Microseismic and Infrasound Monitoring of Low Frequency Noise and Vibrations from Windfarms

Recommendations on the Siting of Windfarms in the Vicinity of Eskdalemuir, Scotland

Professor Peter Styles, Dr Ian Stimpson, Mr S Toon, Mr R England, Mr M Wright

Applied and Environmental Geophysics Research Group
Earth Sciences and Geography
School of Physical and Geographical Sciences
Keele University
Keele
Staffs ST5 5BG

18 July 2005

Abstract

In order to meet, and in fact exceed, Kyoto targets, the UK government has set a challenging target of reducing the UK's carbon dioxide emissions by 60% by 2050. The development of renewable energy, especially wind power, will be an important contributor to the success of that policy.

 Some 40% (in excess of 1 Gigawatt), of this wind generation capacity, was planned for the southern uplands of Scotland. However, the United Kingdom seismic monitoring site which constitutes our component of the Comprehensive Test Ban Treaty compliance for nuclear testing is situated at Eskdalemuir near Langholm in the Scottish Borders. The Ministry of Defence therefore placed a precautionary blanket objection to any wind farm developments within 80 km of Eskdalemuir in case this compromised UK capability to detect distant nuclear test and breached our agreement under the CTBT. This effectively removed at least 40% of the UK renewable wind resource identified by the DTI.

Because of our previous, unique experience in monitoring seismic vibrations from wind turbines in the UK, the Applied and Environmental Geophysics Group of the School of Physical and Geographical Sciences at Keele University, were asked by the MOD, the DTI and the British Wind Energy Association to investigate whether there was a solution to this impasse. By carrying out a detailed programme of seismic and infrasound measurements in the vicinity of several wind farms in Scotland we have been able to identify the characteristic frequencies and mode of propagation of seismic vibrations from wind turbines and develop a model for the integrated seismic vibration at the Eskdalemuir site which will be created by any distribution of wind farms. By carefully considering the present ambient background experienced at the monitoring site it has been possible to set a noise budget which is permissible at Eskdalemuir without compromising its detection capabilities, and we have demonstrated that at least 1.6 GW of planned capacity can be installed and have developed software tools which allow the MOD and planners to assess what further capacity can be developed against criteria established by this study.

Introduction

The Eskdalemuir Seismic Array (EKA)

Eskdalemuir in the Scottish Borders is the location of a monitoring facility operated by the British Geological Survey where seismological, magnetic and other environmental parameters are monitored because the site is located in a very quiet magnetic and seismic environment. Measurements include horizontal and vertical magnetic field components and declination, total field intensity, and absolute values of the geomagnetic field. Three-component seismological measurements are made at the sites. An environmental monitoring facility operates at Eskdalemuir, monitoring soil and air temperature, wind speed and direction; UV and nuclear radiation; sunshine; concentrations of ozone, SO2 and NOx gases; rainfall; humidity and surface wetness.

In addition the UK seismological array **(EKA)** operated by AWE Blacknest is also sited at Eskdalemuir. The facility at Eskdalemuir is part of the auxiliary seismic network of the International Monitoring System (IMS) being set up to help verify compliance with the Comprehensive Test Ban Treaty (CTBT) which bans nuclear-test explosions. So far the CTBT has been signed by 175 states, and ratified by 121. The UK and France were the first nuclear-weapons states to ratify the treaty. The facility at Eskdalemuir is to be upgraded to be an alternate primary IMS seismic station. The treaty requires that States Parties shall not interfere with the verification system, of which Eskdalemuir is an element.

The seismometer array at Eskdalemuir (EKA) (Figure 1) became operational on the 19 May 1962. The recording station comprises a recording laboratory, a seismological vault and an array of seismometers installed in pits spaced over an area 10 km square. The laboratory is situated on the eastern side of the Langholm-Innerleithen road (B709) about 30 km north of Langholm and 3 km north of the Eskdalemuir meteorological observatory. The seismological vault is about 400 m east south east of the laboratory, and the array lies to the east in the form of a cross with its centre, about 2.5 km from the laboratory. The latitude of the point of intersection of the two lines of the array is 55º 20' north and the longitude is 03º 09½' west. The array is situated across the watershed between tributary headstreams of the Teviot and Tweed flowing to the north-east, and headstreams of the Esk which generally flow to the south-west. The ground surface is largely open rolling moorland and forest plantations, which in is in many places peat covered. The altitude of the seismic pits varies from c 210 m to c 430 m. The isolated location ensures that microseismic interference is kept to a minimum. While there is very little light vehicular traffic on the Langholm-Innerleithen road logging trucks and heavy forestry machinery do use this road albeit intermittently.
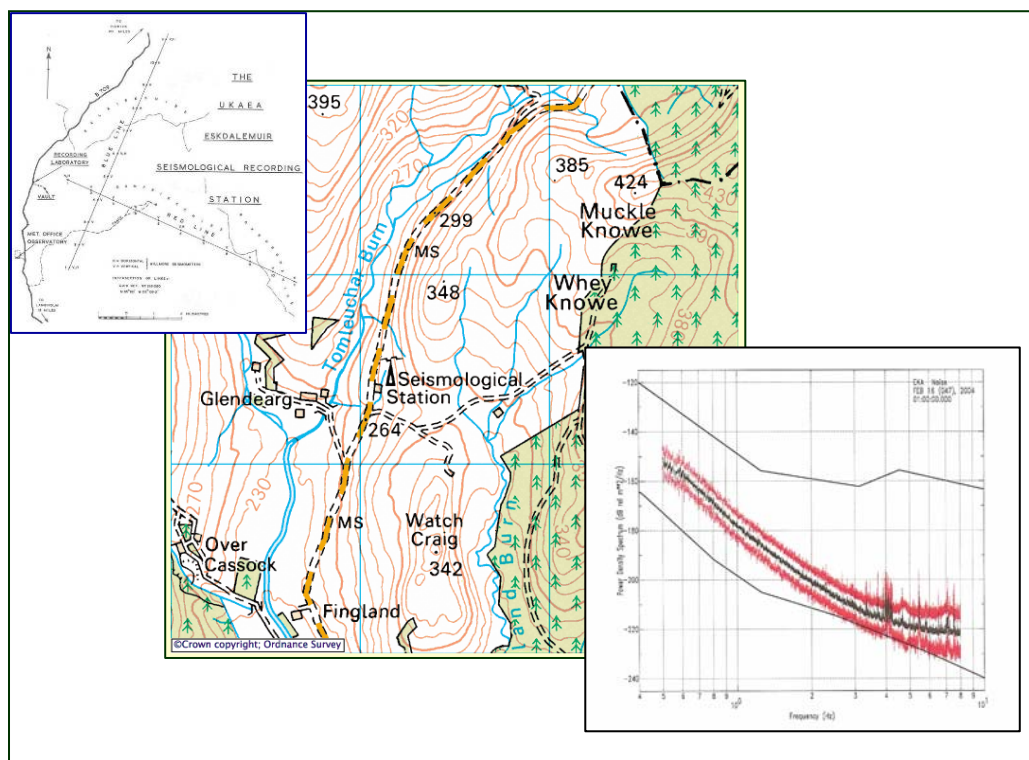
The Array

The array consists of two straight lines of instrument pits intersecting at right angles. Each line has eleven pits (of which only ten on each line are used) approximately 1000 yards apart. Each line intersects the other off centre, forming a cross whose four arms are unequal. The lines run roughly from SSW to NNE and from WNW to ESE. The overall length of each line is approximately 9 km. The seismic pits have been excavated through an overburden of superficial soil (peat in some instances) or thickness from 0 to 1 m into shales of the Llandovery Series (Silurian age). These were folded during late Silurian times, and as a result of the lateral pressures exerted are highly cleaved. Buried recording cables connect each instrument pit to the recording laboratory.

Each pit on the array contains one vertical Willmore MK2 short period seismometer. The signals from the seismometers are transmitted via buried cables back to the recording laboratory where it is then digitised using 3 separate CMG-DM16-R8 digitisers. A central acquisition system then records this data. In addition the seismic vault at Eskdalemuir contains four seismometer plinths. Currently a broadband 120s to 50Hz GURALPCMG-3TD is installed in the vault. The data is transmitted from the vault to the recording station using a leased line modem. Data from this acquisition computer is then transmitted on two separate networks via TCP/IP to a VSAT system link to CTBTO in Vienna and to a local network. From the local network the data is transmitted via VSAT to AWE Blacknest and a second computer records the data locally onto a tape backup system. A study of the background noise at Eskdalemuir was undertaken in 1997/8 as an AWE report (Trodd 1998). The winter and summer RMS averages of the unfiltered summed channels of the array were found to be 8.96 and 1.65 nanometres respectively.

EKA has two arms, each of ten seismometers. The array comprises sensitive seismometers that have recorded signals associated with about 400 nuclear explosions (up to 15,000 km away from EKA). Why is Eskdalemuir so good at this? The main reason is that it occupies a seismically very quiet site (one of only three ever considered in the UK, (Bache et al., 1986)), approaching the low noise model of Petersen (1993), and its history of operation. EKA is the longest operating steerable array in the world has long experience of detecting events over 42 years, is well calibrated, and has detected signals from areas of low seismicity. It has detected signals generated from the detonation of c 100 tonnes of conventional explosive in Kazakhstan. The seismometers are deployed in shallow pits which means that the constructive interference between the up-going and reflected P-waves (compressional-dilatational first arrivals) from the free surface , effectively doubles the amplitude for vertically arriving (teleseismic) phases from distant events in addition to the increase in signal to noise ratio obtained by stacking the 20 seismometer records.

