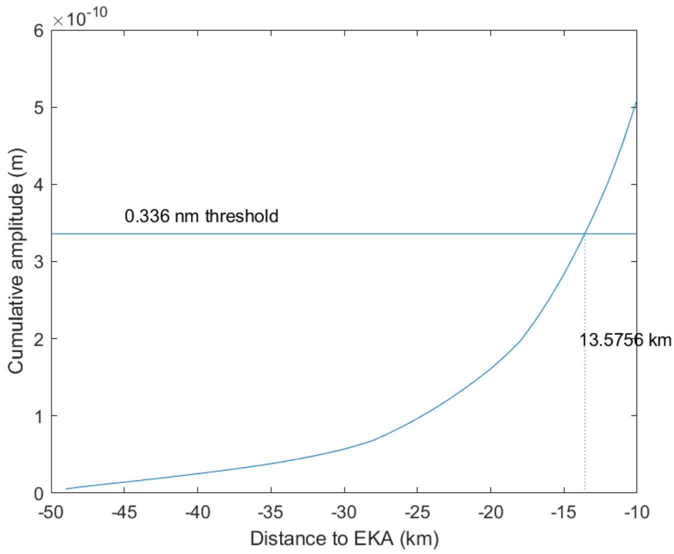


Figure 14 – Scenario 1 population from the outside towards the inside using the algorithm based on Middle Muir reaches the threshold at 13.58 km

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

Xi

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.

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

Xi Engineering Consultants, CodeBase, Argyle House, 3 Lady Lawson Street, Edinburgh, EH3 9DR, United Kingdom
T +44 (0)131 290 2250 **E** enquiries@xiengineering.com **xiengineering.com**
Registered address: Xi Engineering Consultants Ltd, 5th Floor, 125 Princes Street, Edinburgh, EH2 4AD, Company no. SC386913

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

Matters relating to this document should be directed to:

Donald Black — E: donaldblack@xiengineering.com

Senior Project Engineer — T: 0131 290 2253

Dr Brett Marmo — E: brettmarmo@xiengineering.com

Technical Director — T: 01312902249

Principal contacts at client's organisation

Temeeka Linton — E: temeeka.linton@gov.scot

Onshore Wind Policy Manager — T: 0300 244 1243 (ext. 41243)

Lesley McNeil — E: Lesley.McNeil@gov.scot

Head of Wind Energy Policy and Development — T: 0300 244 1243(ext. 41243)

M: 07973 879888

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.

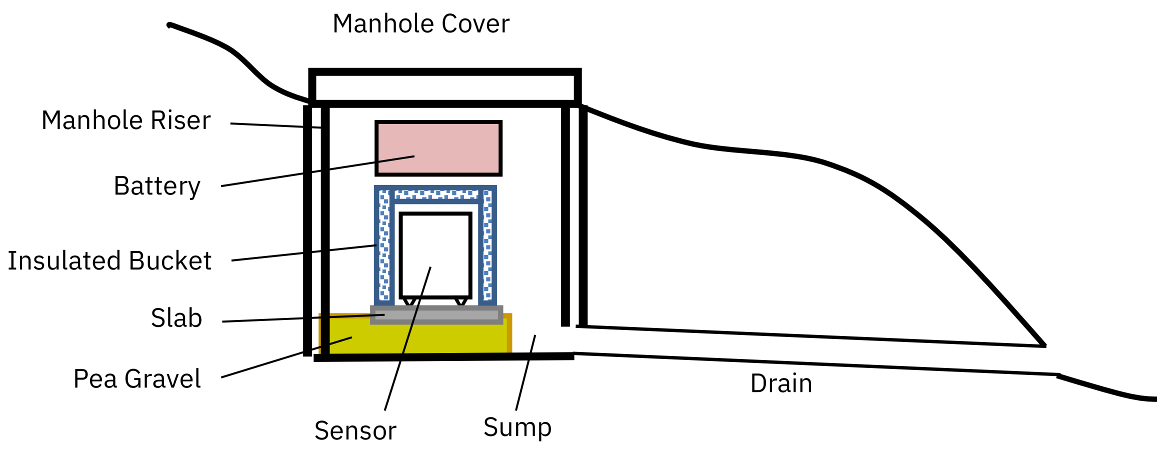


Figure 16: Typical Seismometer Pit Deployment

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.

Xi

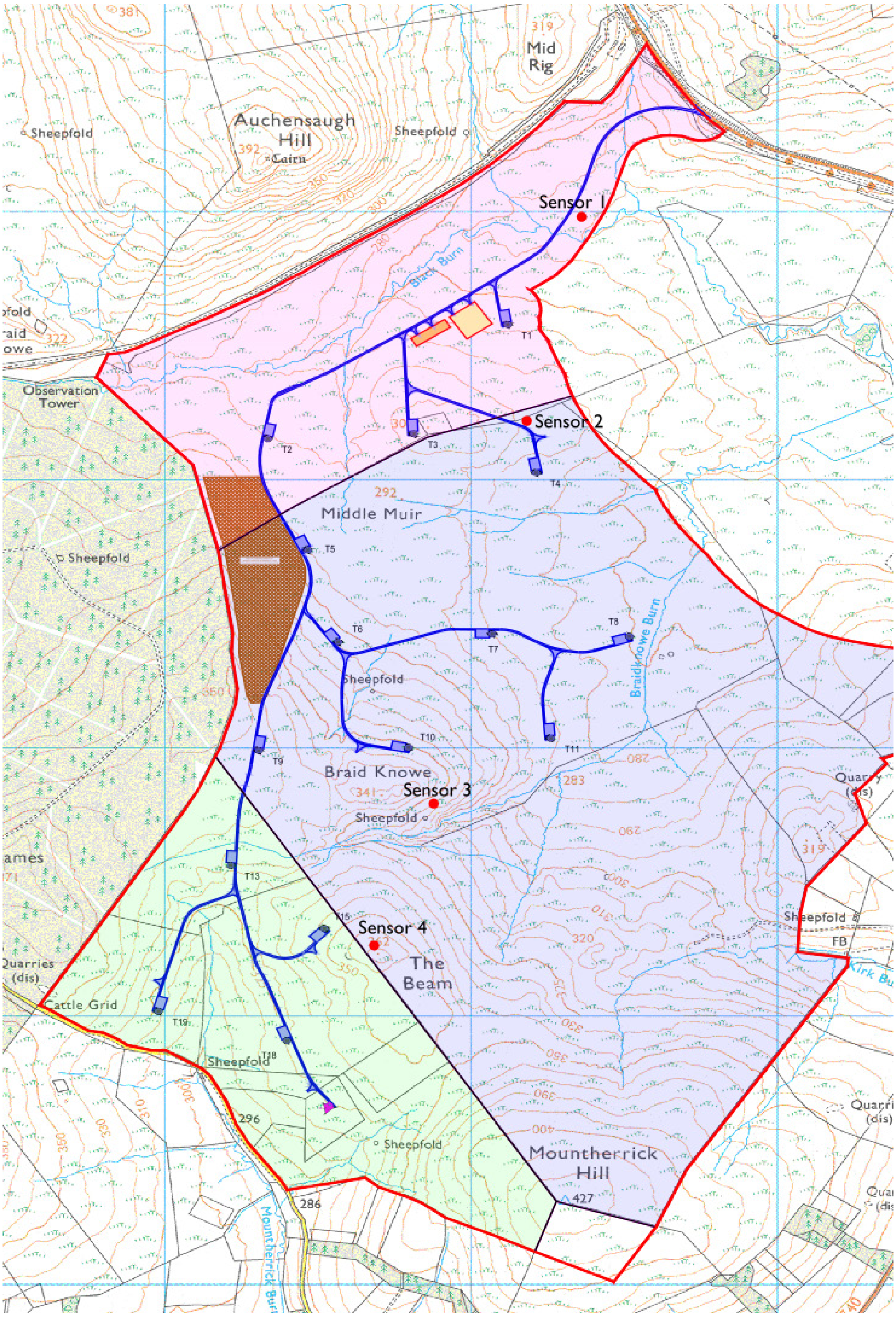


Figure 18 – Location of seismic sensors at the Middle Muir site

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

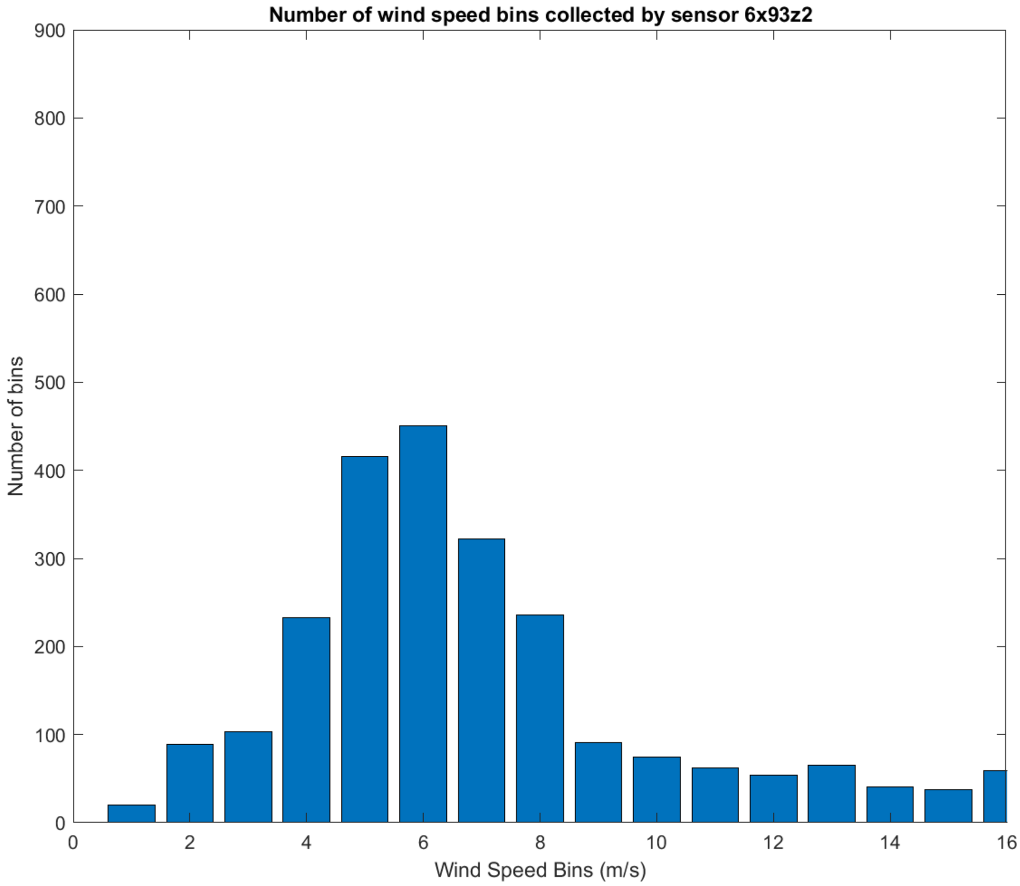


Figure 19: Wind speed bins distribution for S1.

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.

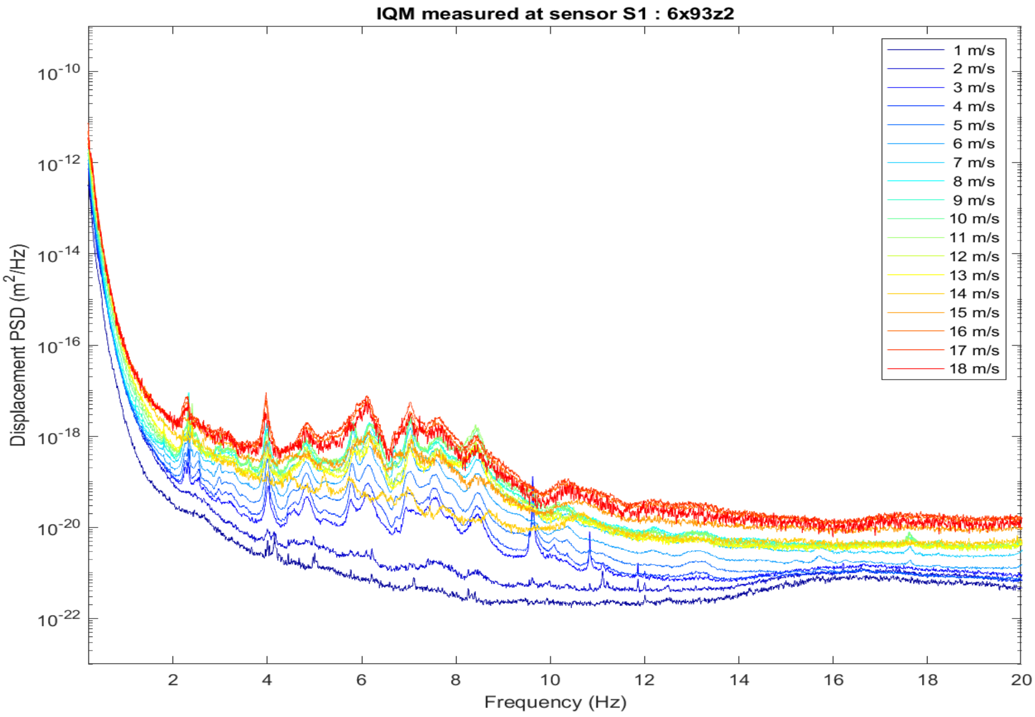


Figure 20: Frequency spectra recorded by S1 with respect to different wind speeds on the range from 1 to 18 m/s.

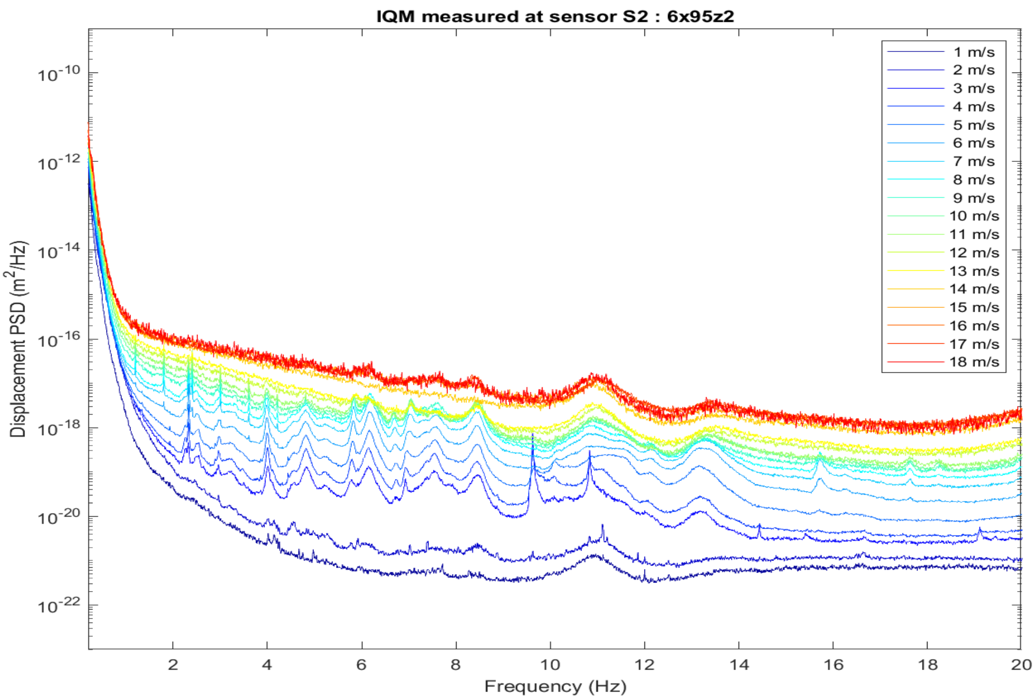


Figure 21: Frequency spectra recorded by S2 with respect to different wind speeds on the range from 1 to 18 m/s.