EKA(AS104) was offered by the UK during negotiations with the Comprehensive Test Ban Treaty Organisation (CTBTO) as an auxiliary station and EKA was designated a substitute for a primary seismic station (CTBT/WGB-10/1,1999). EKA data is widely used by the international research community in the pre-Entry into Force (EIF) phase

Figure 1   The Location of the EKA seismological array, the detailed layout of the arms of the array and the noise spectrum at the array which closely approaches the Low Noise Model of Petersen (1993).

Figure 2 indicates the detection sensitivity of the Eskdalemuir array as it clearly show the discrimination of the detonation of 100 T of conventional explosive in Kazakhstan a distance of some 5250 km away! The subsequent table which shows the statistics of ambient background is a partial explanation of this exceptional sensitivity as the median noise during a windy period was only 0.25 nm. This, together with years of historical data, makes EKA an unparalleled resource for forensic seismology, i.e. the discrimination of distant nuclear detonations.

EKA signals from a 100 t chemical explosion, Kazakhstan

EKA signals from 100 ton chemical explosion East Kazakhstan 22 August 1998: Distance = 5250 km
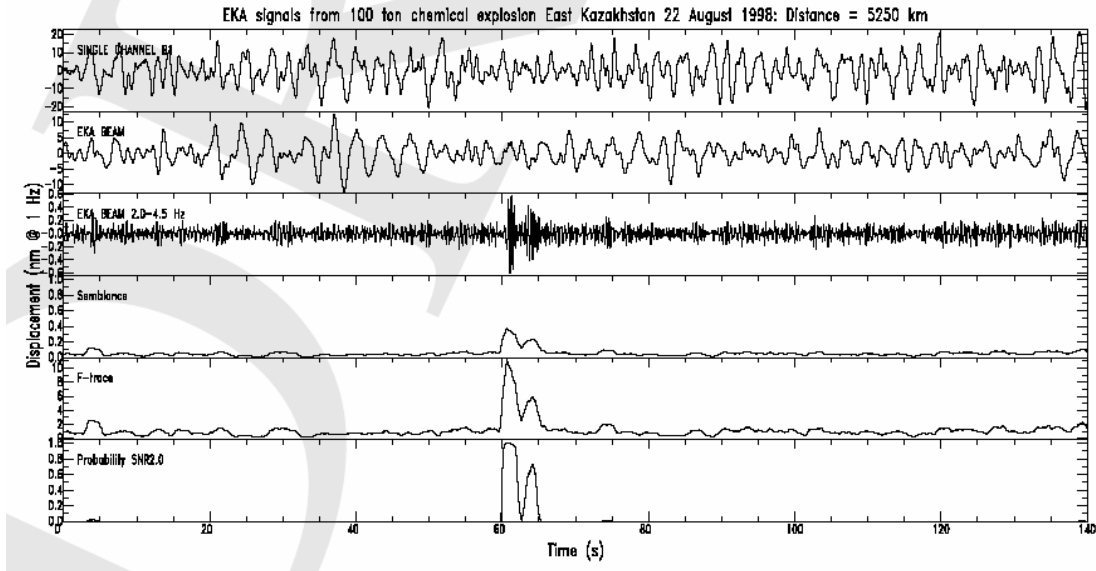
Passband (Hz)	Quiet rms (nm)			Windy rms (nm)		
	Mean	SD	Median	Mean	SD	Median
1.0-2.0	1.425	0.144	1.454	1.900	0.331	1.857
2.0-3.0	0.245	0.116	0.202	0.497	0.292	0.454
3.0-4.0	0.147	0.097	0.111	0.341	0.220	0.317
4.0-5.0	0.116	0.079	0.088	0.271	0.178	0.253

Quiet times: 2003/12/08 02:00 (1), 2003/12/08 10:00 (1) , 2003/12/08 22:00 (2), 2003/12/09 02:00 (1), 2003/12/09 10:00 (1), 2003/12/09 22:00 (1).

Windy times: 2003/12/01 22:00 (16). 2003/12/02 02:00 (19), 2003/12/02 03:00 (20), 2003/12/02 10:00 (11), 2003/12/02 11:00 (9), 2003/12/06 10:00 (7).

Figures in parenthesis are mean wind speed in knots (1 knot = 0.51 m s^{-1}) at Eskdalemuir weather station (source: Met. Office website).

Figure 2   Statistics of ambient microseismic noise at Eskdalemuir during quiet and noisy wind periods and an example of the detection capability of the array in the 2 to 4.5 Hz band (from Bowers (2004) , Elliot and Bowers 2004).

The International Monitoring System (IMS) network will eventually comprise:

1. 50 primary seismic stations,
2. 120 auxiliary seismic stations,
3. 60 infrasound stations,
4. 11 hydroacoustic stations,
5. 80 radionuclide stations

The IMS station at Eskdalemuir is part of the verification system. Article IV, Paragraph 6 of the CTBT means that as a state signatory the UK is not allowed to interfere with (degrade) the performance of the verification system.

Renewable Energy in the Southern Uplands of Scotland and its implications for Seismic Verification.

The hills of the Lake District and Scottish Borders constitute a major wind resource and some existing wind farms have been operating for many years and many new facilities are planned. As part of the UK renewable energy targets set in order to meet the Kyoto protocol, in excess of 1 GigaW of wind energy capacity are planned for the Southern Uplands of Scotland, a valuable wind resource area. In late December 2003 AWE/MoD recognised that many wind farm developments are planned in the vicinity of the Eskdalemuir International Monitoring Site which constitutes part of the CTBTO monitoring network and that the discrimination capabilities of it might be affected by possible vibration intrusion by wind turbines erected in proximity to the array and that this might have implication for its performance in discriminating nuclear weapons tests.

Wind turbines are large vibrating cylindrical towers, strongly coupled to the ground with massive concrete foundation, through which vibrations are transmitted to the surroundings and with rotating turbine blades generating low-frequency acoustic signals which may couple acoustically into the ground. This may occur in several ways:

1.   As a cantilever carrying the nacelle/blade mass, with   frequencies typically less than 1Hz, depending on height of tower.
2.   As a torsional oscillator at low frequencies.
3.   As a complex distributed system at higher frequencies

Additionally, the blade tower interaction is a source of pulses at a low repetition rate, which contain components in the infrasound region. The local and surrounding geology especially layering may play an important part in determining vibration transmission. Energy may propagate via complex paths including directly through the ground or principally through the air and then coupling locally into the ground and it is hope that this study will be able to clarify this.

The site is of national and international significance and requires protection. Because of uncertainty at that time as to the actual levels of seismic vibration generated by large UK wind farms, the Ministry of Defence implemented interim proposals for 30km and 80km cautionary distances. Holding objections were placed on wind farm development within a radius of 30 km from the seismic detection facility near Eskdalemuir and developments up to 80 km radius would be re-examined.

Potential Scottish Wind farm developments which might be affected by this objection are:

Within a 30 km. radius:

Minch Moor, Over Dalgleish (Mast), Craik Forest (Mast)
Corbie Shank, Carlesgill , Ewe Hill/Haggy Hill Allfornought Hill, and Ae
Forest

Between 30 km and an 80 km. radius:

Auchencorth Moss , Bowbeat, Broadmeadows, Carcant, Soutra,
Fallagore Ridge, Black Hill. Clints Hill, Lauder Common/Sell Moor, Long
Park (mast), Crystal Rig, Monashee , Dalswinton and Kyle Forest.