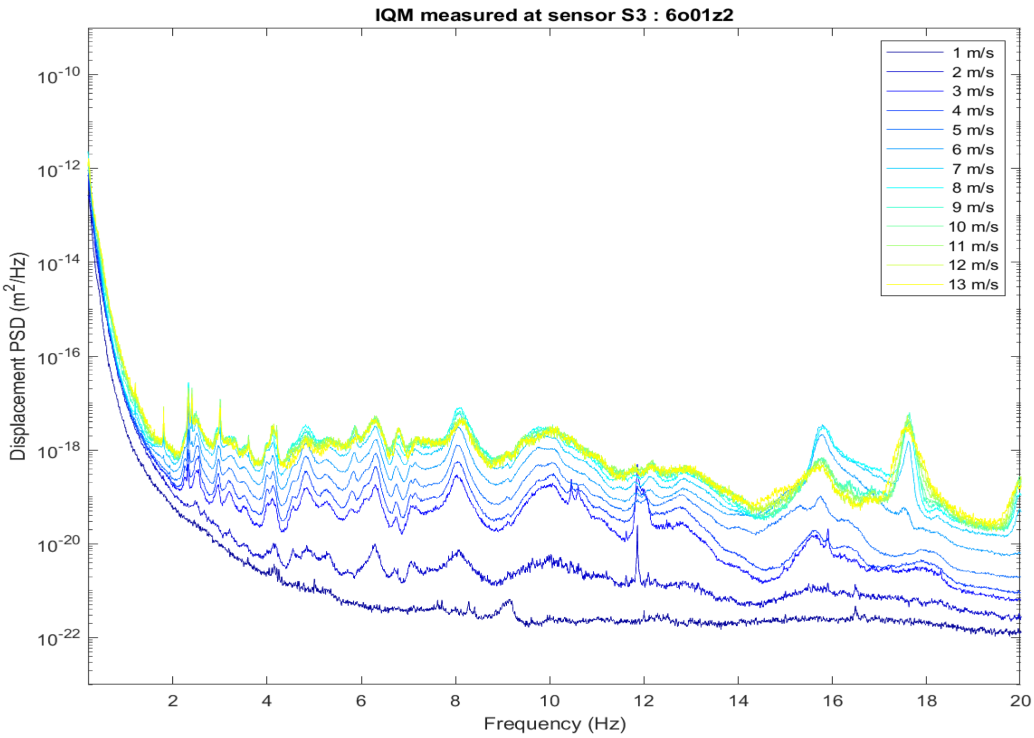


Figure 22: Frequency spectra recorded by S3 with respect to different wind speeds on the range from 1 to 13 m/s.

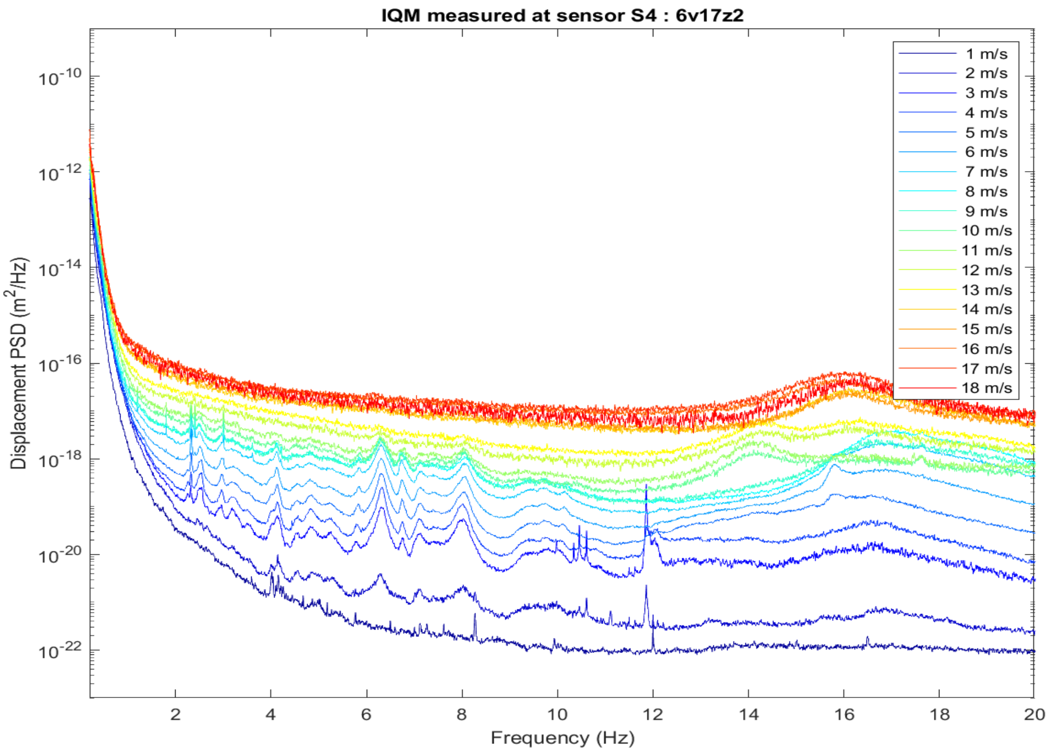


Figure 23: Frequency spectra recorded by S4 with respect to different wind speeds on the range from 1 to 18 m/s.

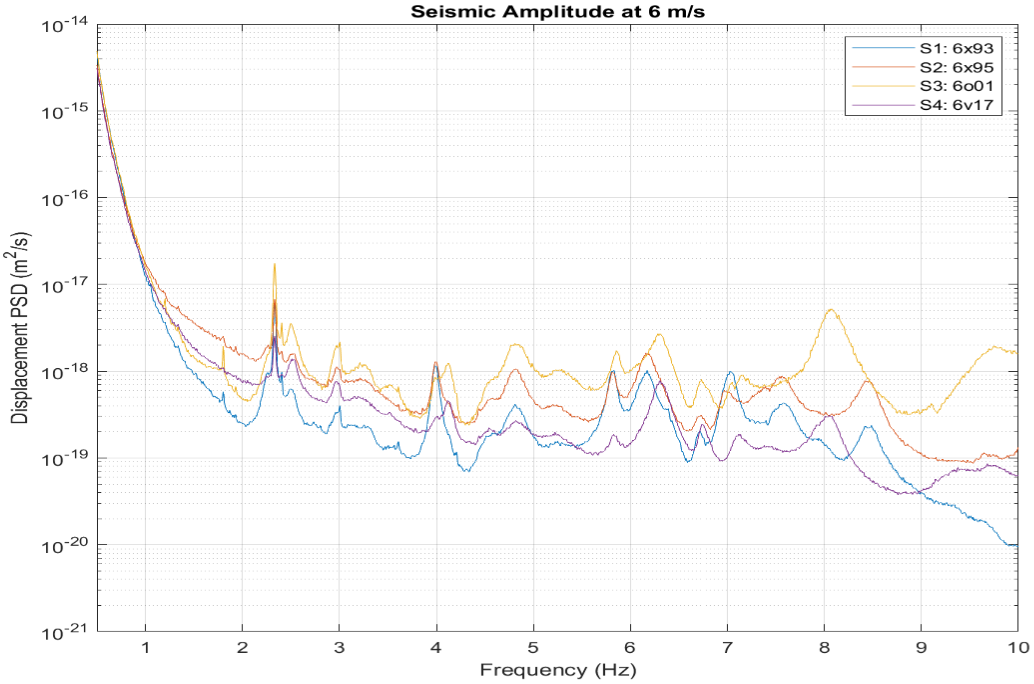


Figure 24: Comparison of signals across all four sensors at 6 m/s wind speed.

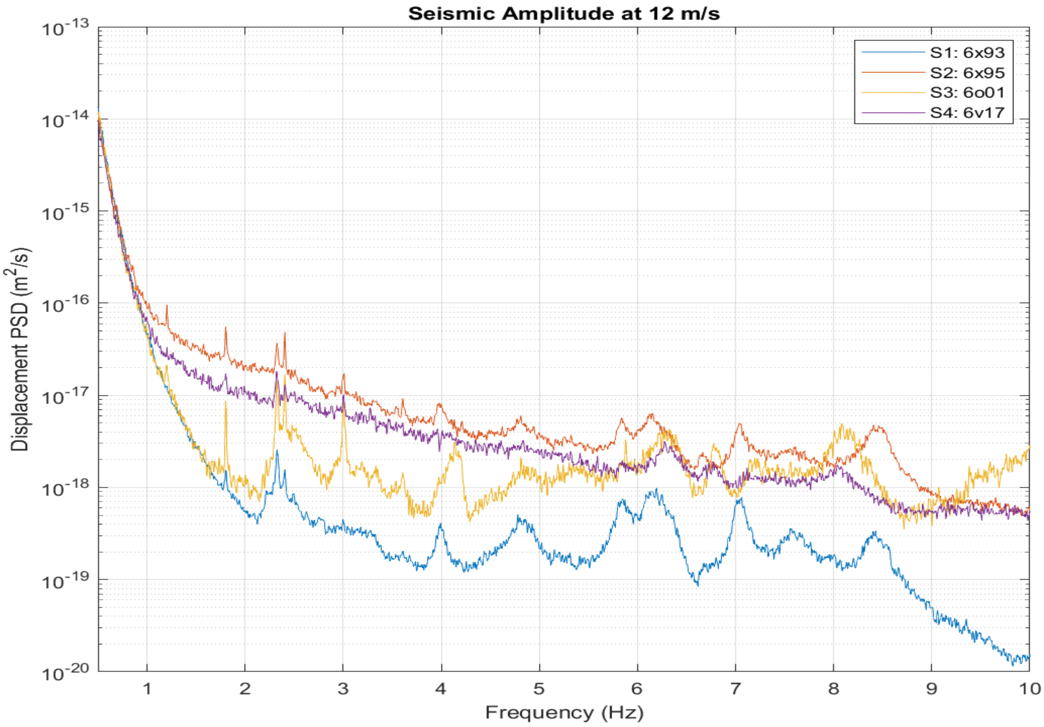


Figure 25: Comparison of signals across all four sensors at 12 m/s wind speed.

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.

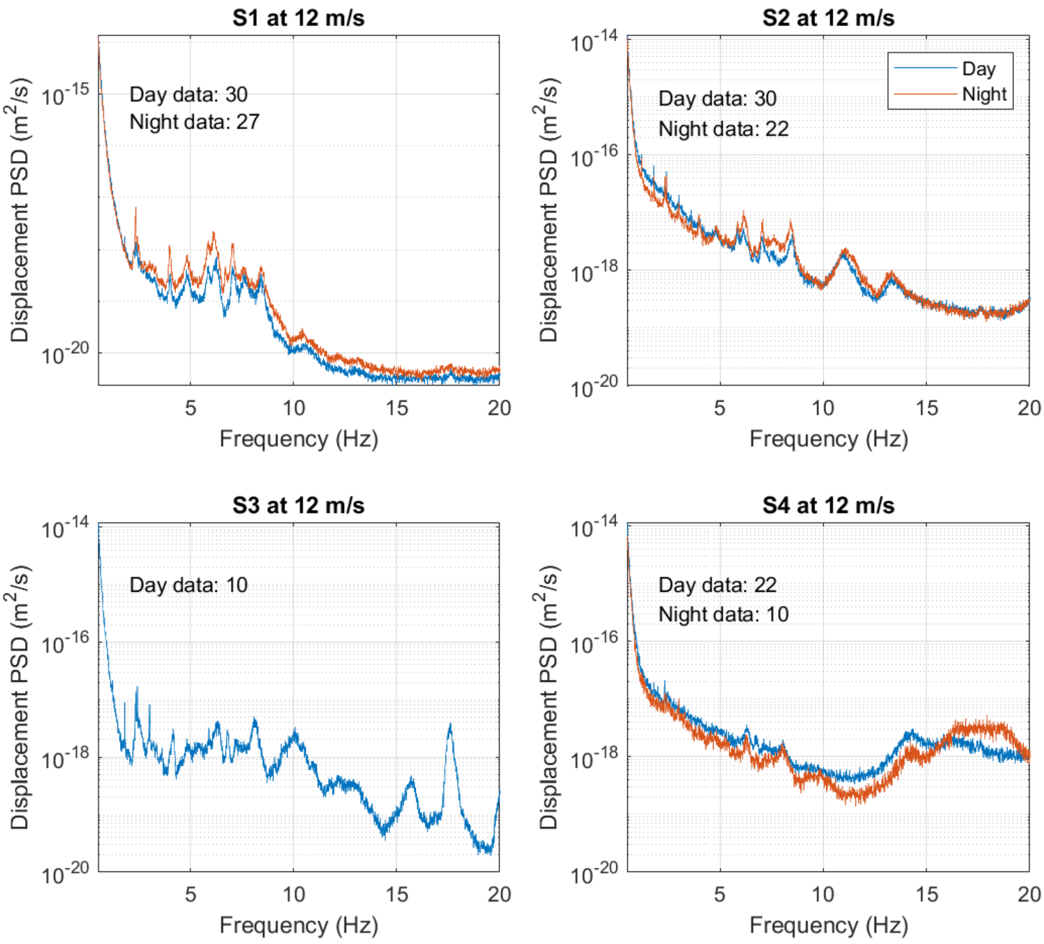


Figure 26: Diurnal variation - comparison of day and night data across all four sensors for 12 m/s wind speed.

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

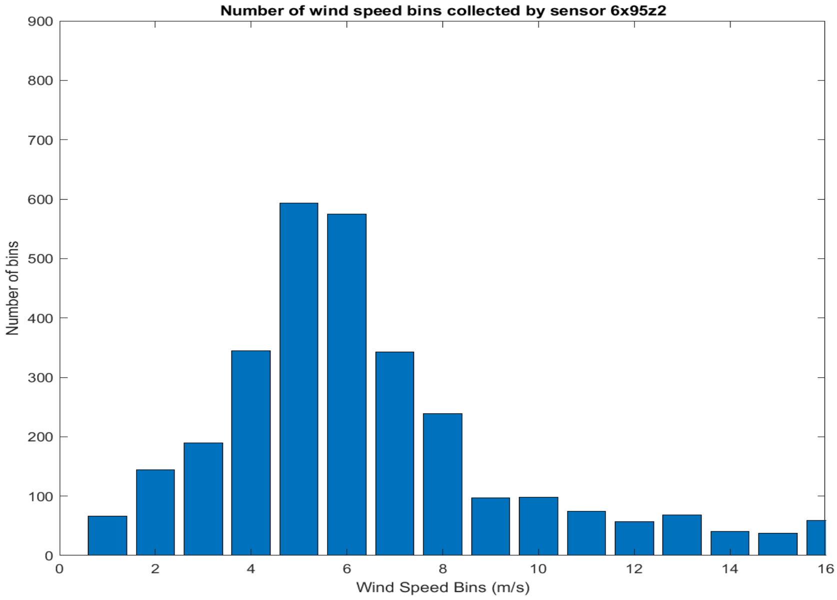


Figure 27 - Wind speed bins recorded by sensor S2: 6x95.

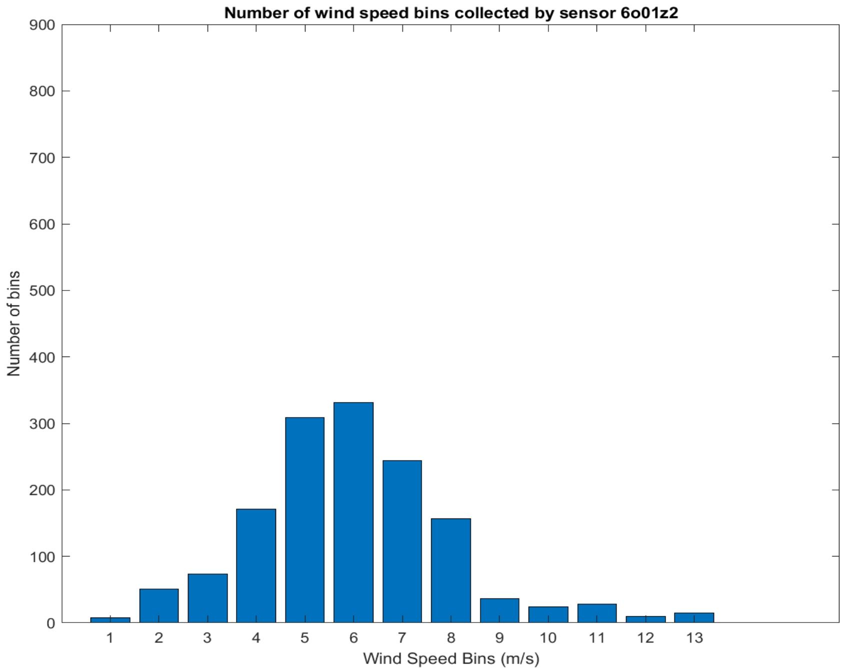


Figure 28 - Wind speed bins recorded by sensor S3: 6o01.

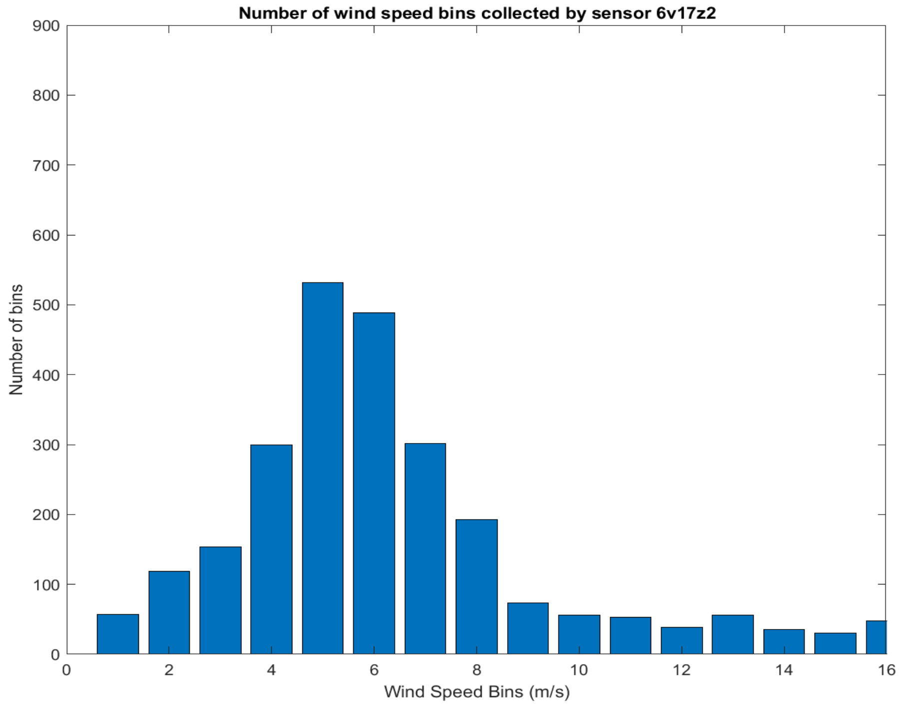
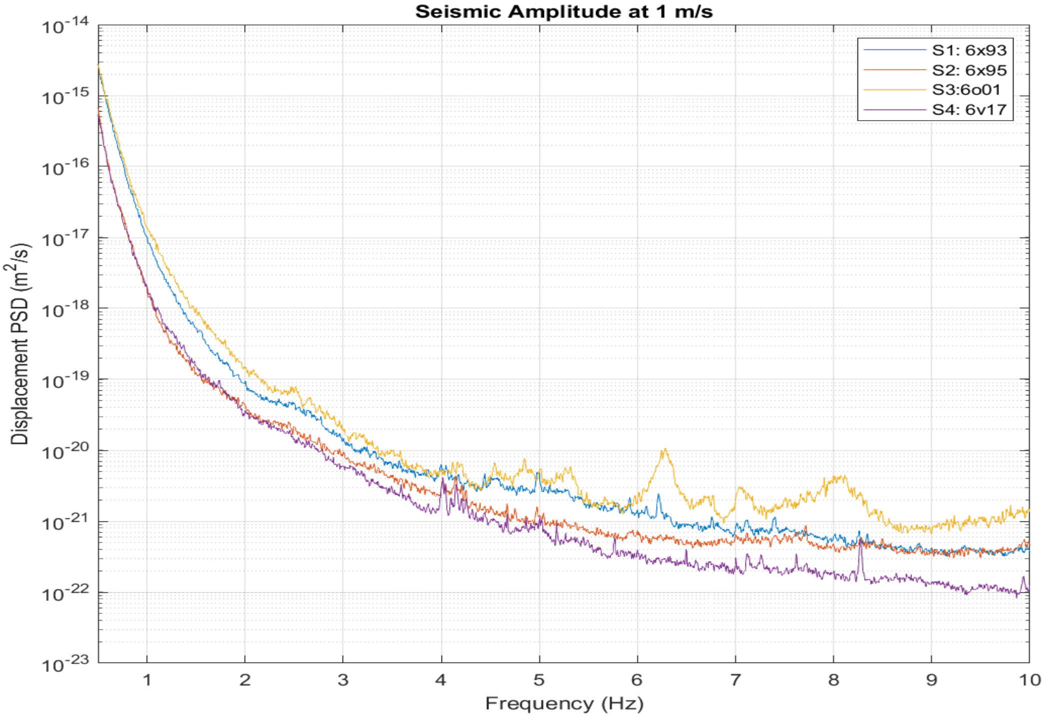
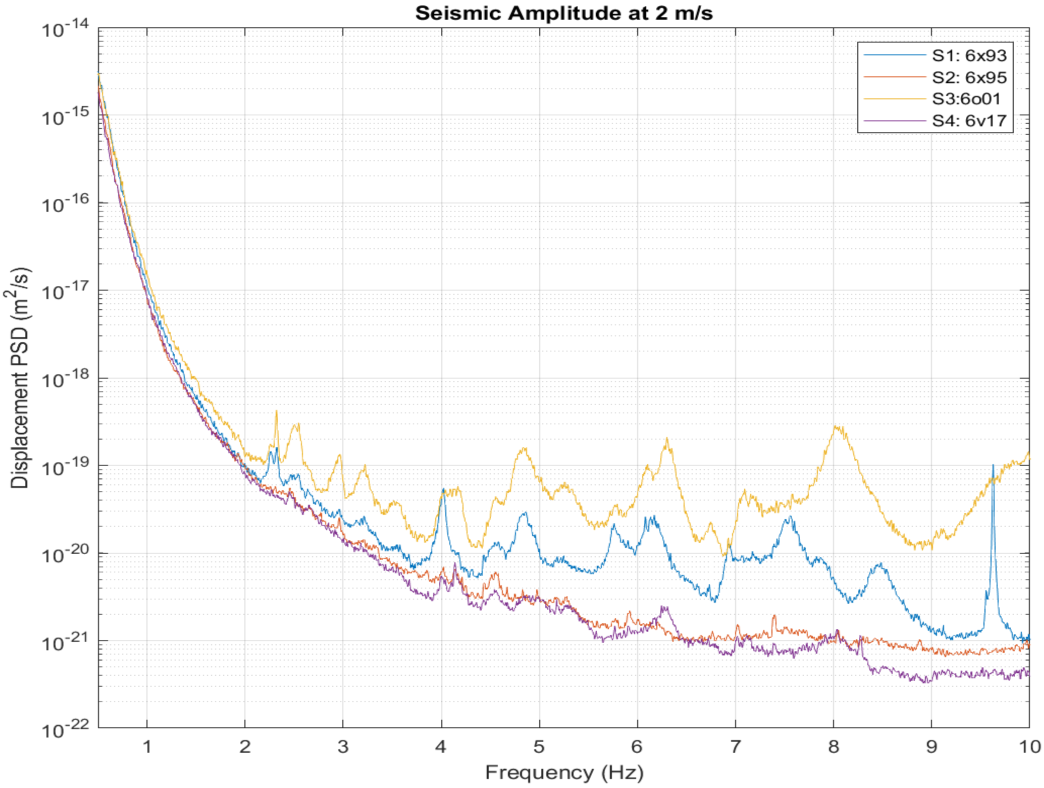
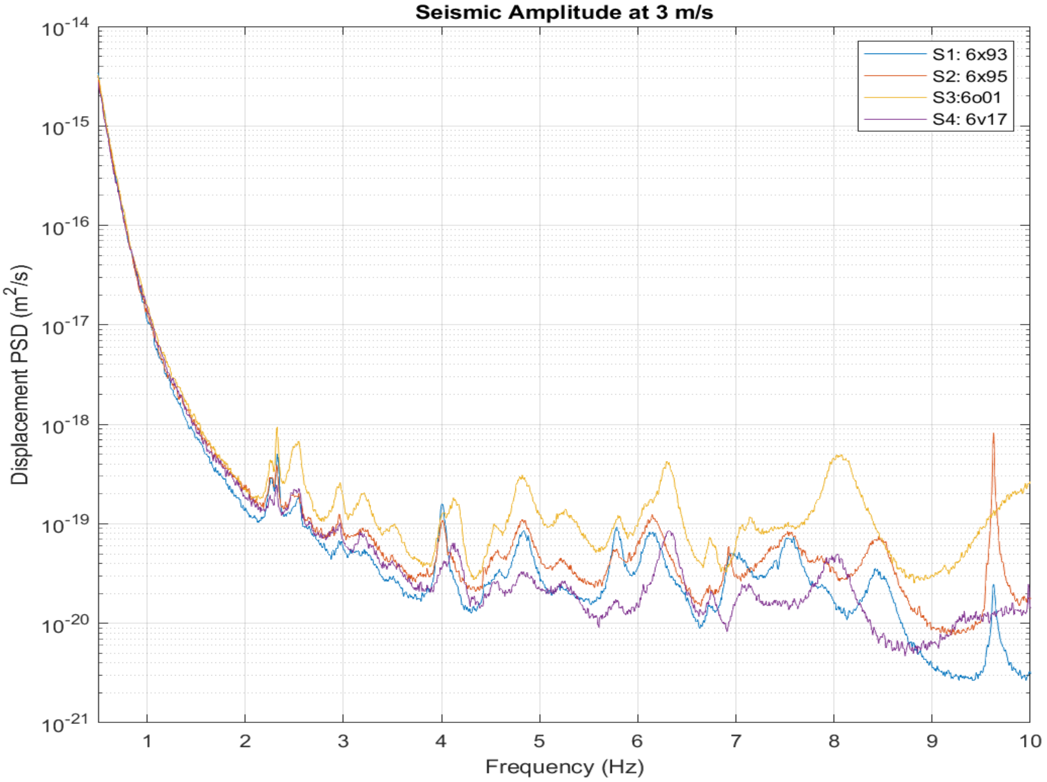


Figure 29 - Wind speed bins recorded by sensor S4: 6v17.

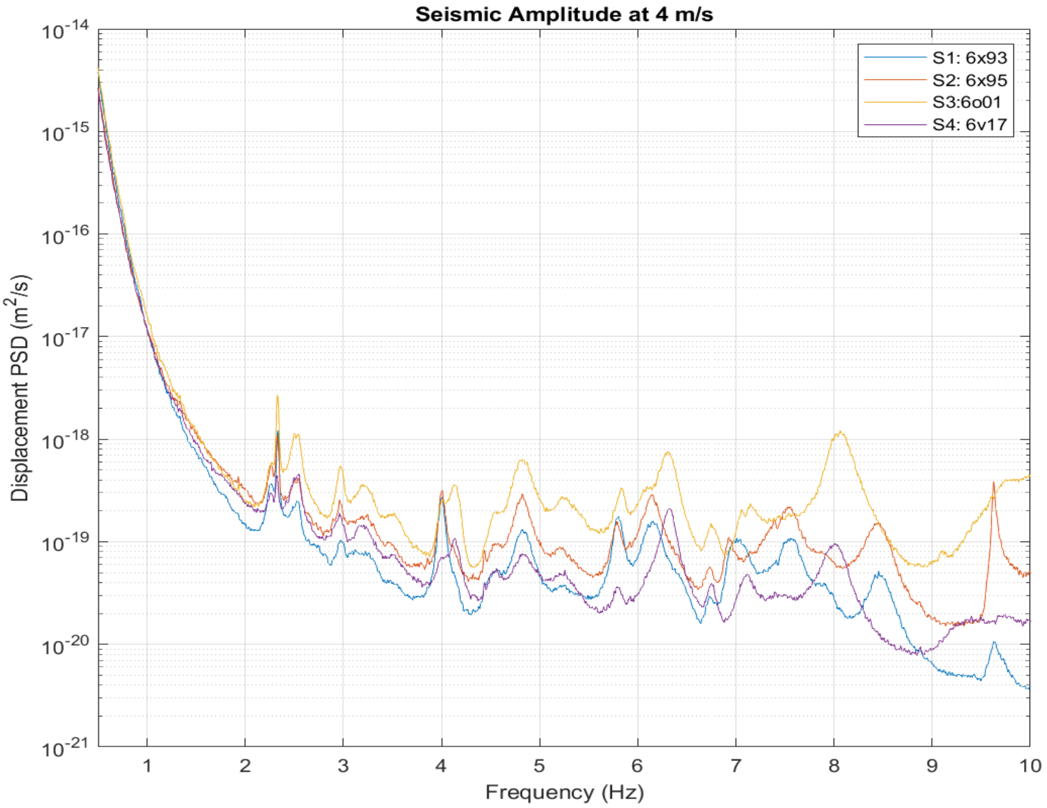
12.7 Measurement Appendix B – Frequency Spectra per Wind Speed



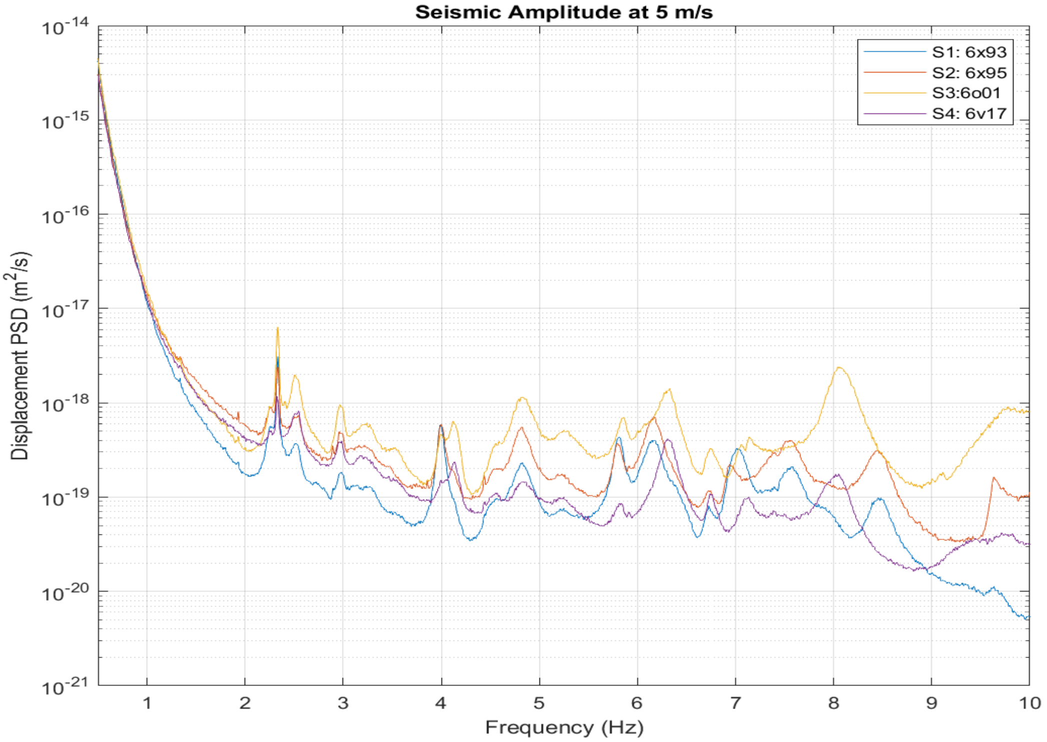


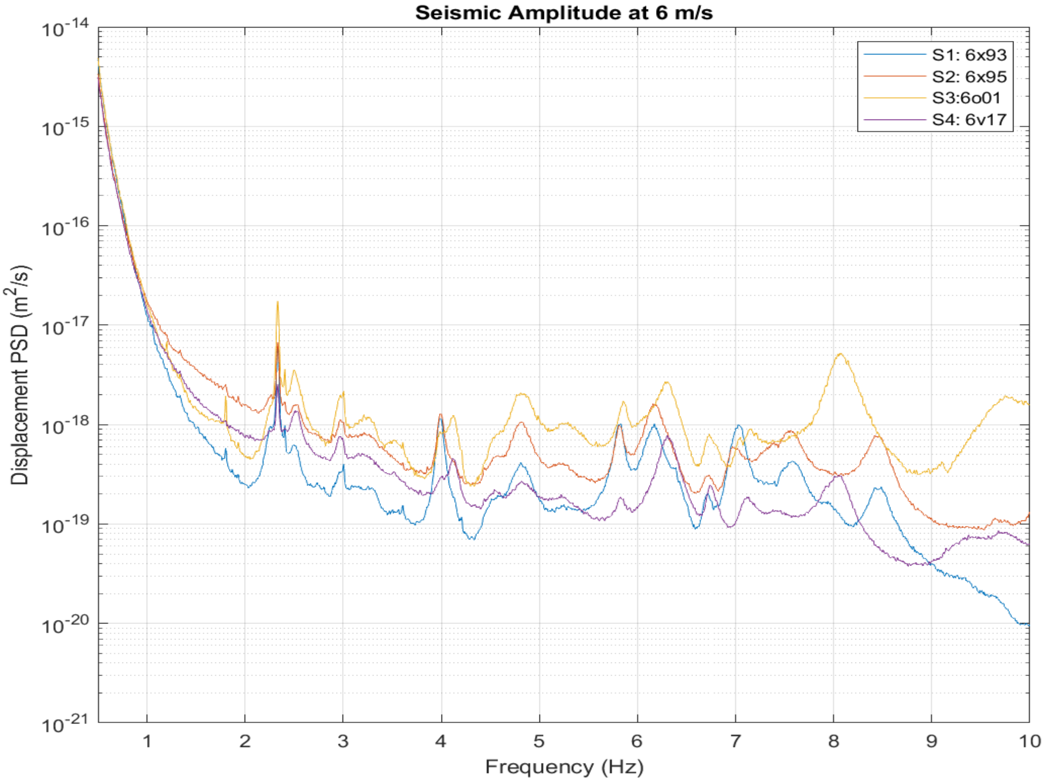


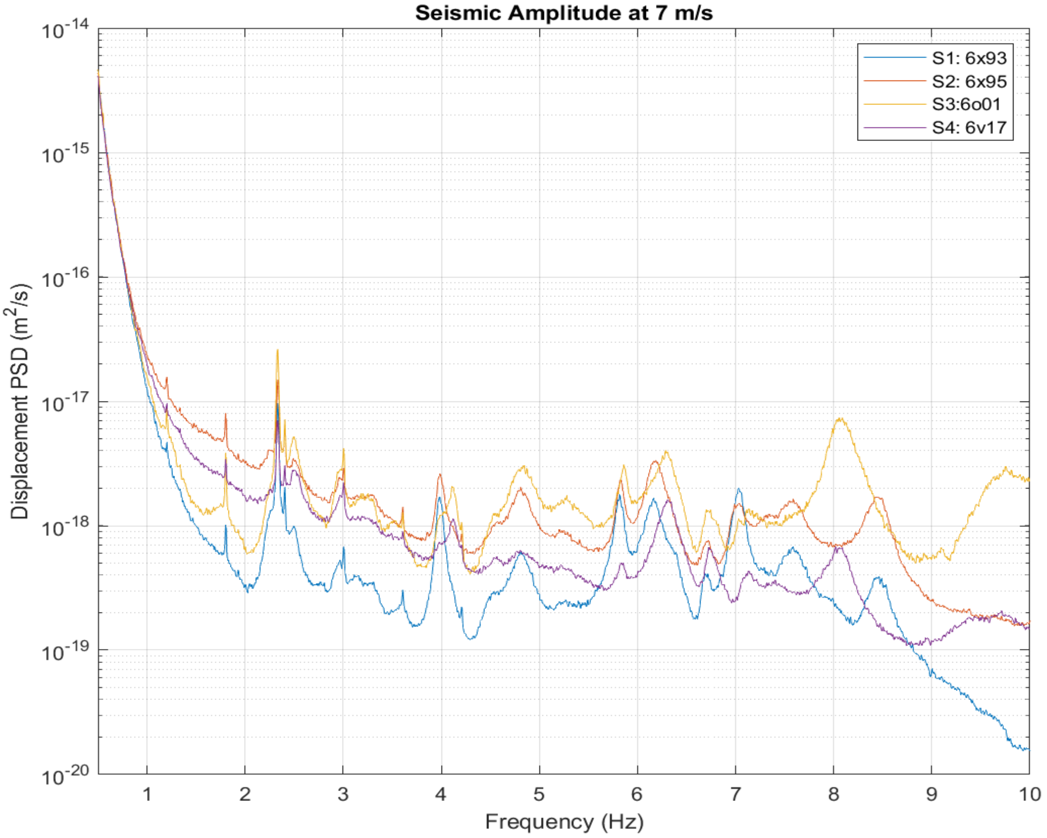
Seismic Amplitude at 3 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)