In addition, many Cumbrian and Northumbrian windfarm sites or
planned developments lie within or close to the 80 km re-examination
zone.
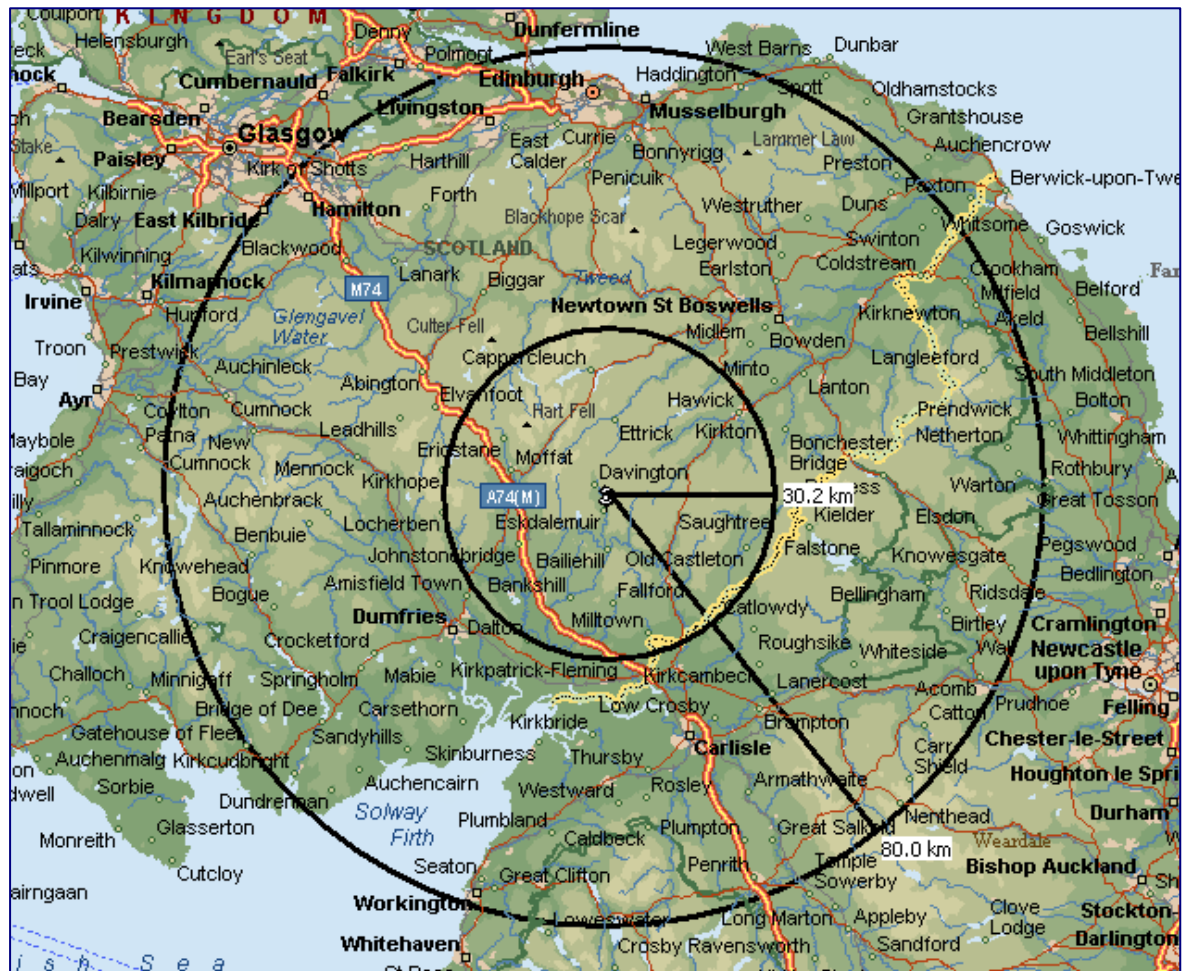
Figure 3   Interim precautionary distances of 30 and 80 km from Eskdalemuir indicating the large areas (2800 km² and 20000 km²) which would be excluded from windfarm development.

This preliminary assessment was based on results from literature and web searches presented to BWEA/MoD meeting on 10 February2004 by Dr David Bowers of AWE Blacknest.

It was recognised that further research was urgently required in order to establish guidelines for future wind-farm development in the vicinity of EKA. The Eskdalemuir Working Group was established to ensure the guidelines had a sound scientific basis and to investigate whether these are the appropriate distances and if necessary develop guidelines for this protection.

Very few studies of the microseismic vibrations from wind farms have been carried out anywhere. The only UK studies prior to this were carried out by the Microseismology Research Group at the University of Liverpool (led by Dr Peter Styles)

The Department of Earth Sciences at the University of Liverpool operated a single three-component seismic station at the Powys Observatory, Knighton, Powys for several years to monitor the seismicity of the Welsh Borders after the large (5.1) Bishop's Castle earthquake of 2 April 1990 and when plans were submitted for a windfarm development a few kilometres away on an adjacent farm it raised concerns that this might produce vibrations which would interfere with the detection of seismic events. Preliminary experiments were carried out near existing Mid-Wales windfarms followed by a significant study at St Breock Down, Cornwall funded by POWERGEN and ETSU (Styles P. (1996), Low-Frequency Wind Turbine Noise and Vibration: ETSU/POWERGEN, Contract Number 503922) and reported by SNOW, (ETSU W/13/00392/REP Low frequency noise and vibration measurements at a modern wind farm, D.J. Snow (1997)) and also reported by Manley and Styles (1995) and Legerton et al. (1996).

In addition a NERC funded studentship was awarded for Microseismic Investigation of Infrasonic Environmental Noise and Vibration (Rushforth, I, PhD Liverpool (2002), While vibrations were found to be well below the BS standards for disturbance to populations they were not interpreted in the light of possible disturbance to ultra-sensitive monitoring facilities.

Details of the various experiments which constitute these studies follow.

Previous Microseismic Monitoring of Wind farms in the UK

1   St. Breock Downs, Cornwall, SW 970 683, 50º 28' 33", 04º 51' 40"

Rated Power: 4.95MW
Wind Turbines: 11 Bonus 450kW
Rotor Diameter: 36 metres
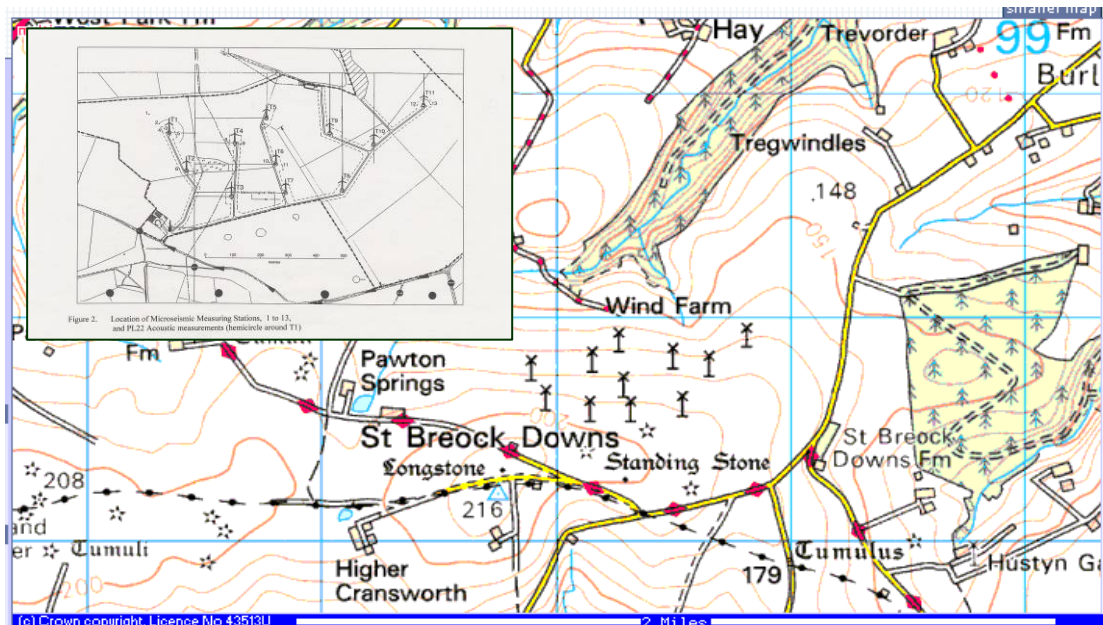Hub Height: 35m
Connection Voltage: 33 kV
Site Design and Environmental Impact Assessment: EcoGen
Planning Consent: August 1993
Developer: EcoGen SeaWest Tomen Joint Venture
Commissioning: June - July 1994
Owner: PowerGen

Figure 4   Location of recording stations for the St Breock Downs experiments

A sequence of three experiments were carried out

1   Deployment of VIBROSOUND SP1 24-bit Digital Recorder with LENNARTZ LE-3D/1 Seismometers in buried pits. Two sets of three-component seismometers were used with specifications and calibrations given in Appendix 1. These were deployed from 18 March until 30 March in order to record data from a wide range of wind speed and directions and were the principal instruments on which this investigation was based. Measurements were made at distances of 100 metres, 50 metres and 25 metres for Turbine 1 (positions 1, 2 and 3 on Figure 3).

**Figure 5   Recording Equipment for experiment 1**

2   Deployment of GEOSENSE DV1 three component digital seismographs with direct PC interface. This was a portable, compact three-component instrument with a bandwidth from 0.2 Hz to 64 Hz which could be quickly and easily moved from site to site. This was ideal for measuring the variation in the low-frequency signal form different turbines and at a range of distances. This experiment took place during the period 18 to 20 March 1996 and measurements were made at positions 4 through 13 on Figure 4 and also at a distance of c 1 kilometre at Pawton Springs Farm (Figure 4).

3   Measurement of Acoustic Noise Level Variation with azimuth around a wind-turbine using Diagnostic Instruments PL22 FFT Frequency Analyzer and a Cirrus Research Ltd ZE901-40F with MK 182LF Microphone Capsule. This was supplied directly from the manufacturers with a dedicated calibrator. This instrument was also used to measure the actual machinery vibration using B&K Type 5318 accelerometers mounted on the base of Turbine 1. (Figure 6).