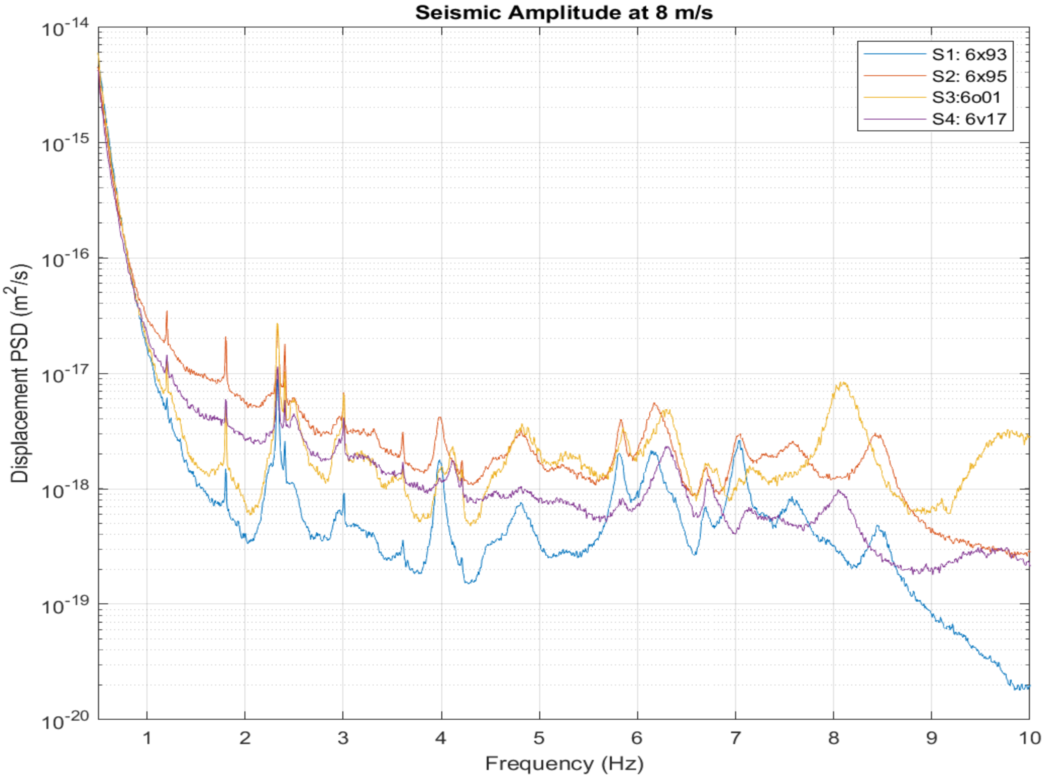
Seismic Amplitude at 4 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)


Seismic Amplitude at 5 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)

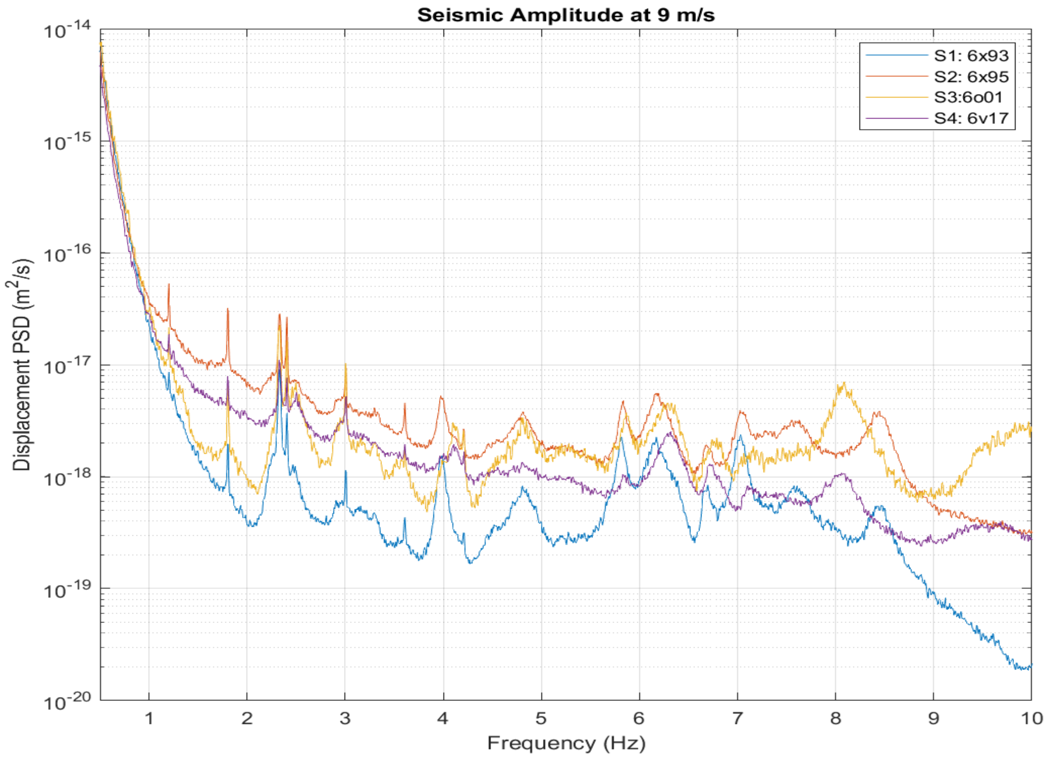

Seismic Amplitude at 6 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)

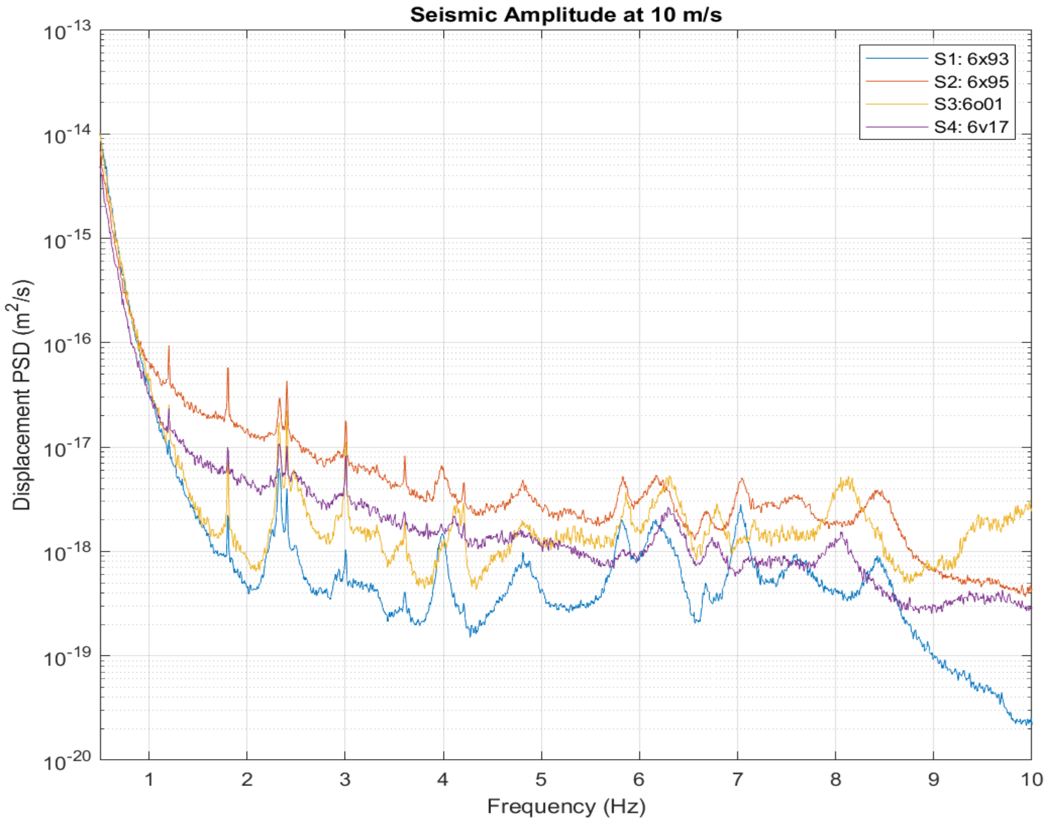


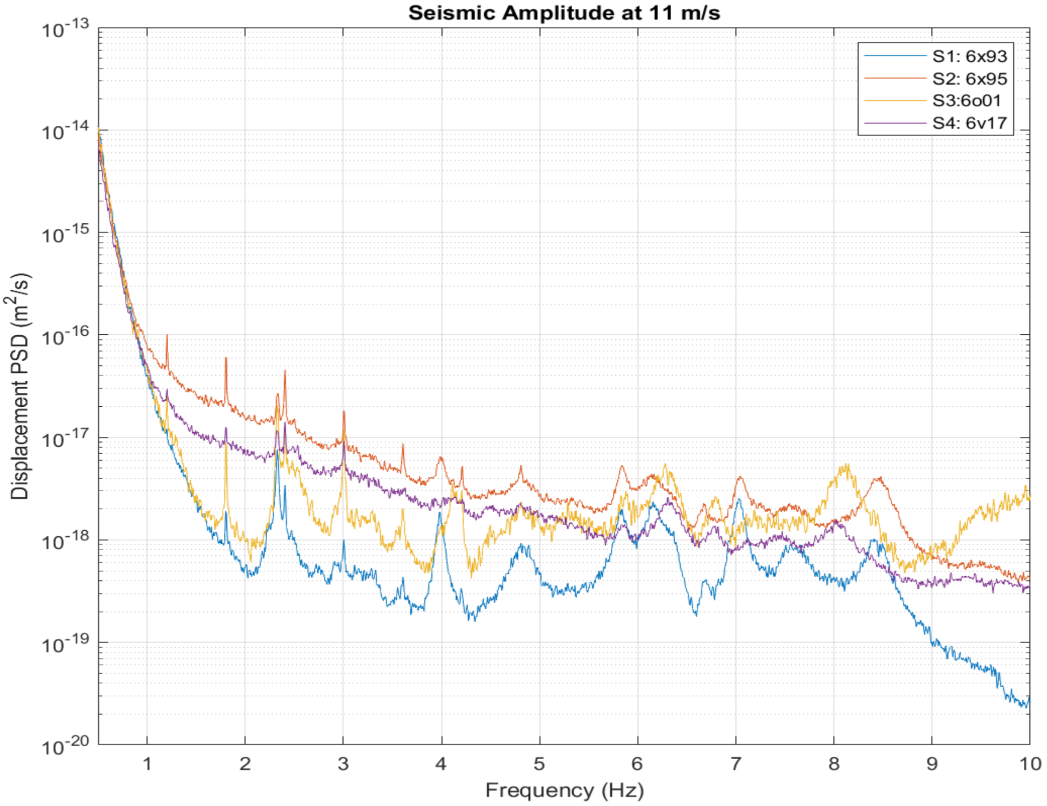
Seismic Amplitude at 7 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)

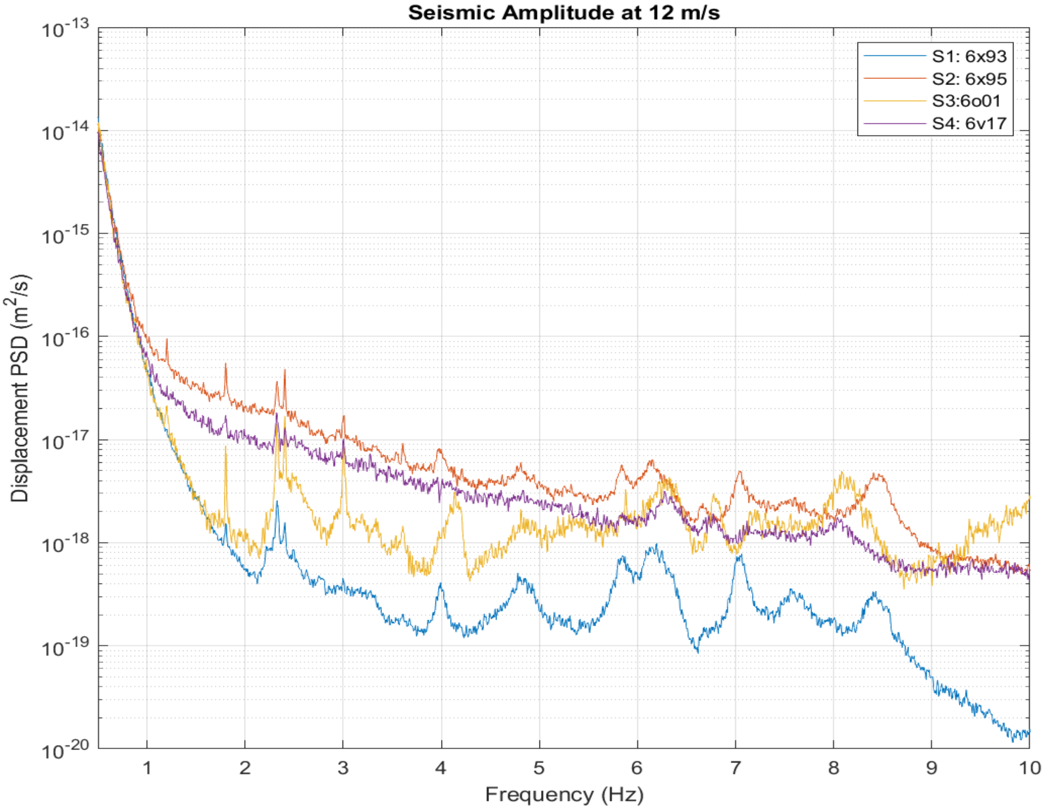


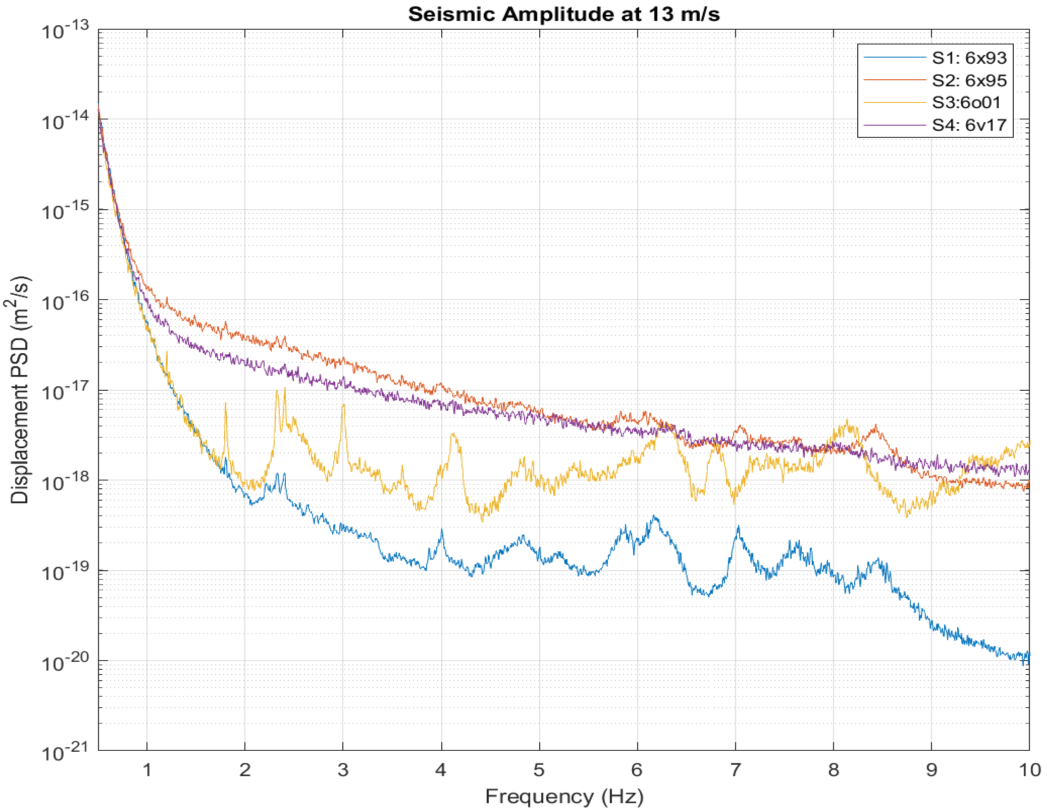
Seismic Amplitude at 8 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)

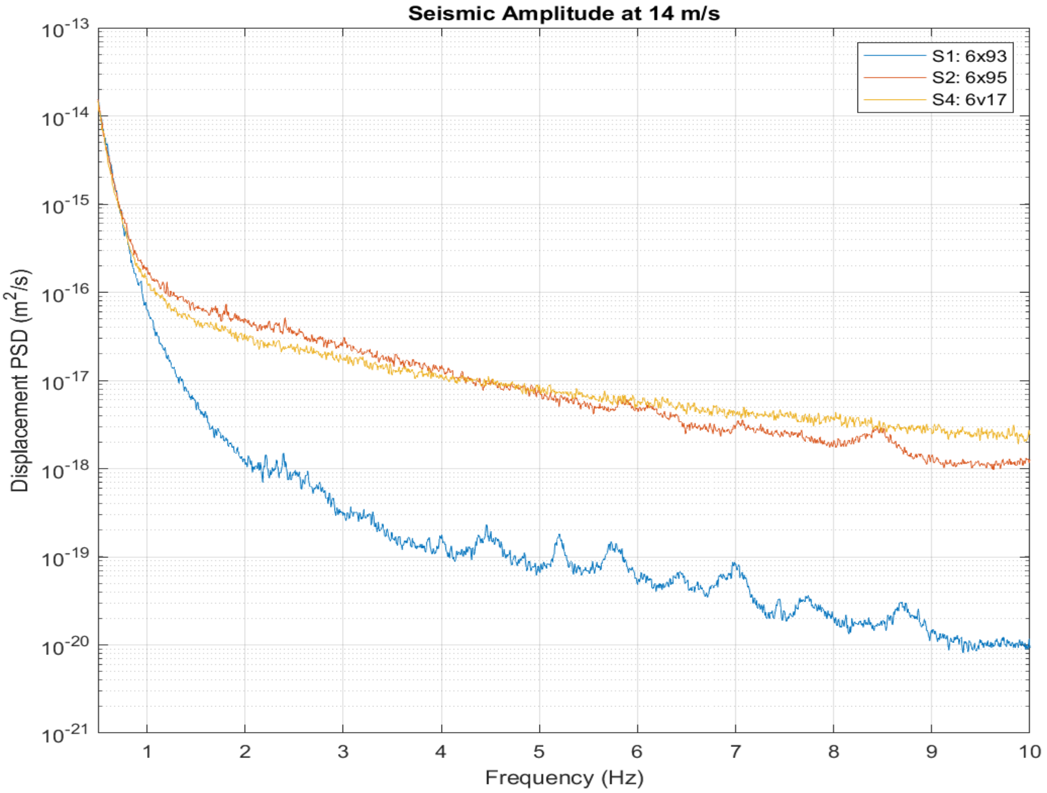

Seismic Amplitude at 9 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)

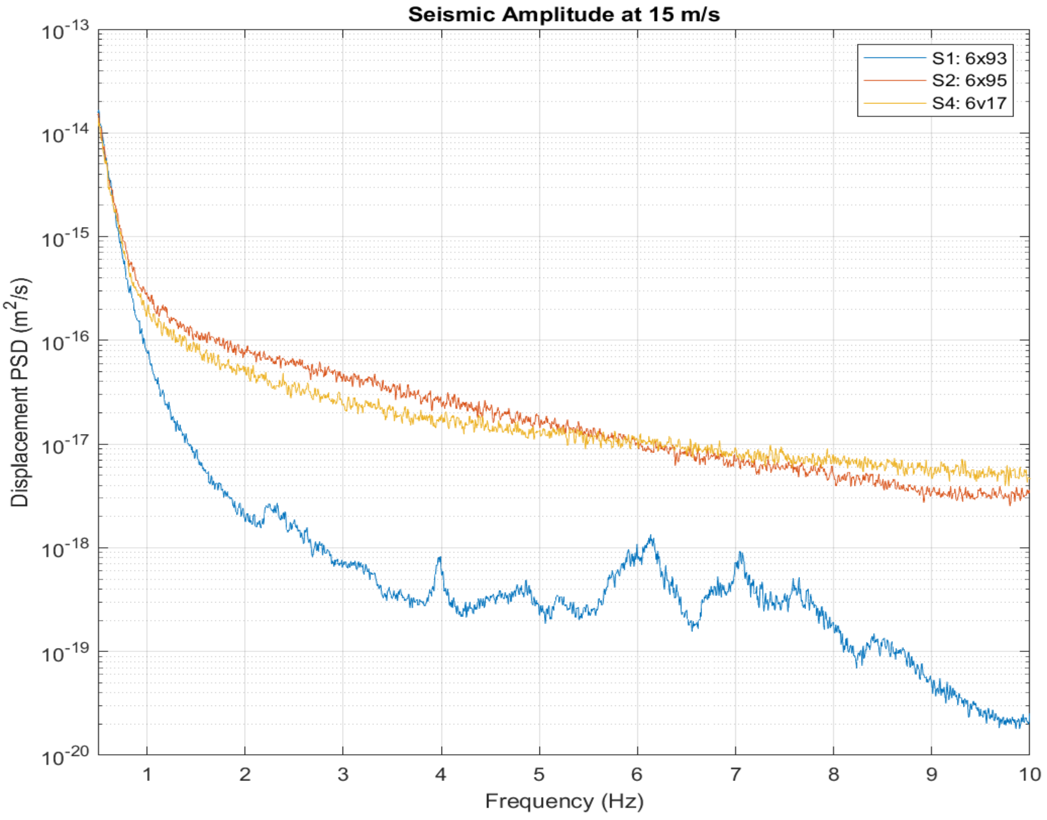

Seismic Amplitude at 10 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m²/s)
Frequency (Hz)


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

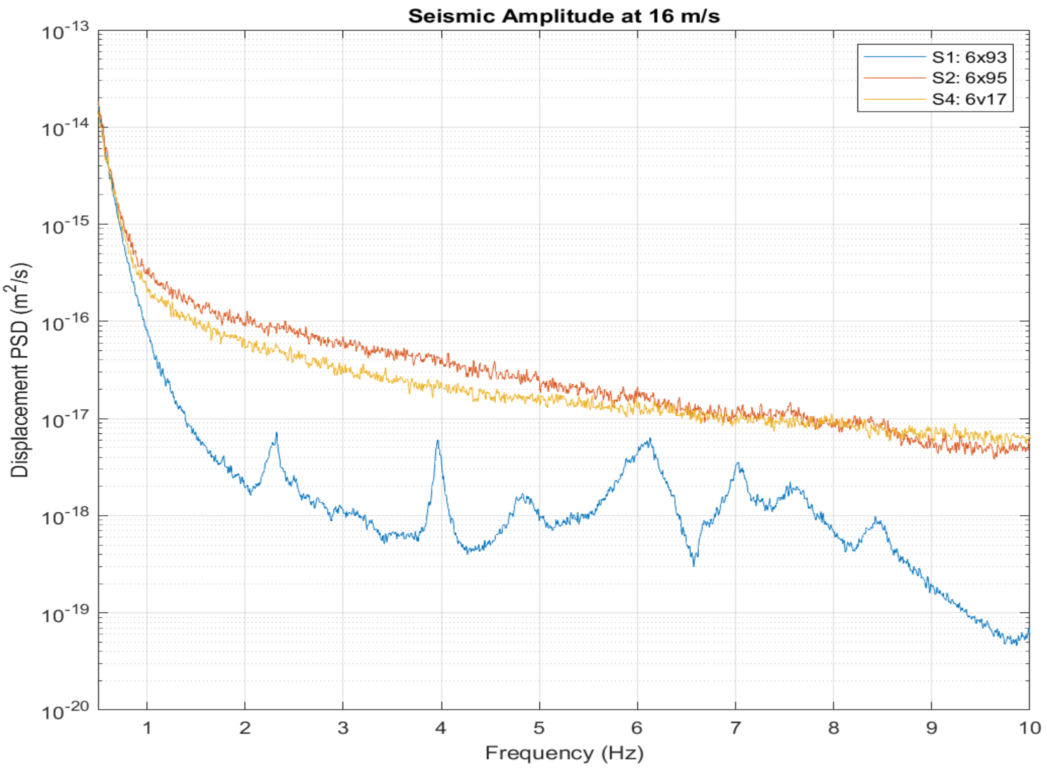

Seismic Amplitude at 12 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m^2/s)
Frequency (Hz)


Seismic Amplitude at 13 m/s
S1: 6x93
S2: 6x95
S3:6o01
S4: 6v17
Displacement PSD (m^2/s)
Frequency (Hz)

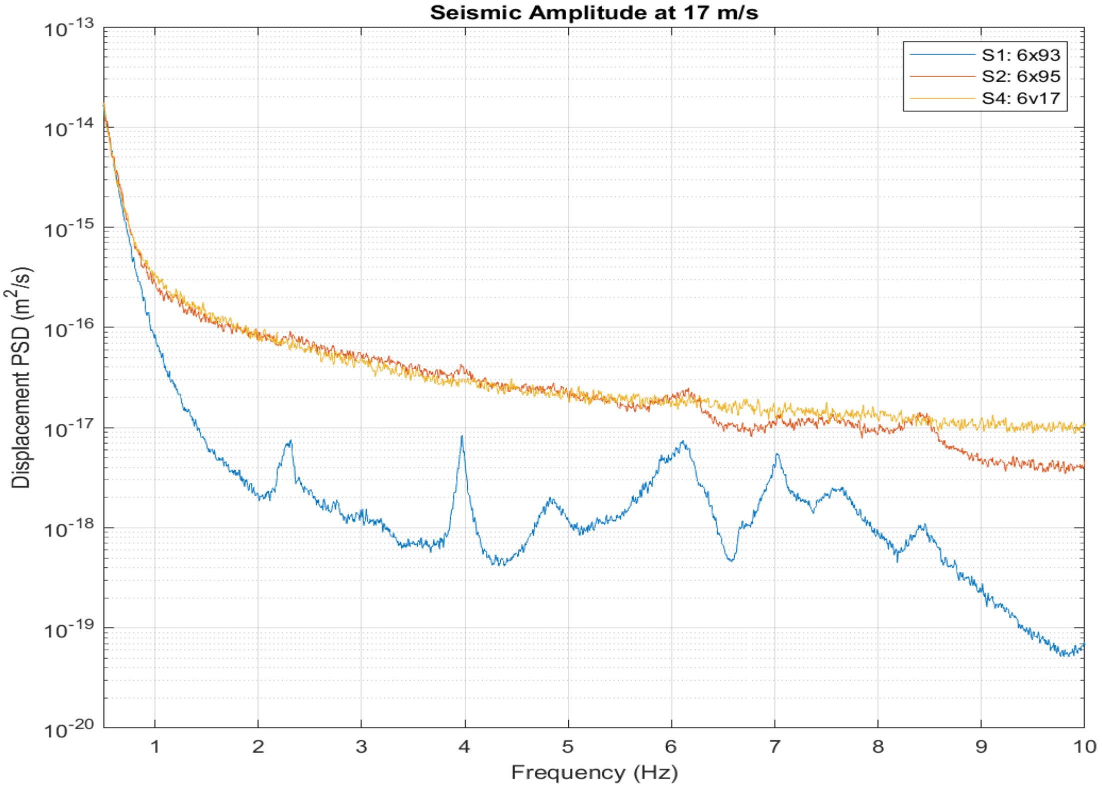

Seismic Amplitude at 14 m/s
S1: 6x93
S2: 6x95
S4: 6v17
Displacement PSD (m^2/s)
Frequency (Hz)



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

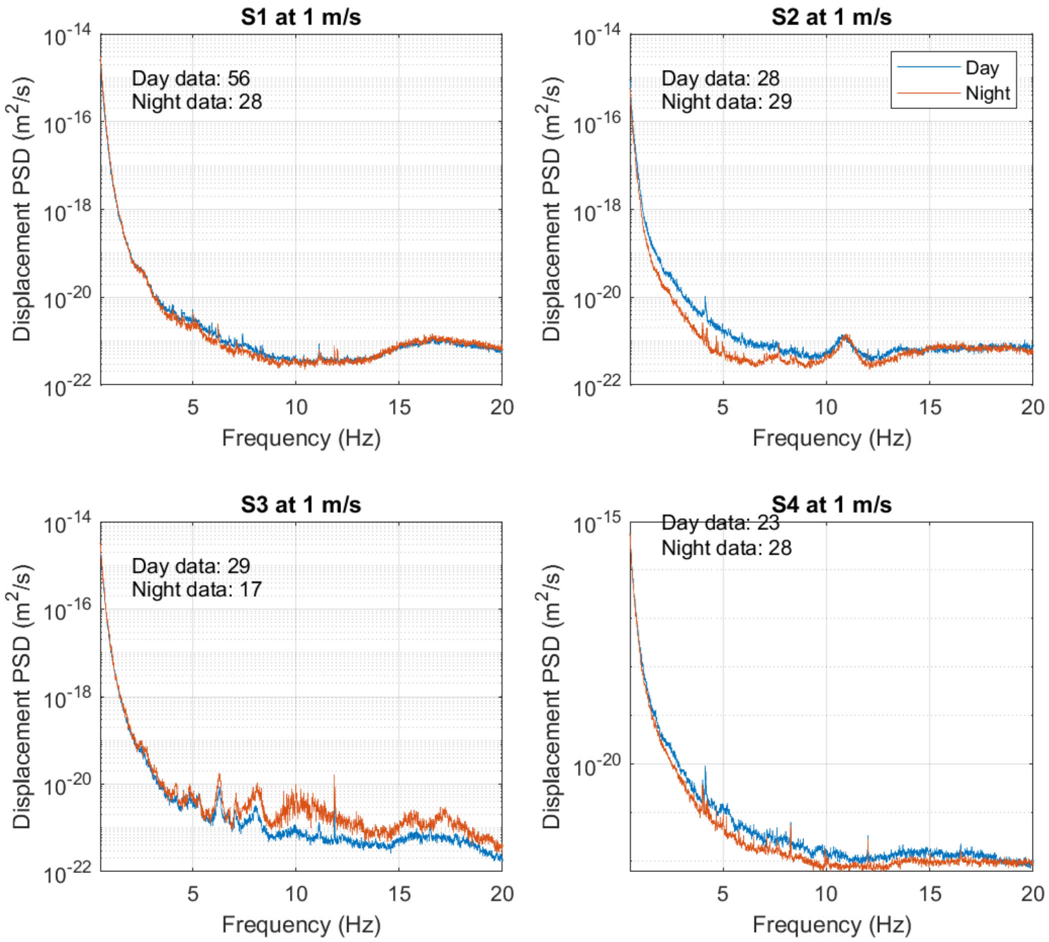


Seismic Amplitude at 16 m/s
Displacement PSD (m²/s)
Frequency (Hz)
S1: 6x93
S2: 6x95
S4: 6v17