Figure 6   Recording equipment for the on-tower experiment 3

The following objectives were addressed: and the following main conclusions were reached:

1   **To determine whether low frequency vibrations (down to 0.1 Hz) are transmitted through the ground from a modern wind farm and if so to measure their amplitude and frequency content**.
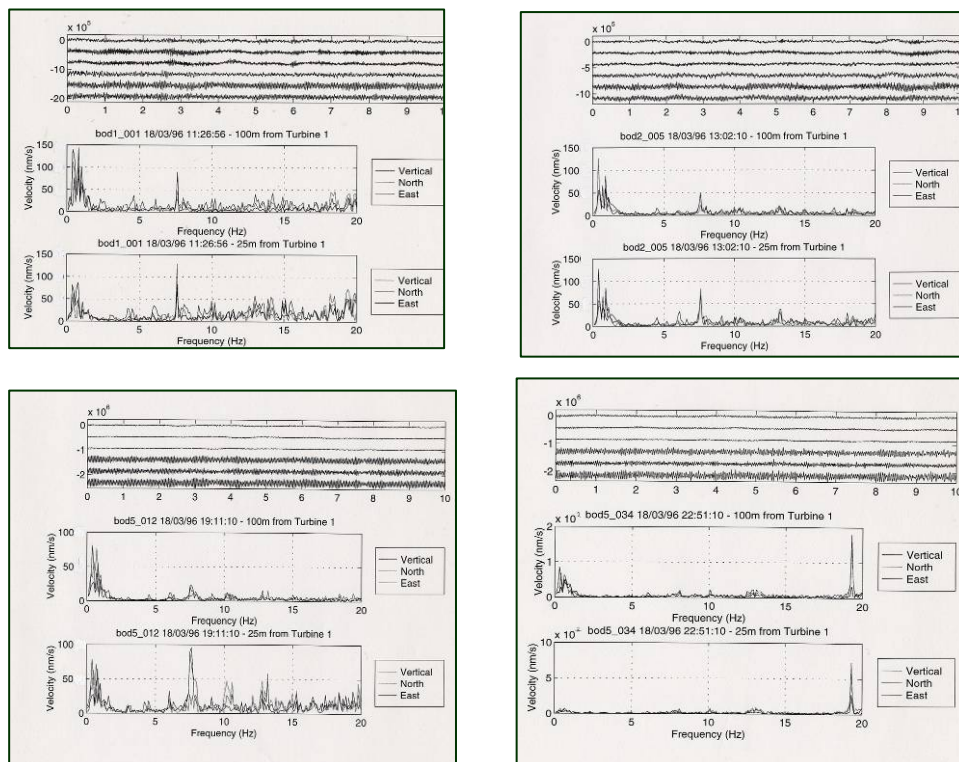
Figure 7   A selection of seismic signals and their spectra measured at St Breock Downs

Clear harmonic components at multiples of 0.5 Hz were observed on the majority of the spectra with particular peaks at 0.5, 3.0, 4.5, 6.0, 7.5 Hz and higher frequencies at levels of up to 250 nanometres s^{-1} (0.25 microns s^{-1}) and general levels of 50 to 80 nanometres s^{-1} (Figure 6) . The presence of so many harmonics which are multiples of the blade passing frequency and the clear attenuation of signal amplitude with distance especially for the 7.5 Hz component is a prima facie argument that the signals are being generated from the wind turbines and although the levels are small they can easily be detected on appropriate sensors. The 1.5 Hz component is not the strongest harmonic as might have been suspected.

2   To make measurements at a range of distances to determine the variation in frequency and amplitude of low-frequency vibrations

Measurements were made at distances of 25, 50 and 100 metres from Turbine 1 and the frequencies above 3.0 Hz were seen to attenuate with distance with higher frequencies decaying faster as expected. During the sequential shutdown frequencies were observed over a distance of some 500 to 700 metres and significant attenuations noted with the exception of the very lowest frequencies which in fact increased in frequency. This may be a due to interference effects which were less with fewer turbines in operation or the harmonic may be sourced from elsewhere. The 0.5 Hz signals were detected at a distance of c 1 kilometre from St Breocks Down at Pawtonsprings Farm.

3   To make measurements for a range of wind speeds to determine the variation in frequency and amplitude of low-frequency vibrations

Measurements were made over a range of wind speeds from c 7 ms^{-1} to 14 ms $^{-1}$ at a constant direction (Figure 8). The amplitude of the harmonics generally increase with increasing windspeed. This is particularly evident for the 0.5 Hz harmonic, the 3 Hz harmonic and the 7.5 Hz harmonic. However and rather surprisingly the amplitude of the 6 Hz harmonic shows an inverse relationship: as the wind speed rises the amplitude of this harmonic falls. It seems that the partition of energy between the 6 and 7.5 Hz harmonics in particular is strongly dependent on wind-speed. Notwithstanding the reservations expressed concerning the nature of the ultra-low vibrations, the increase in amplitude of the 0.5 Hz component with wind speed suggests that it does have a source which is related in some way to the wind turbine farm.

4   To make measurements for a range of wind directions to determine the variation in frequency and amplitude of low-frequency vibrations

Measurements were made over a range of wind directions from c 120^0 to c 310^0 at a constant wind speed of 10 ms^{-1}. Clear variations in amplitude were

observed with levels varying by about a factor two. The variation had the same spatial pattern for most frequencies and this pattern correlated with acoustic measurements made at closer angular increments within the limitations of the data
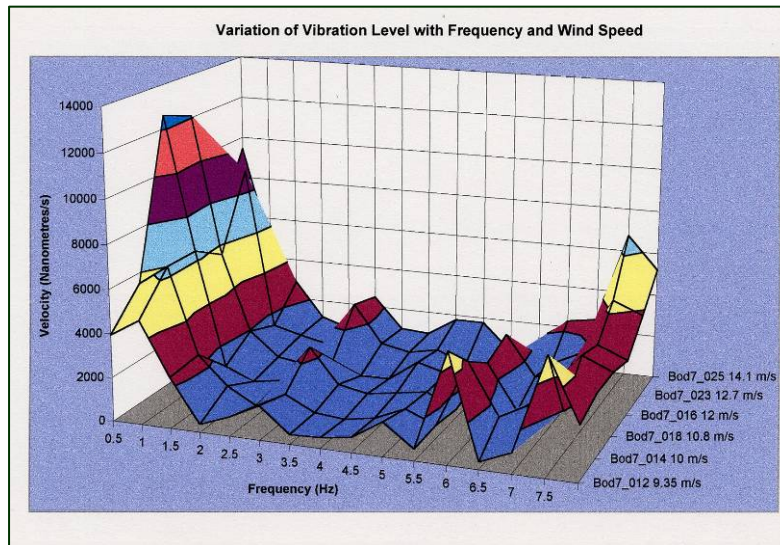
Event Number	Wind Speed	Wind Direction
Bod7_012	9.35	119.5
Bod7_014	10.0	113
Bod7_016	12	123
Bod7_018	10.8	110
Bod7_023	12.7	118.5
Bod7_025	14.1	120

Figure 8   Variation of Amplitude and frequency with windspeed

5   To investigate the variation of amplitude and frequency as a sequence of wind turbines were sequentially switched off
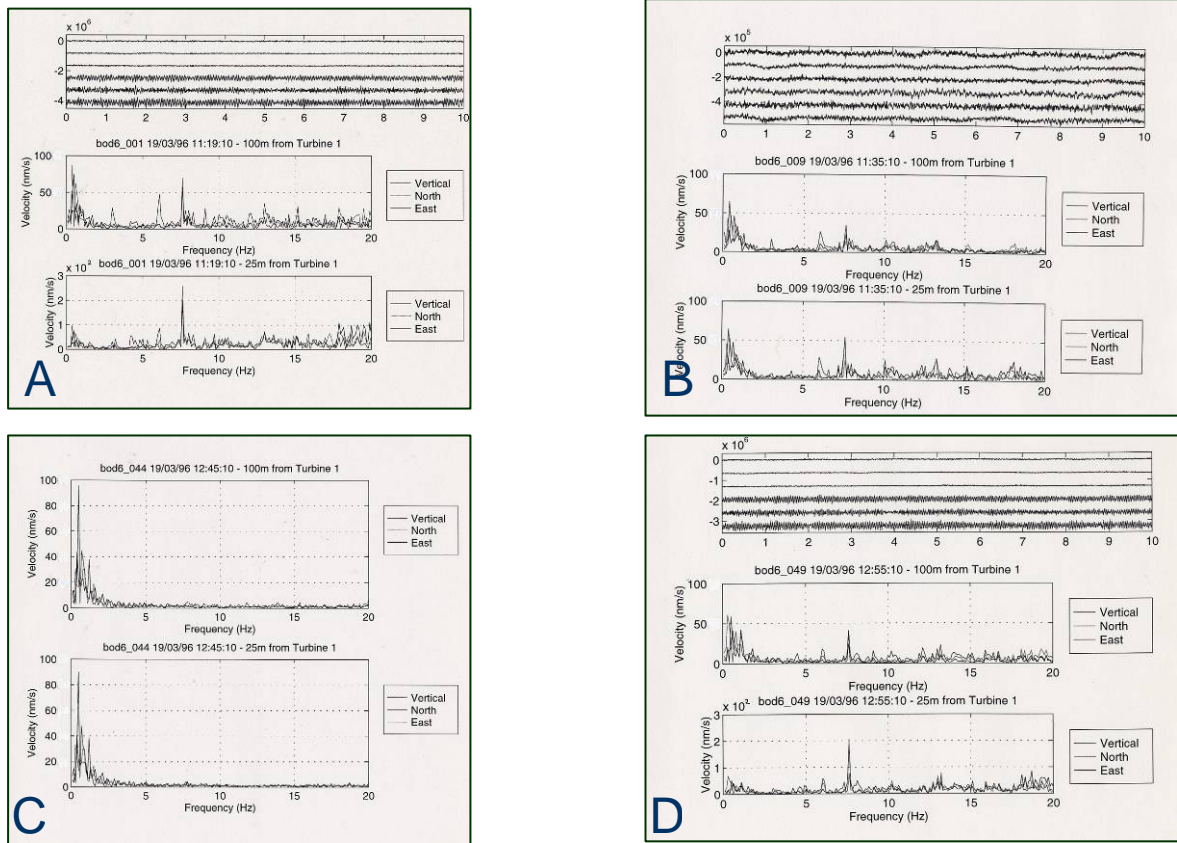
Figure 9   Sequential Shutdown