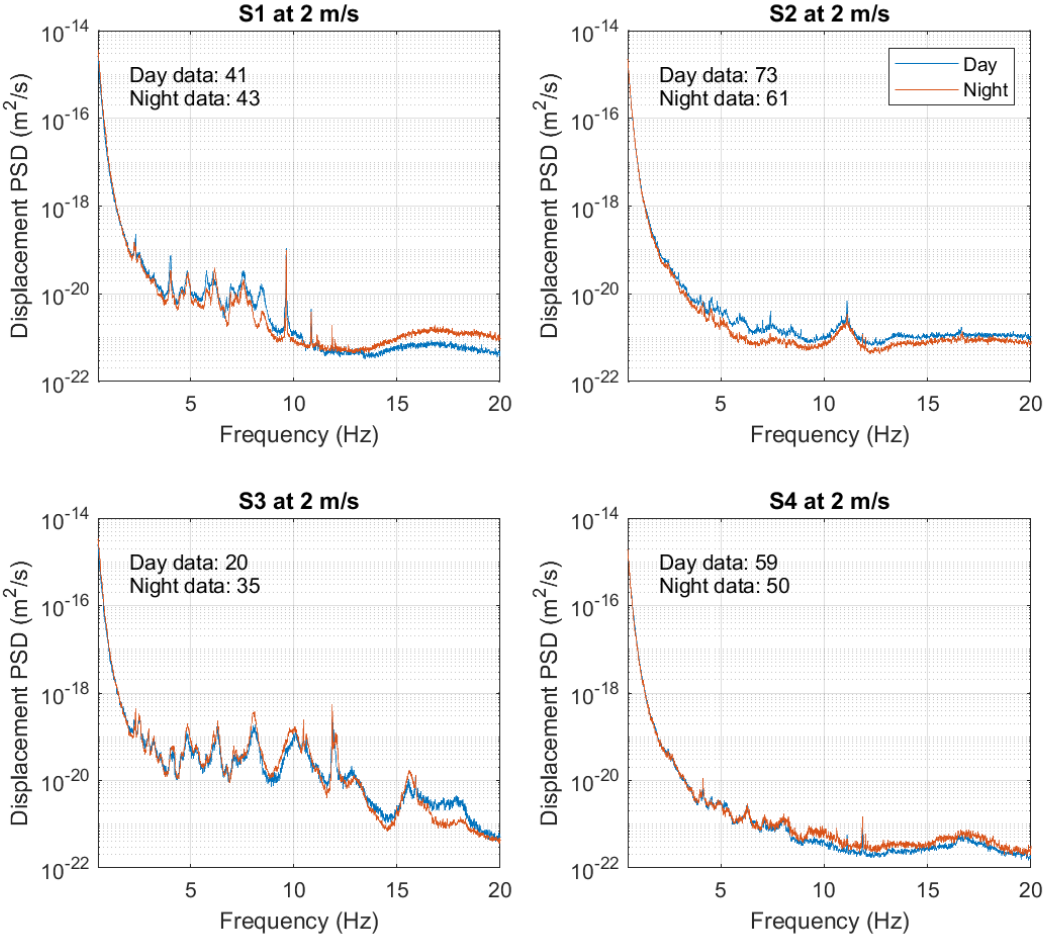

Seismic Amplitude at 17 m/s
S1: 6x93
S2: 6x95
S4: 6v17
Displacement PSD (m2/s)
Frequency (Hz)
10-13
10-14
10-15
10-16
10-17
10-18
10-19
10-20
1
2
3
4
5
6
7
8
9
10

12.8 Measurement Appendix C – Comparison of Diurnal variation

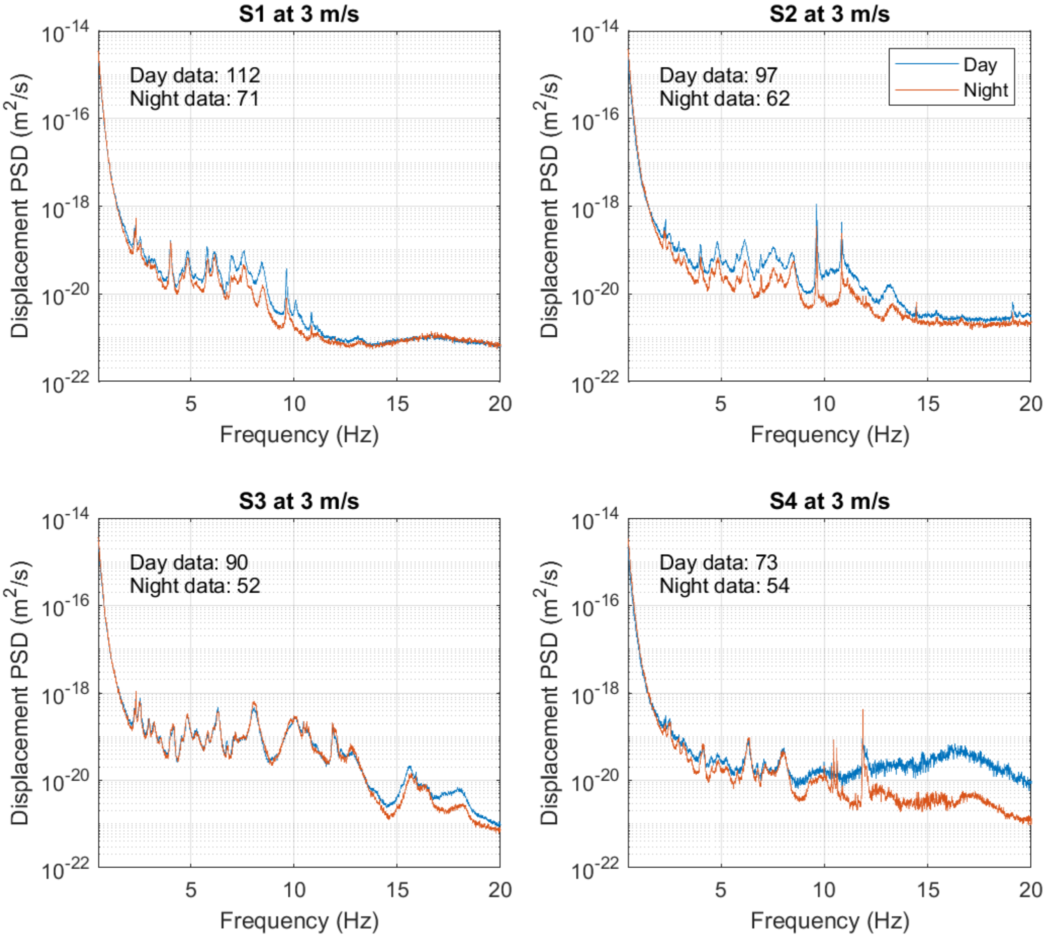
12.8.1 DIURNAL VARIATION AT WIND SPEED OF 1.0 M/S



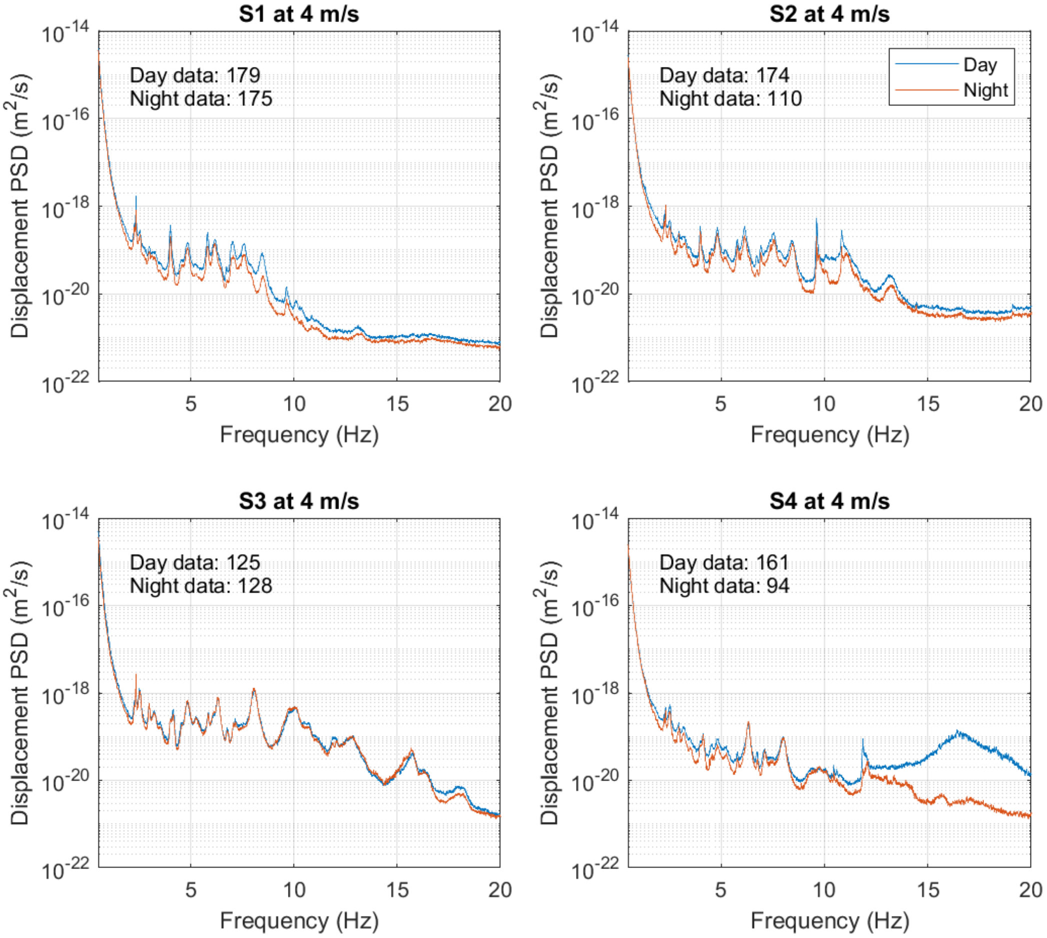
12.8.2 DIURNAL VARIATION AT WIND SPEED OF 2.0 M/S



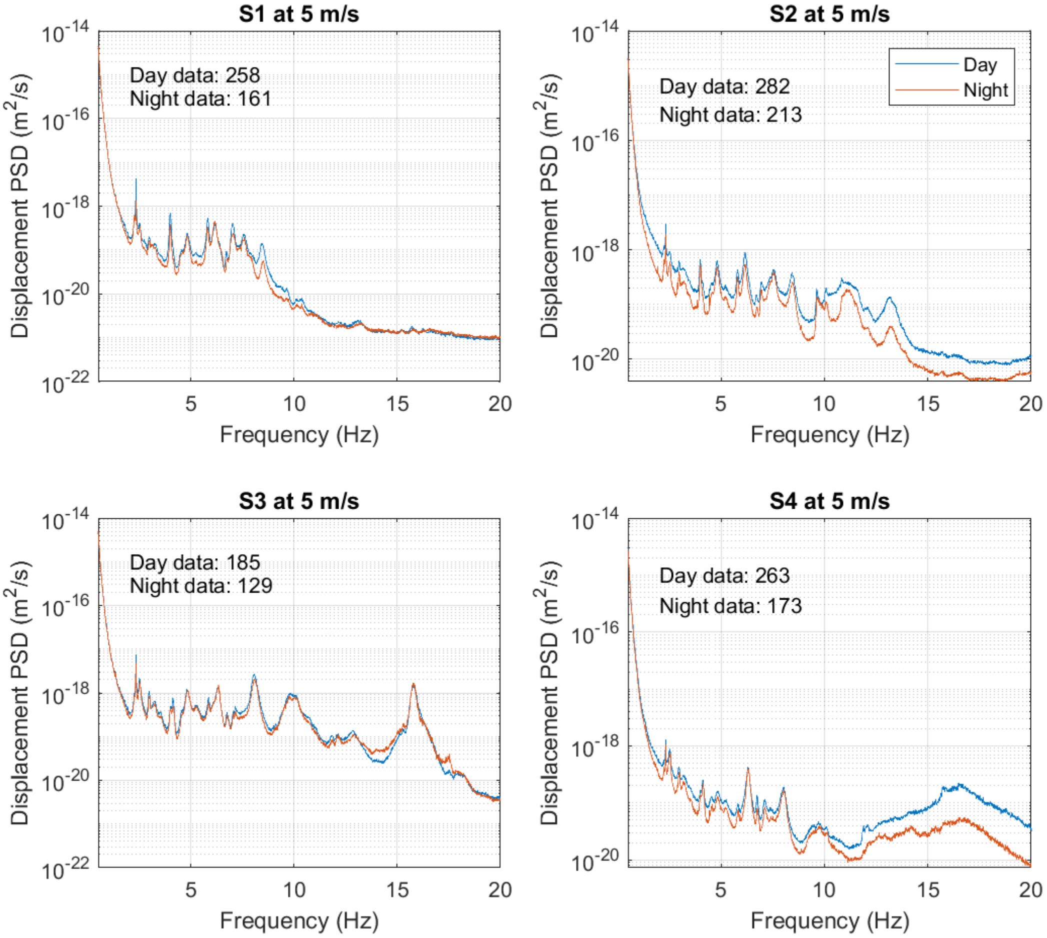
12.8.3 DIURNAL VARIATION AT WIND SPEED OF 3.0 M/S



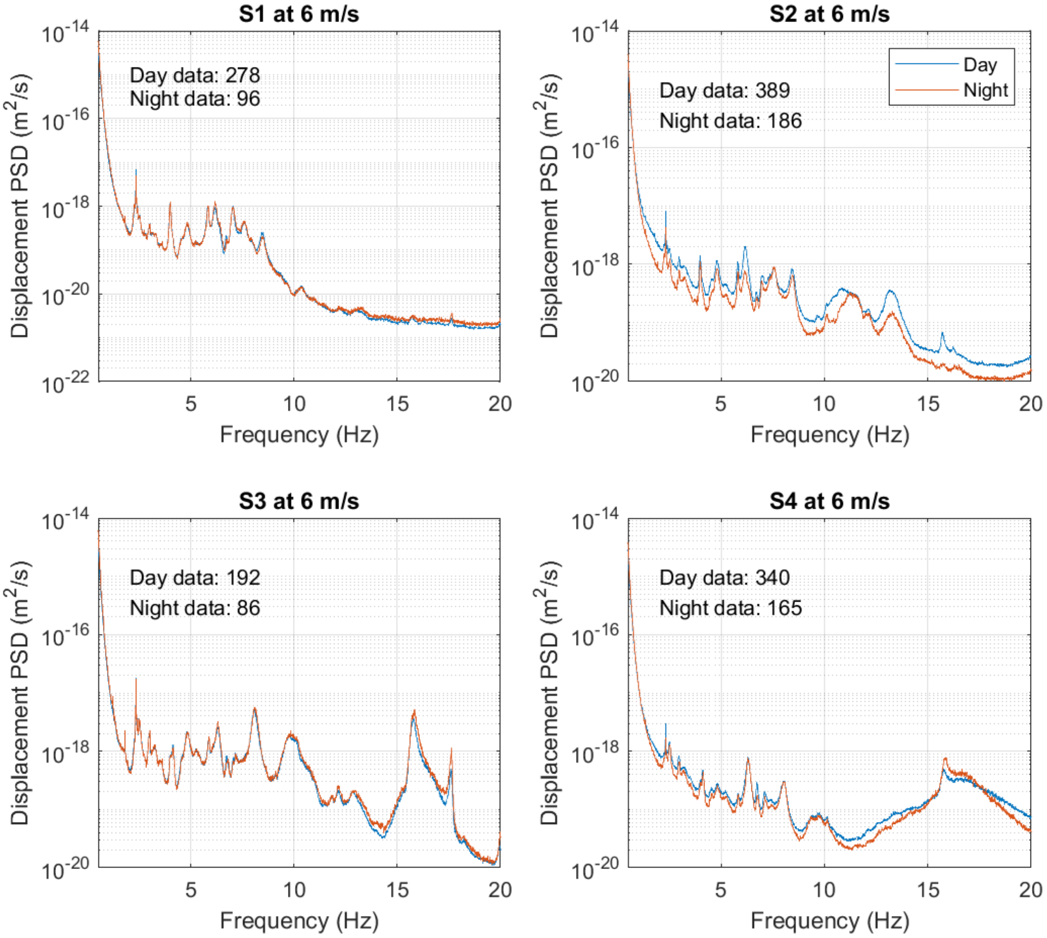
12.8.4 DIURNAL VARIATION AT WIND SPEED OF 4.0 M/S



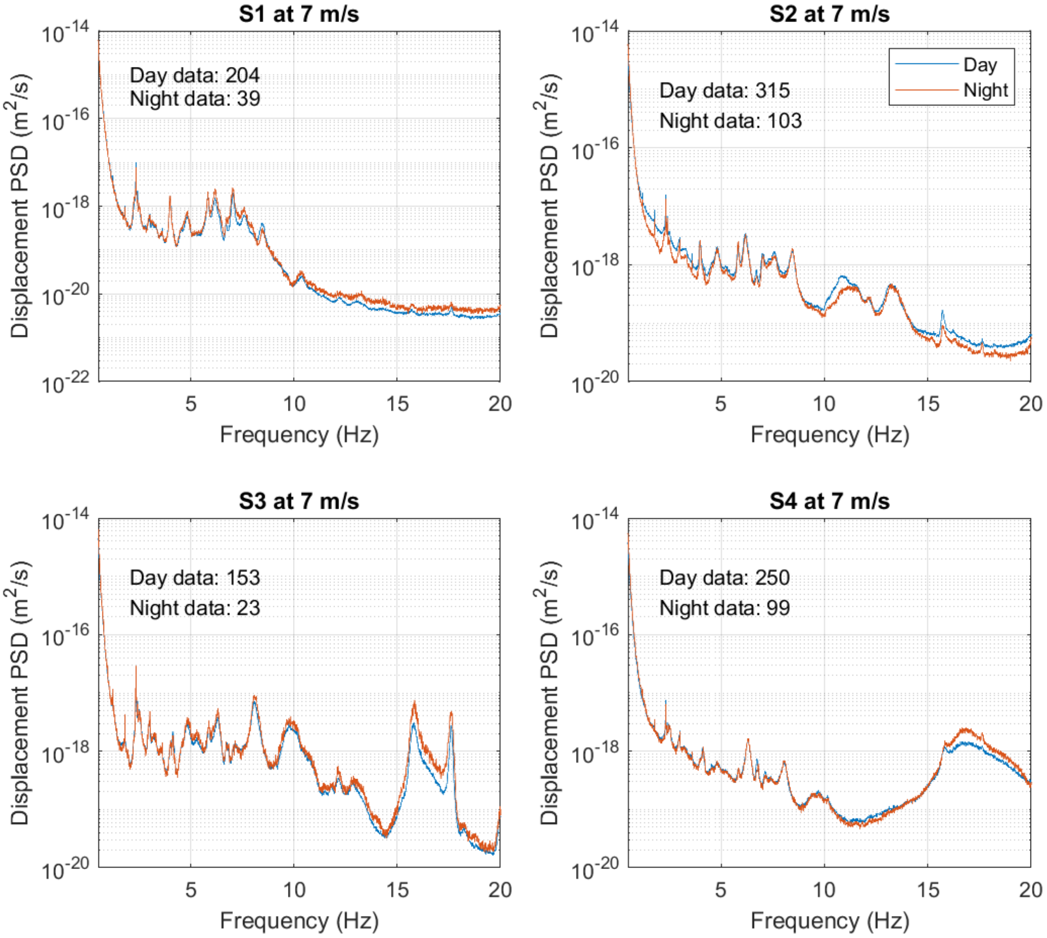
12.8.5 DIURNAL VARIATION AT WIND SPEED OF 5.0 M/S



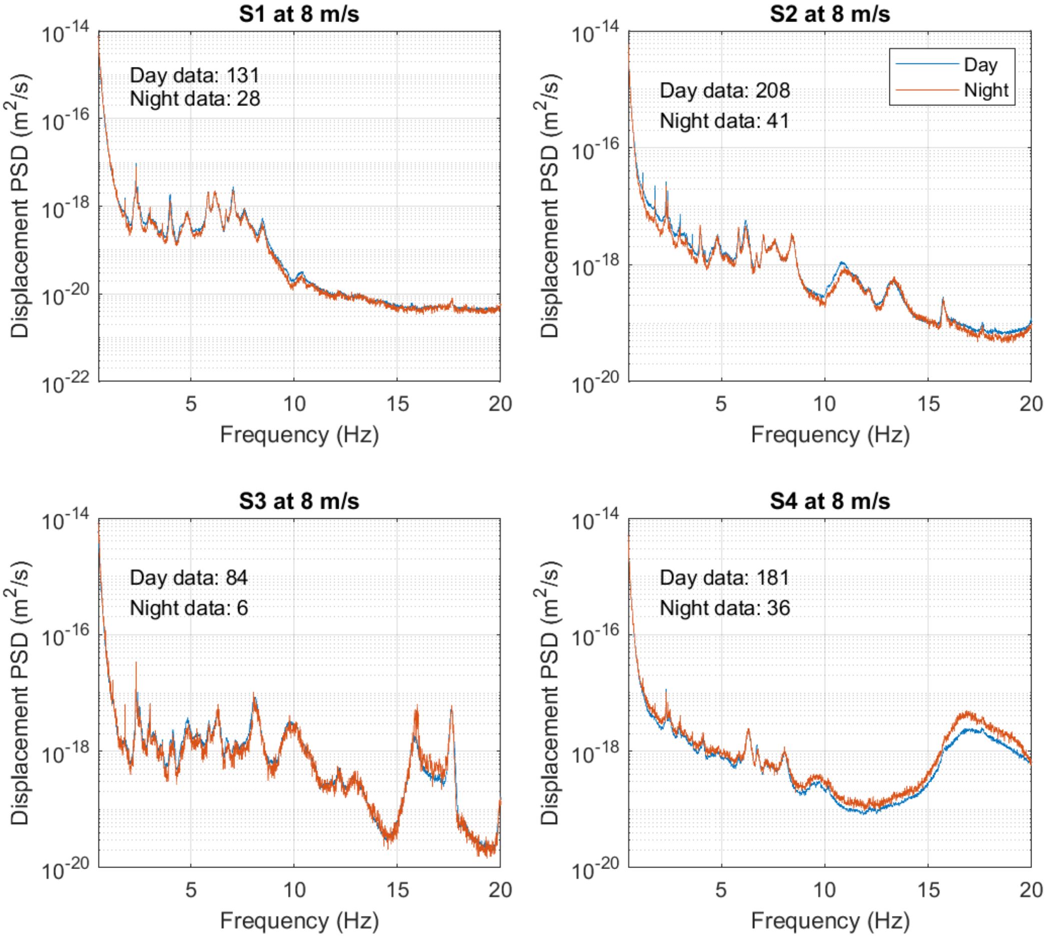
12.8.6 DIURNAL VARIATION AT WIND SPEED OF 6.0 M/S



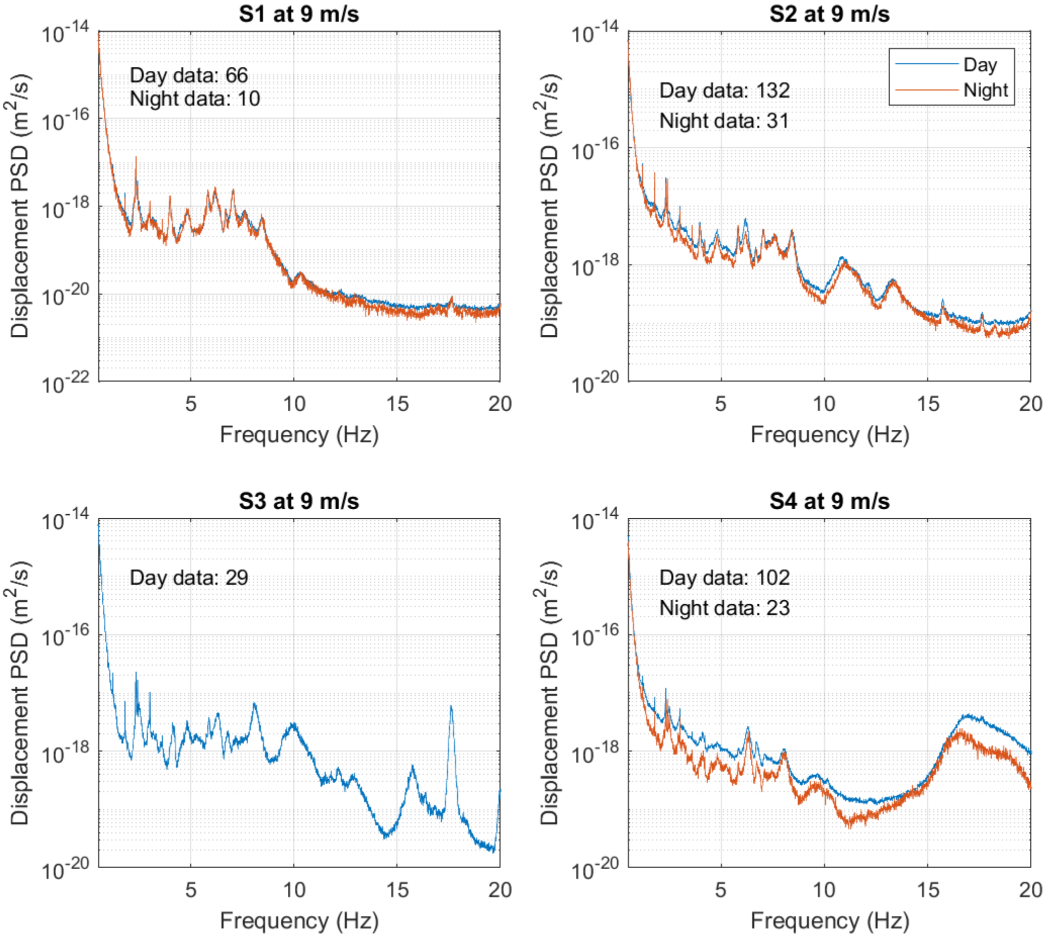
12.8.7 DIURNAL VARIATION AT WIND SPEED OF 7.0 M/S



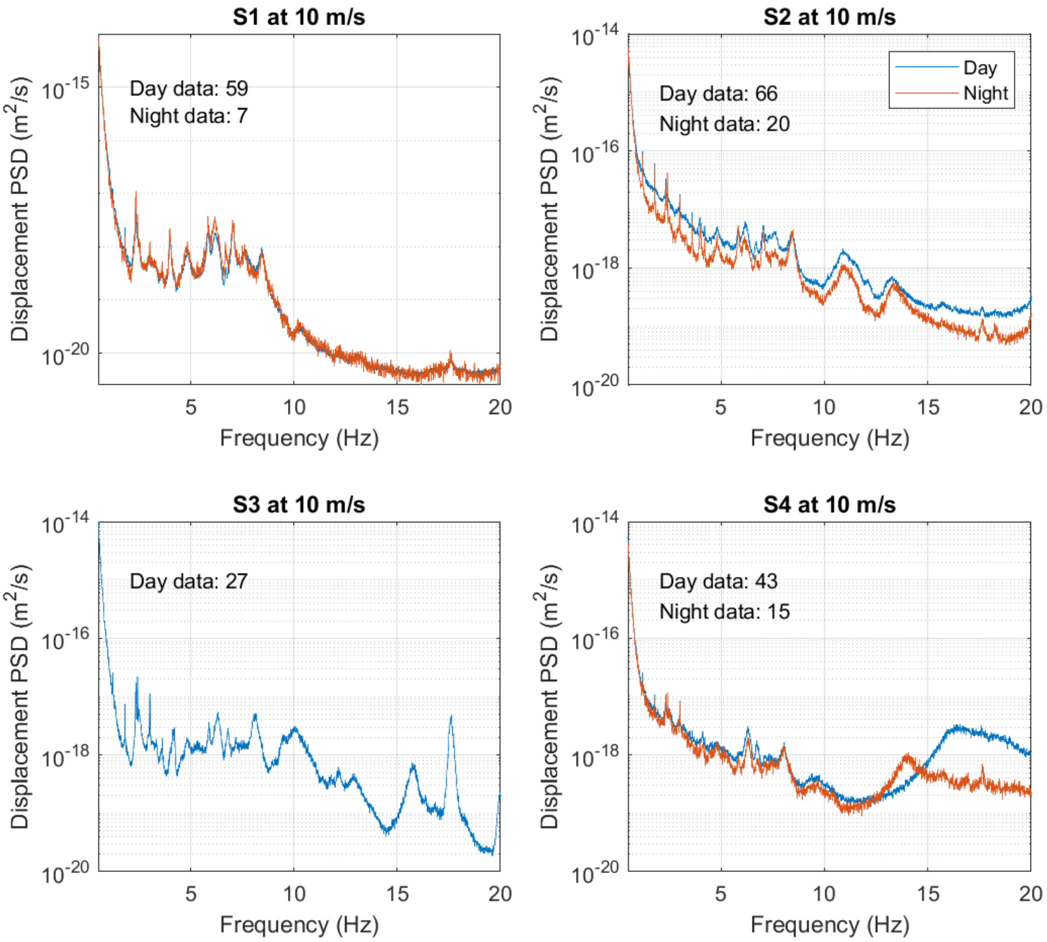
12.8.8 DIURNAL VARIATION AT WIND SPEED OF 8.0 M/S



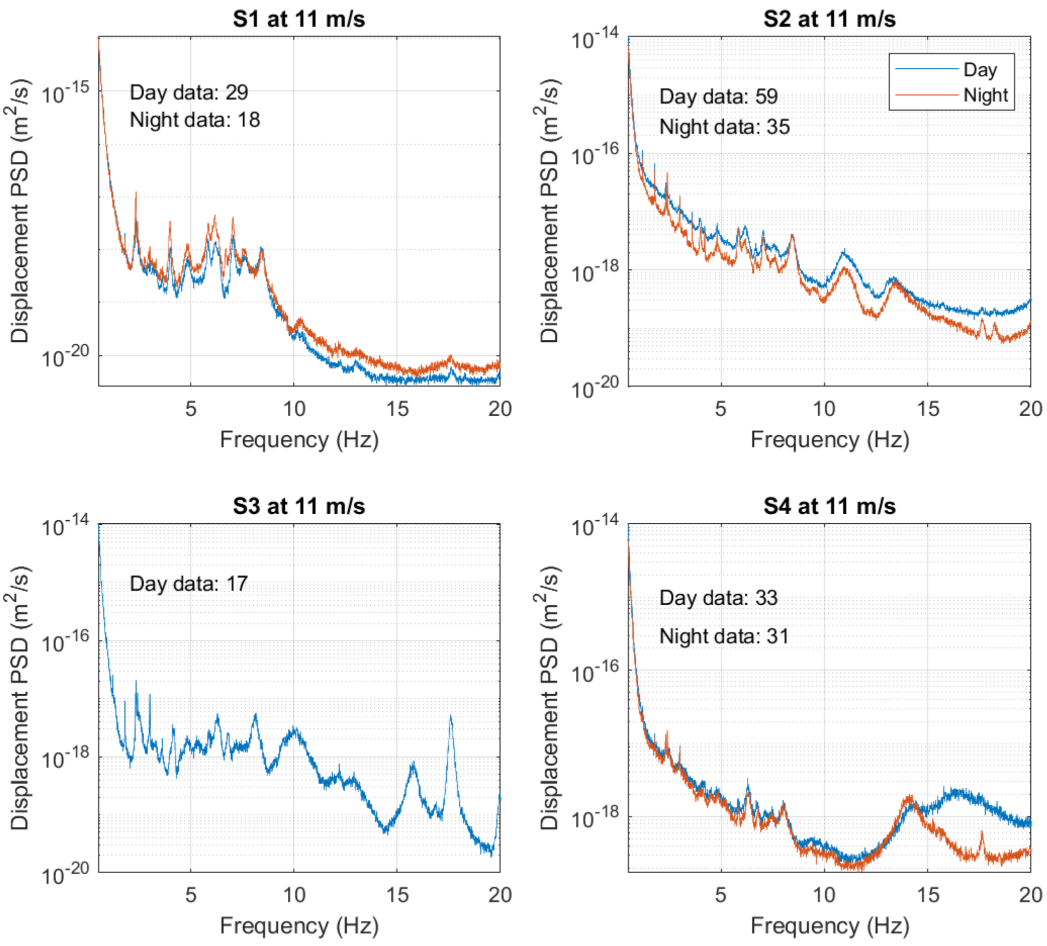
12.8.9 DIURNAL VARIATION AT WIND SPEED OF 9.0 M/S



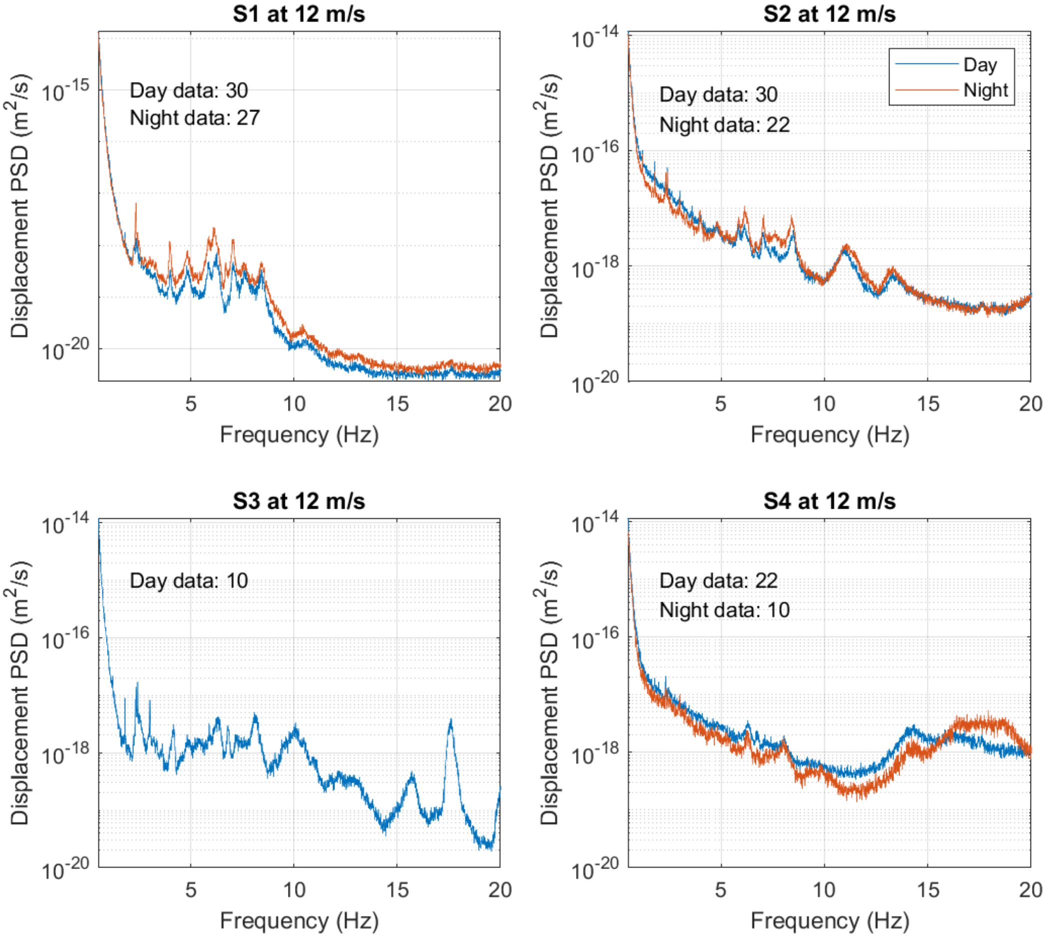
12.8.10 DIURNAL VARIATION AT WIND SPEED OF 10.0 M/S