A) All On, B) T1 Off, C) All Off, D) Only T1 On

Time Interval	Turbines On	Turbines Off	Event Numbers
11:19 to 11:28	All 1 to 11	None	Bod6_001 to Bod6_005
11:29 to 11:48	2 to 11	1	Bod6_007 to Bod6_016
11:49 to 12:08	3 to 11	1,2	Bod6_017 to Bod6_025
12:09 to 12:10	4,5,6,7,8,9,10,11	1,2,3	Bod6_026
12:11 to 12:12	5,6,7,8,9,10,11	1,2,3,4	Bod6_027
12:12 to 12:23	3,5,6,7,8,9,10,1	1,2,4	Bod6_028 to Bod6_3
12:24 to 12:41	5,6,7,8,9,10,11	1,2,3,4	Bod6_034 to Bod6_041
12:42 to 12:49	None	1,2,3,4,5,6,7,8,9,10,11	Bod6_042 to Bod6_046
12:50 to 12:56	1	2,3,4,5,6,7,8,9,10,11	Bod6_047 to Bod6_050
12:57 to 13:13	None	1,2,3,4,5,6,7,8,9,10,11	Bod6_053 to Bod6_058
13:14 to 13:15	3	1,2,4,5,6,7,8,9,10,11	Bod6_059

16
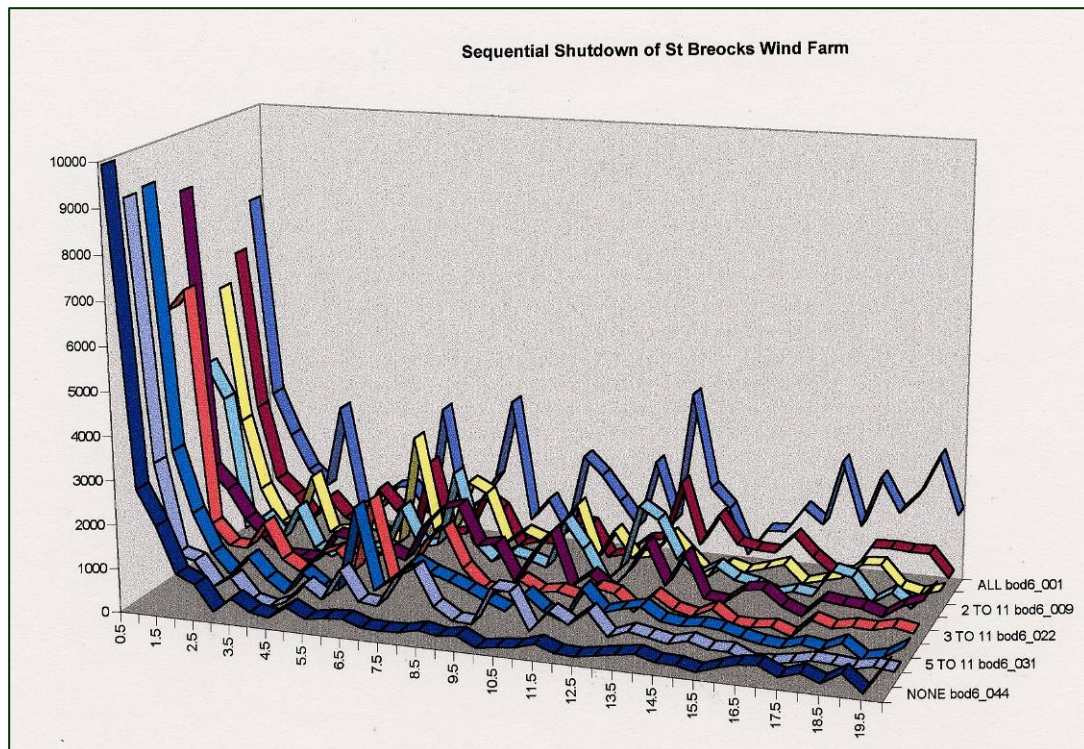
Figure 10   Shutdown Summary

The levels of vibration fell in a manner which was consistent with their origin being from the wind turbine farm. The lowest frequencies persisted even when the whole turbine field was shut-down which indicates that their source may be external to the site or that some complex interference is happening between the multiple vibration sources such as the resonance of the tower structure itself under wind loading.

6   To investigate the variation of amplitude and frequency between individual wind turbines

The presence of large wind components on the shallowly buried instrument masked some of the subtler variation but the levels of vibration (c 50 to 100 nms^{-1}) were consistent between machines although individual frequencies showed considerable variation over the whole St Breocks site.

7   To investigate the frequencies present in the vibrational spectrum of the turbine tower itself for comparison with the microseismic measurements

Figure 11, recorded using accelerometers mounted on the base of Turbine 1, clearly show tonal components which correspond with the frequencies observed out as far as 1 km away from the windfarm. The 4.5 and 7.5 Hz components seen on the microseismic records are particularly pronounced within the infrasonic band (sub 20 Hz) as are other harmonics of 1.5 Hz.

17
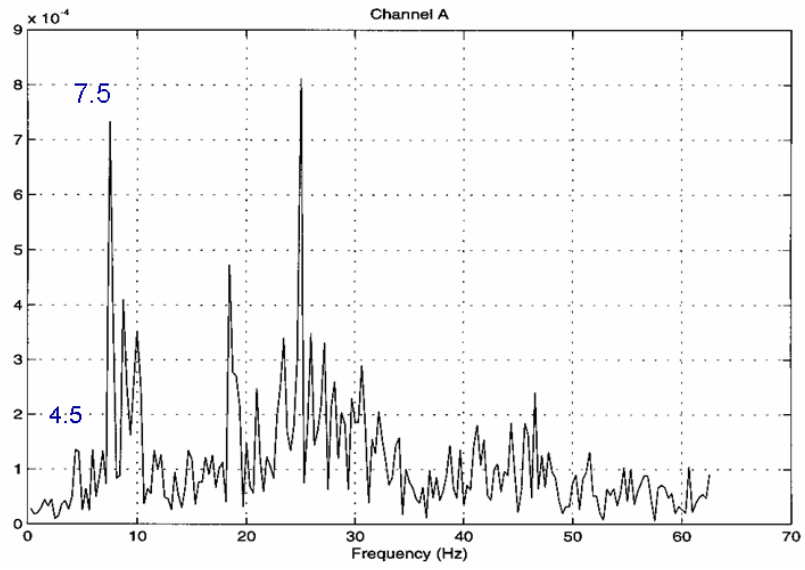
Figure 11   On-tower accelerometer spectrum at Turbine 1 recorded while all other turbines were switched off.
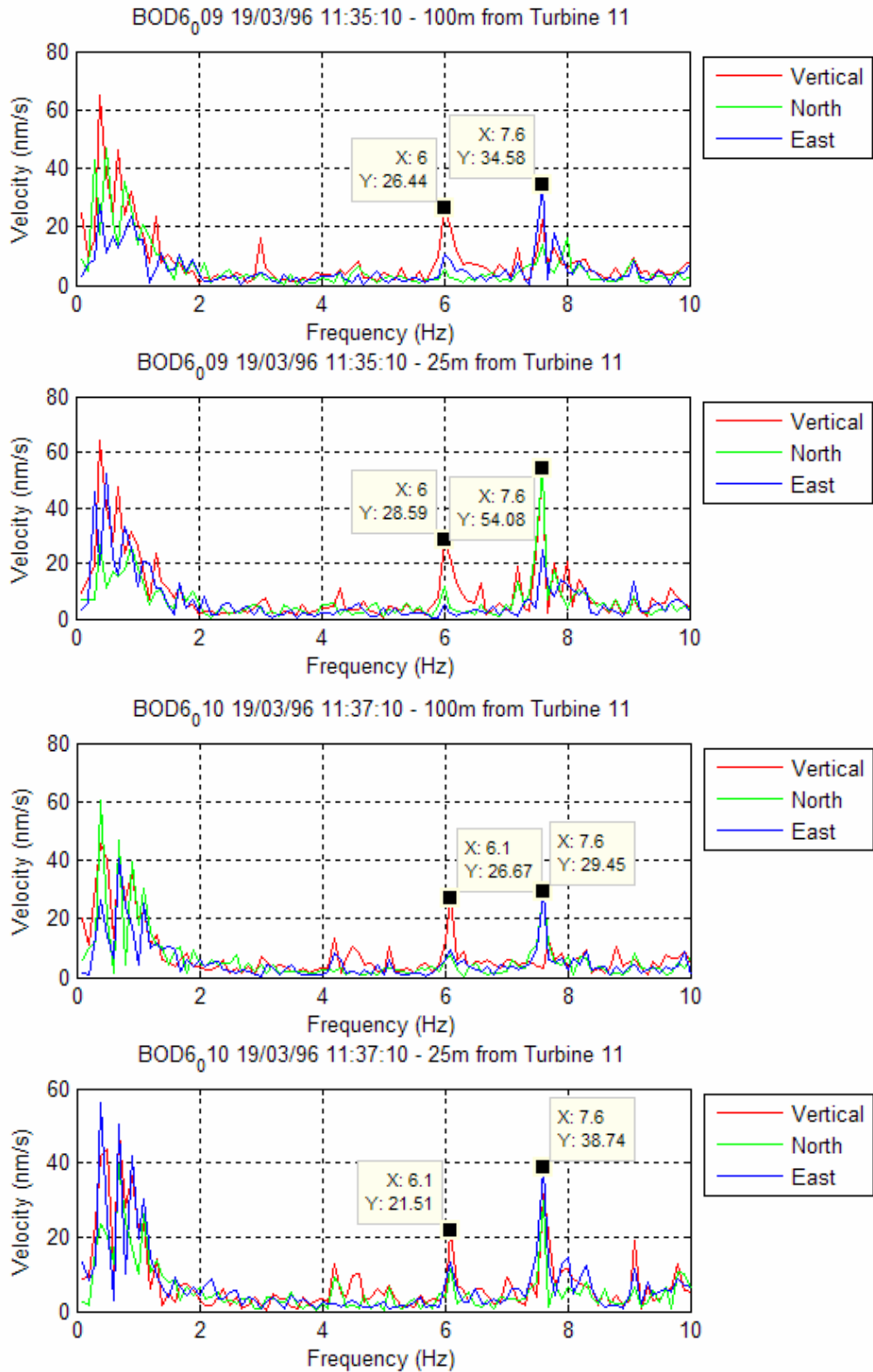
**Figure 12   Selected spectra during the sequential shut-down at St Breock Downs**