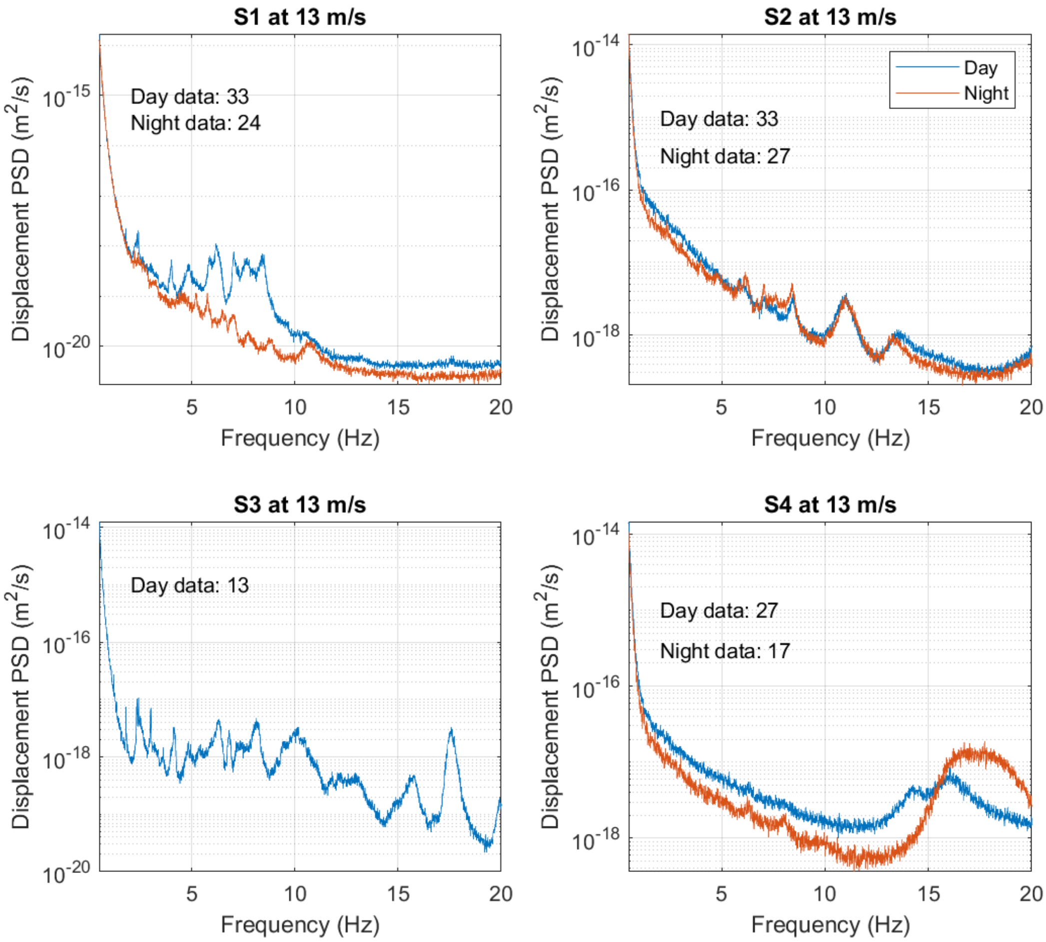
12.8.11 DIURNAL VARIATION AT WIND SPEED OF 11.0 M/S



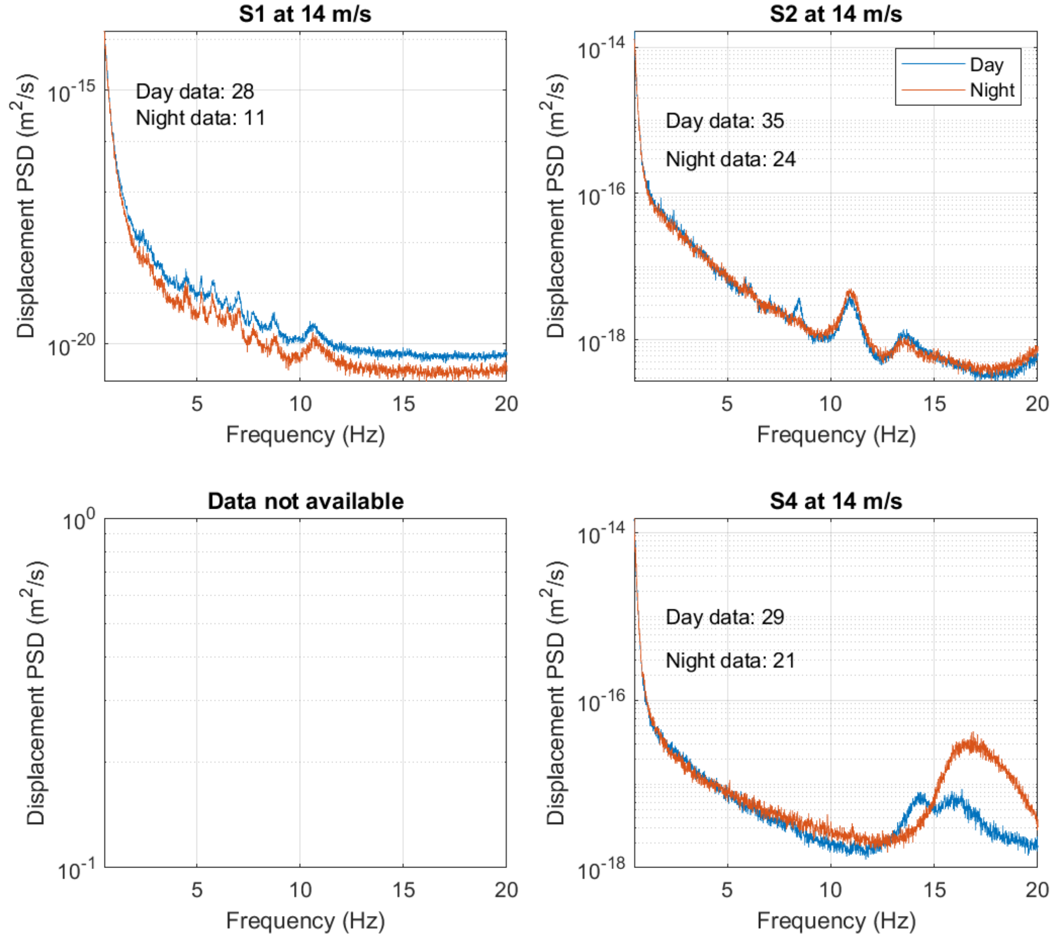
12.8.12 DIURNAL VARIATION AT WIND SPEED OF 12.0 M/S



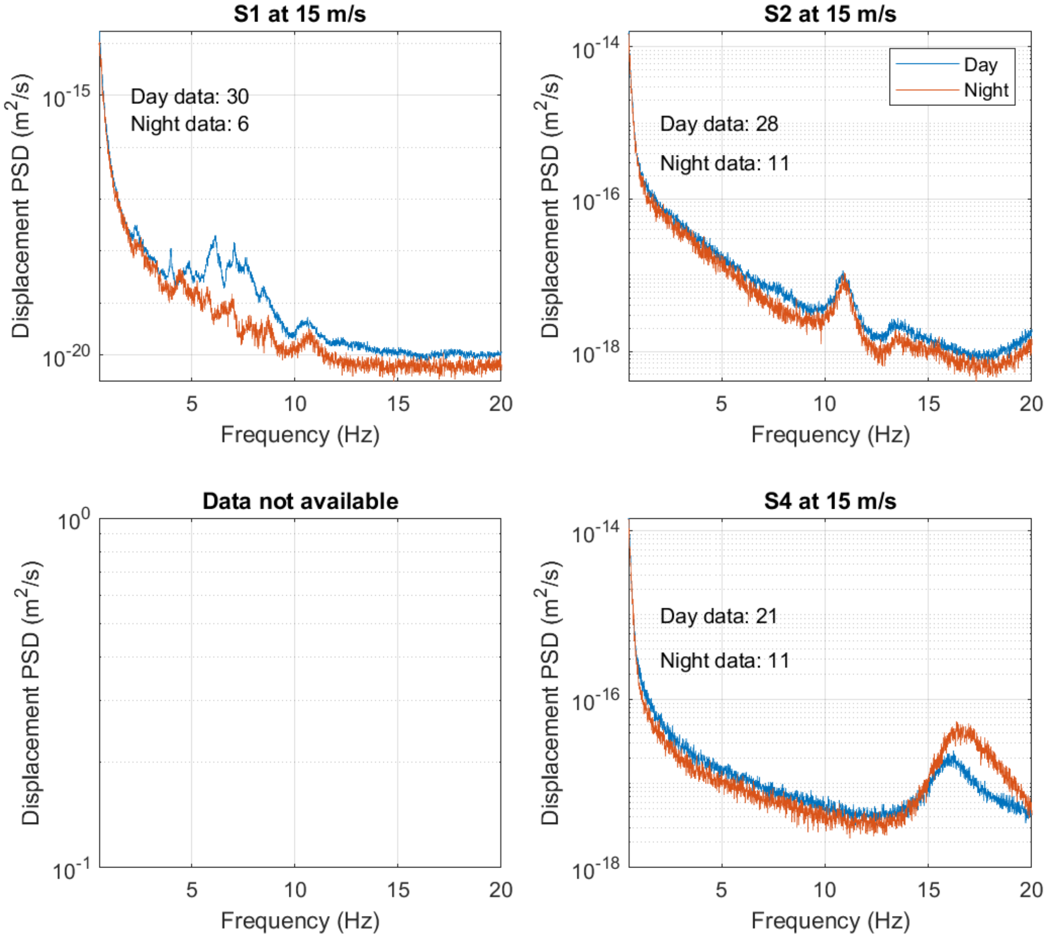
12.8.13 DIURNAL VARIATION AT WIND SPEED OF 13.0 M/S



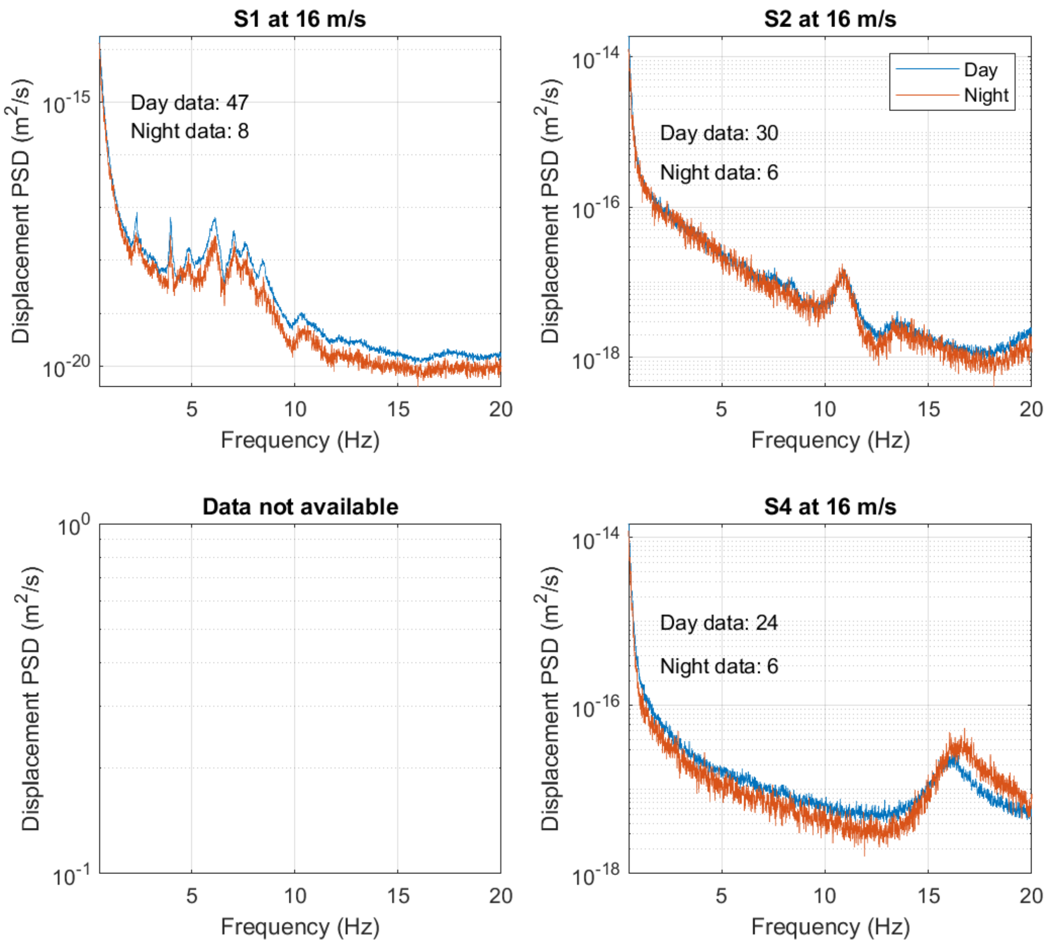
12.8.14 DIURNAL VARIATION AT WIND SPEED OF 14.0 M/S



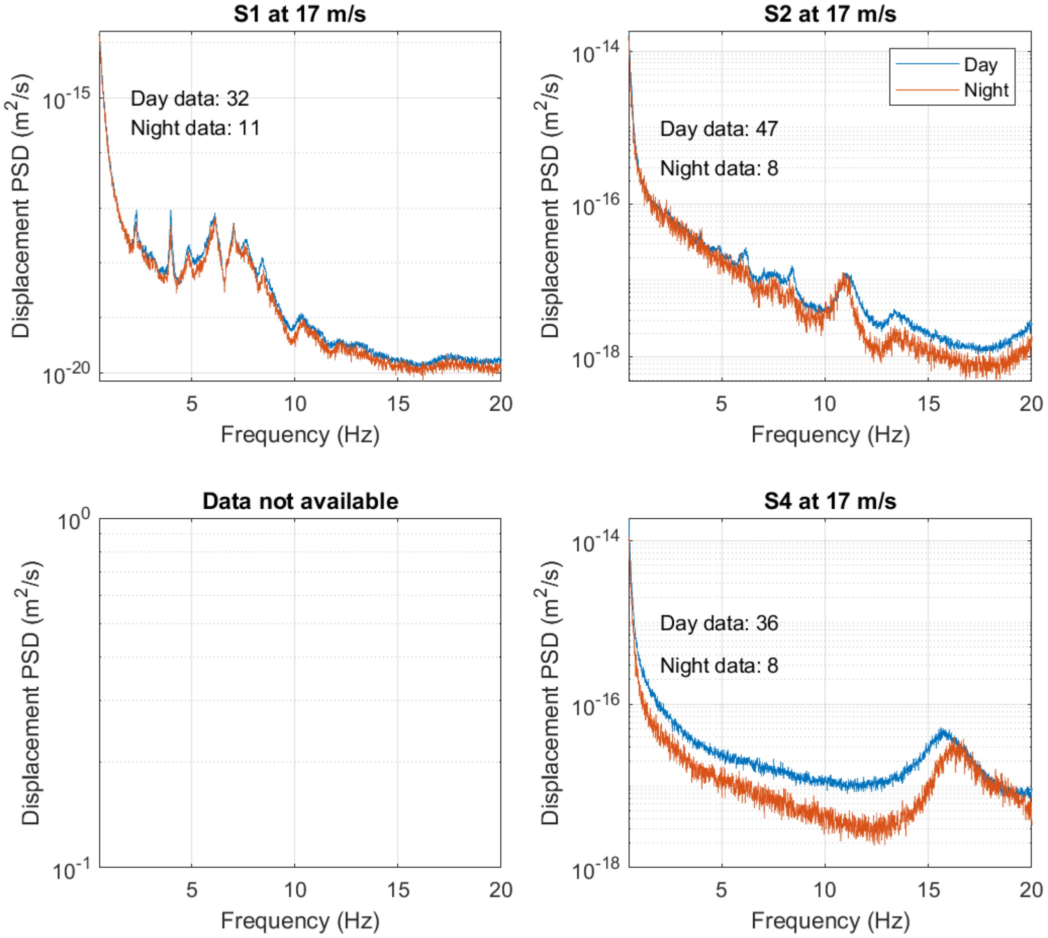
12.8.15 DIURNAL VARIATION AT WIND SPEED OF 15.0 M/S



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