8   To investigate the mode of propagation of the seismic vibrations

The spectra above and the following figure show the variation in amplitude of the best detected 6 and 7.5 Hz harmonics, against distance from the turbine during the switch-off experiment. These and their averages have then been compared with different models for the attenuation of the amplitude with distance. There is considerable variation but the data fit a $r^{-(1/2)}$ model much better than a r^{-1} model.
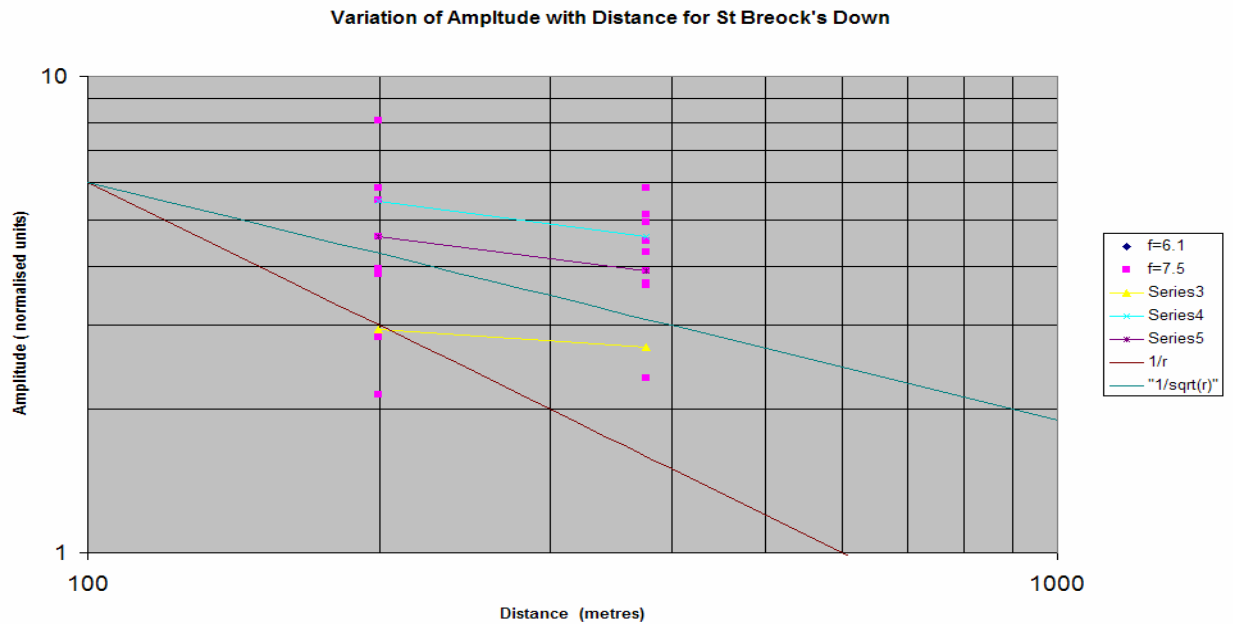
Figure 13   Variation of amplitude of well-detected frequencies with distance and a comparison with various attenuation models.
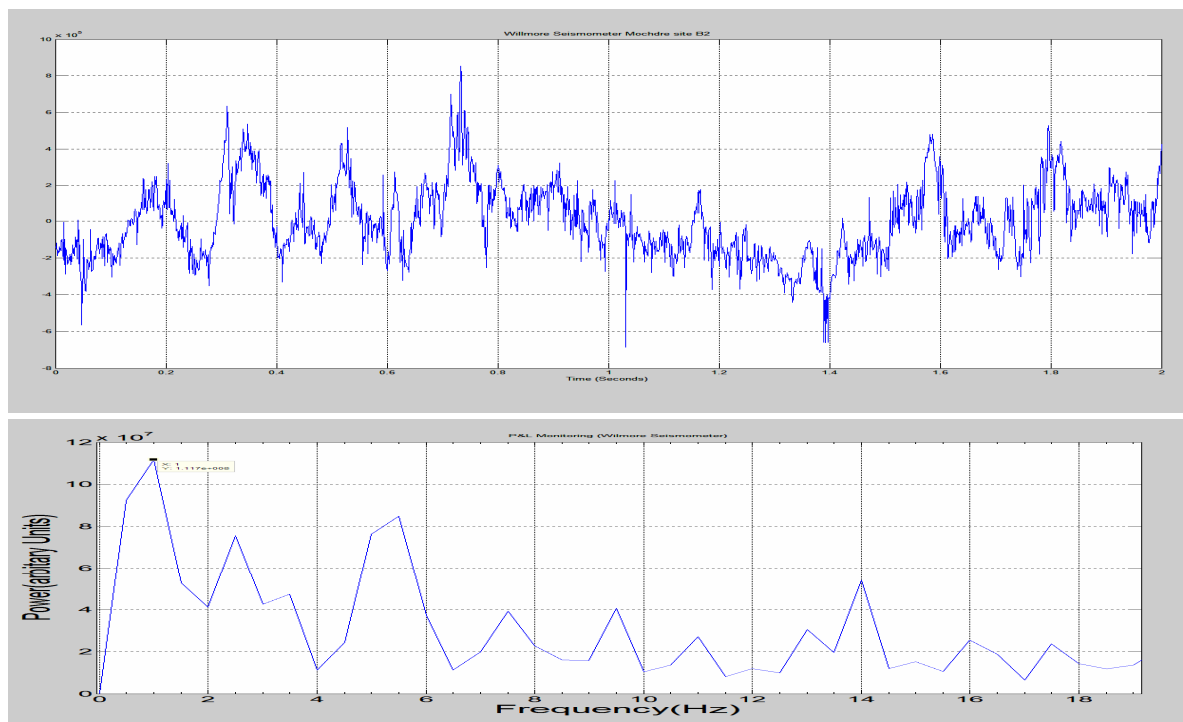
Llandinam
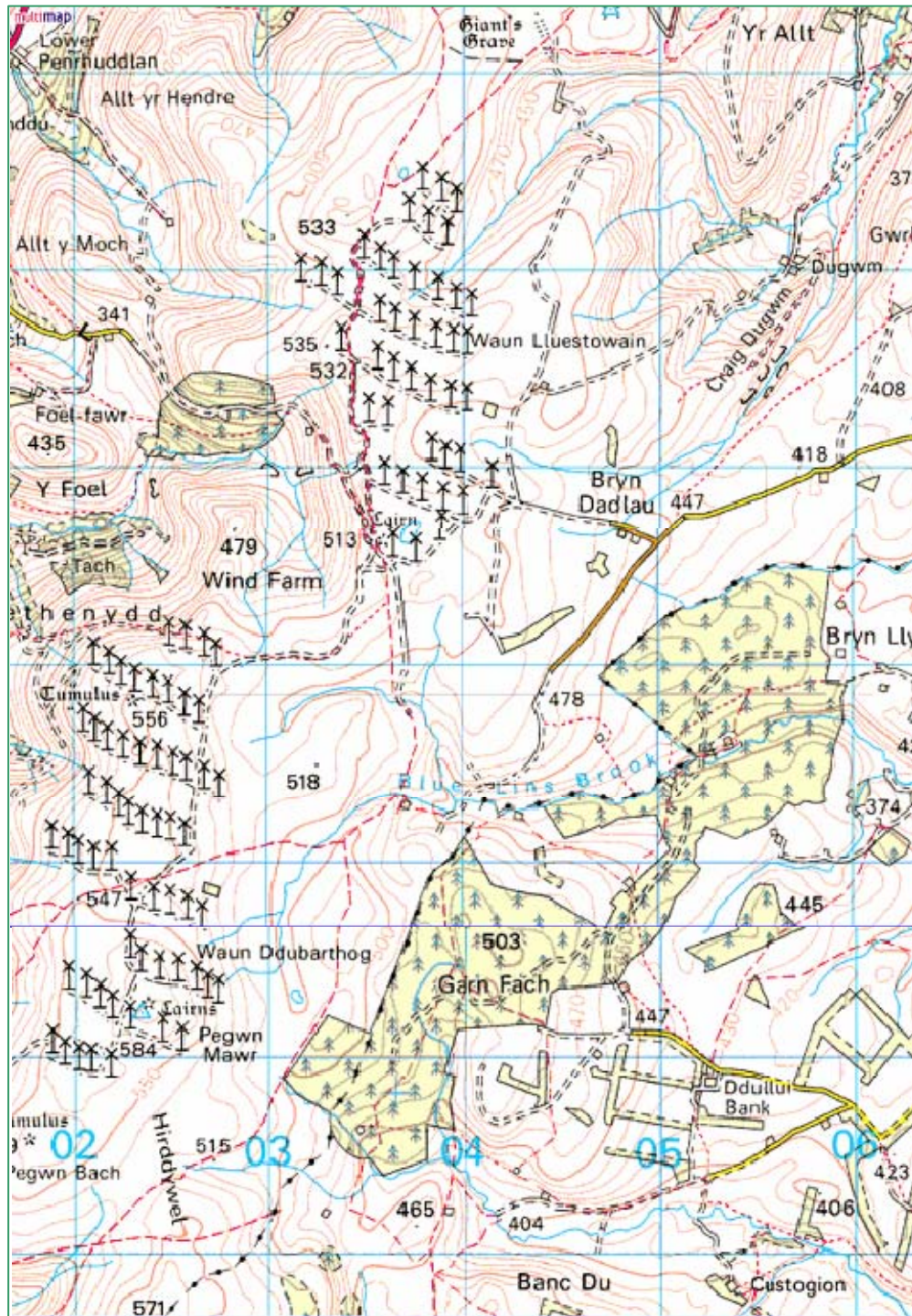
Fig 14

Llandinam P+L Powys
Mitsubishi 300
103 turbines   30.9MW.
N52^o 26.11 W03^o 24.49

Llandinam wind farm lies 10km south of Newtown and has been operational since January 1993. At the time of its construction it was both Europe's and the UK's largest wind farm, both in terms of number of turbines and generating capacity consisting of 103 Mitsubishi turbines, each rated at 300kW, giving a total capacity of 30.9 MW. The site is owned by CeltPower Ltd., a joint venture between Scottish Power plc (50%) and the Tomen Corporation of Japan (50%). The site is colloquially known as the 'P&L'. (Penrhydlan & Llidiartiwaun)

This monitoring was carried out first during September 1994

Figure 15   Microseismic Data acquired at Lllandinam during 1994.

Figure 15 show the presence of apparent harmonic structure but the resolution of the recording system was insufficient to properly characterize it. A system with greater bandwidth (1 KHz) became available and subsequent data were acquired during 1996 at a property adjoining the wind farm called Y Graig. An example of this data during a period of high (but undetermined) wind speed and low wind speed are shown below (Figure 16) where the tonal components can be clearly seen during high, but are significantly reduced during low, wind speeds.
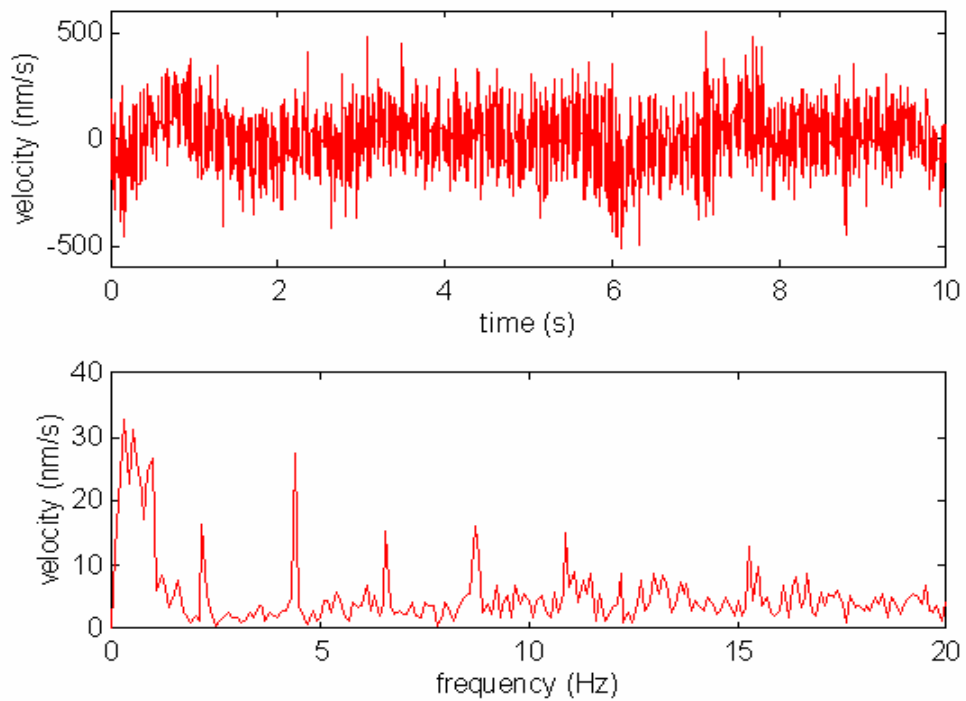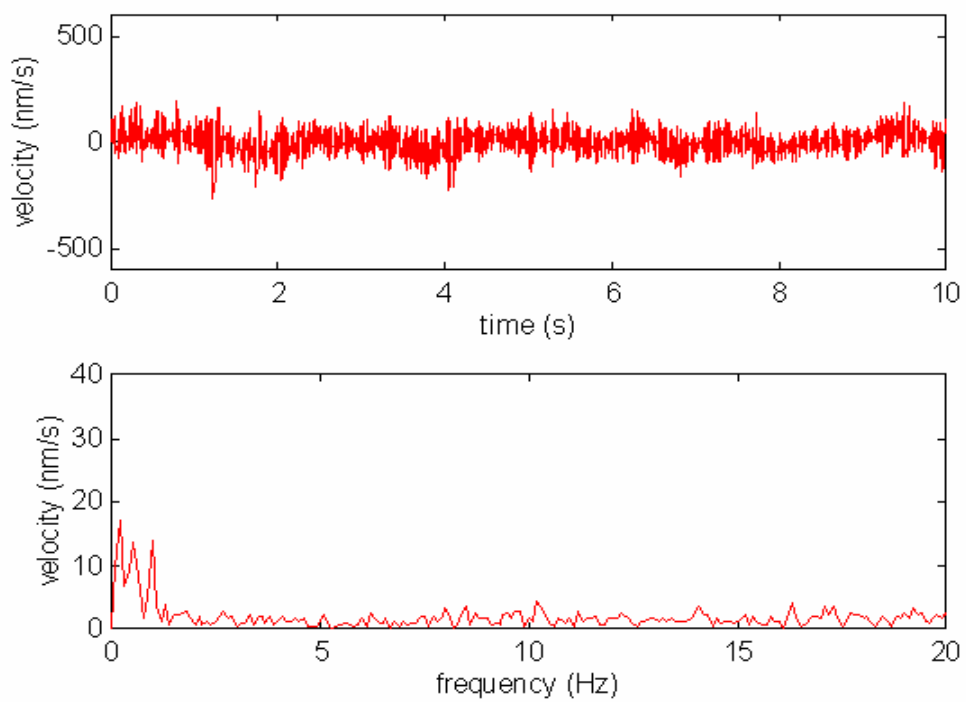
Figure 16   Microseismic data acquired at Y Graig, Llandinam during periods of high and low wind speed.

Previous Relevant Microseismic Monitoring in the USA

Stateline Survey Schofield (2001) 399 VESTA V47 Turbines

The new Maiden Windfarm development of 150 MW capacities was proposed to be sited c 20 km away from the LIGO, (Laser Interferometry Gravitational Observatory) at Hanford in Washington State. This is the machine which will try to detect Gravitational waves from black holes and supernovae to test the predictions of Einstein's General Theory of Relativity. Schofield (2001) carried out an appraisal of vibrations for the operational Stateline Windfarm (also in Washington State) which comprises 399 Vesta V47 Turbines and confirmed Styles (1996) and Snow (1997) conclusions that harmonic seismic signals (summarised below) were generated from windfarms and could be detected to considerable distances. These results are especially relevant to the site used for this study (Dun Law) as the wind turbines are of the same type. The results of his monitoring are summarised in the following table

Table 1: Peaks that decreased in frequency at low wind velocities

| Approximate frequency at high wind velocity (Hz)	Comments
0.49	rotation frequency of turbine (29 rpm)
1.47	3rd harmonic of rotation frequency (blade pass frequency)
2.95	6th harmonic
4.34	9th harmonic (largest peak relative to background)
5.88	12th harmonic
7.35	15th harmonic
Higher harmonics appeared to be present but were difficult to distinguish	
30	generator frequency

Table 2: Fixed-frequency peaks

Peak Frequency (Hz)	Comments
0.669	
11	broad peak; 5 - 17 Hz

He detected signals above LIGO ambient seismic background out to 18.3 km (Figure 17) which has significant implications for Eskdalemuir particularly as estimates of seismic background noise level at EKA are well below the noise levels measured at Stateline and at the LIGO site. He considered from the decay of signal amplitude with distance that the signals propagated as infrasound signals (acoustic signals at less than 20 Hz) which propagate through the air and which were postulated to couple into the ground to

generate seismic vibrational signals in a manner which was not completely understood.
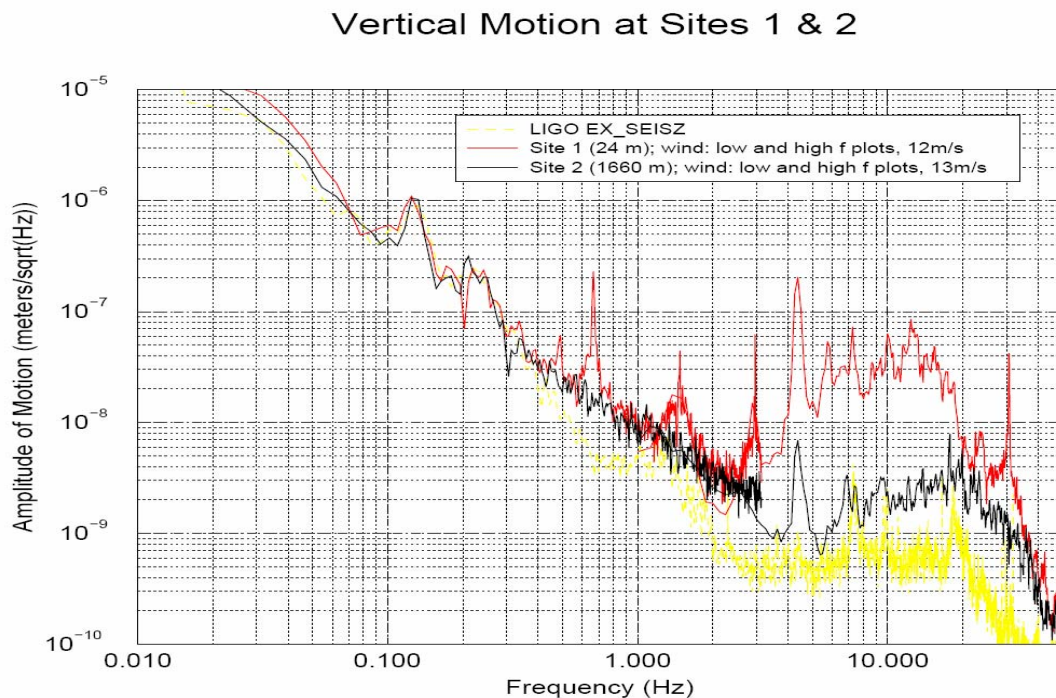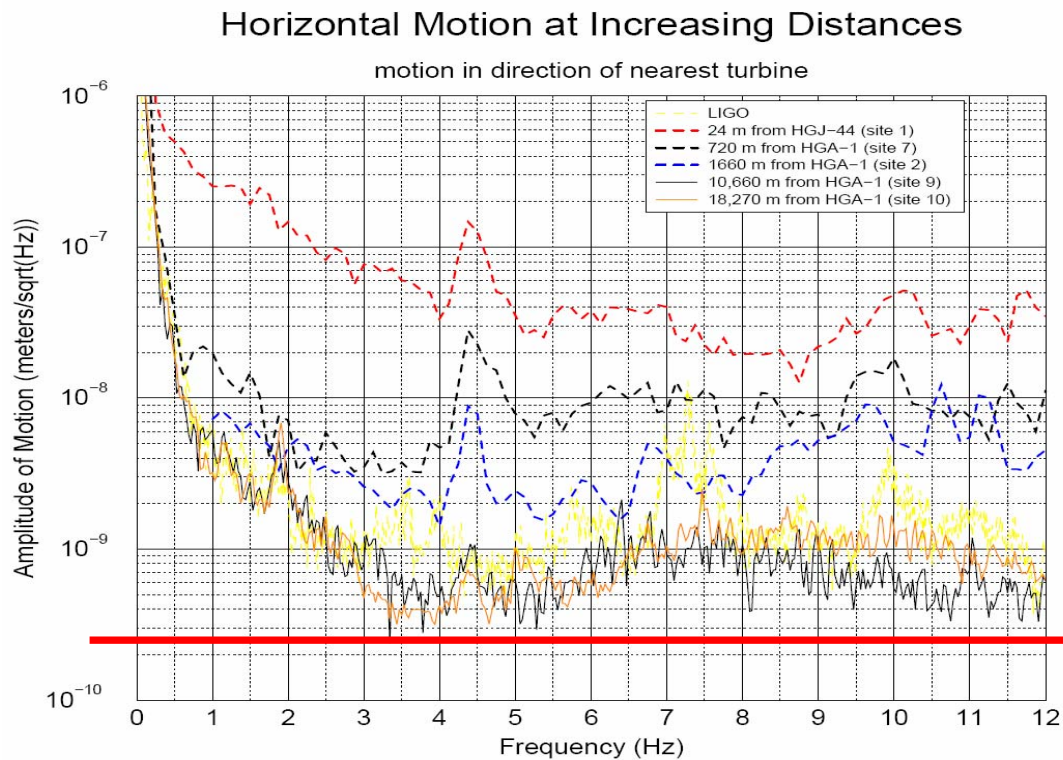
Figure 17   Seismic results from the Stateline windfarm as reported by Schofield (2001). EKA (red line) is over an order of magnitude quieter in amplitude than the LIGO site.

A comparison of the common features of UK and US work leads to the following conclusions:

>
> i   Turbines operating at production rotation rates (high wind speeds of c 10 ms^{-1}) generate harmonic seismic signals in the pass band of interest for seismic monitoring/CTBT verification (0.5-5.0Hz)
>
> ii   The harmonic signal frequencies are related to overtones of the blade-passing frequency of the turbine.
>
> iii   The turbine generated signals can be detected at distances of >10 km.
>
> iv   Seismic spectra from St. Breock show a peaks around 0.5Hz when the turbines rotors are stopped in wind speeds of 9.5 m/s (A study of Bonus 450kW Mk III by the manufacturers shows a peak at 0.8Hz**).** Spectra from Stateline (V47) show a fixed frequency peak at 0.669 Hz.
>
> v   The presence of so many harmonics which are multiples of the blade- passing frequency and the clear attenuation of signal amplitude with distance is a prima facie argument that the signals are being generated from the wind turbines and although the levels are small they can easily be detected on appropriate sensors and are likely to have significance for seismic discrimination at Eskdalemuir

This led to the following key question being posed:

> *What seismic signals are generated by wind turbines in the UK, and are they going to significantly affect the operational performance of EKA?*

Microseismic and infrasound monitoring of windfarms in southern Scotland

In order to address the preceding question, experiments were set up with the following objectives:

i   To deploy appropriate seismic and infrasound sensors and recording equipment to monitor the ground vibration levels and infrasound signals generated by modern wind farms as a function of distance as far as logistically possible

ii   determine the characteristics and mode of propagation and attenuation rates of these signals

iii   To compare these with current ambient seismic levels at the Eskdalemuir IMS monitoring site.

iv   To develop a model for the propagation of seismic signals from windfarms and use this to assess the potential impact of planned capacity on the detection capability of Eskdalemuir.

Three phases of experimental deployment were carried out to address particular aspects of these objectives.

Phase 1   Installation of ten, three component seismic sites at increasing distances away from Dun Law windfarm which were operated almost continuously from July to December 2004

Phase 2   Deployment of four infrasound stations collocated with seismic stations at specific distance from Dun Law to ascertain whether the signals detected propagate as infrasound or as seismic surface waves

Phase 3   Installation of accelerometers on wind turbine towers and strong motion detectors in the immediate vicinity of fixed speed (Dun Law) and variable speed (Ardrossan) to ascertain how the mechanical vibrations of the towers compare to ground vibrations

To support this work the following resources were procured:

1   Long-term equipment hire of Guralp 6-TD three-component broad-band instruments from the NERC geophysical equipment pool SEISUK (Operated by the University of Leicester).
2   Hire of Guralp High Frequency recording system from Guralp UK
3   In-kind support of seismic and infrasound instrumentation and field engineers from the CTBTO.
4   In-kind support of instrumentation from Geological Survey of Canada.

Selection of a Test Site

Criteria

i   Geological setting to be as close as possible to that experienced at Eskdalemuir. Therefore, preferably on Ordovician/Silurian mudstones and shales. These are found in a broad region striking ENE across the Southern Uplands and bounded by the Southern Uplands fault to the north and the England/Scotland border (approximately) to the south.
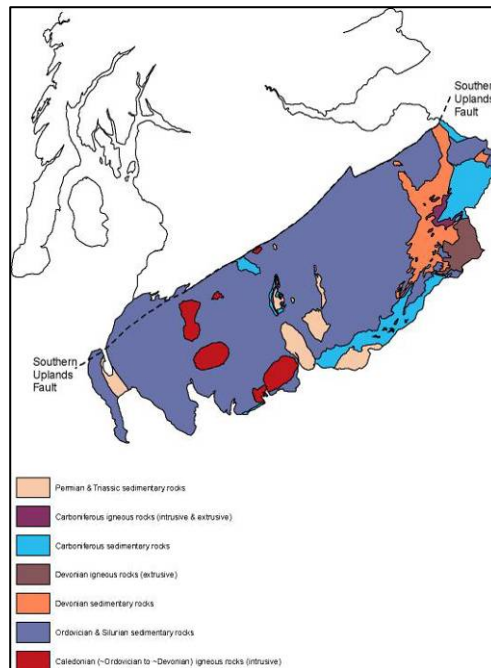
Figure   18   Outline geology of the Southern Uplands and outcrop exposed in a small quarry adjacent to the seismic array showing folded and cleaved Silurian mudstones.

ii   Quiet seismic background in order to be able to detect signals comparable to the seismic background noise at Eskdalemuir

iii   Large area of little or no human habitation/infrastructure to permit a long array of seismometers to be set out

iv   Significant size windfarm with permission to monitor from the operators and potential for carrying out a sequential switch-off.
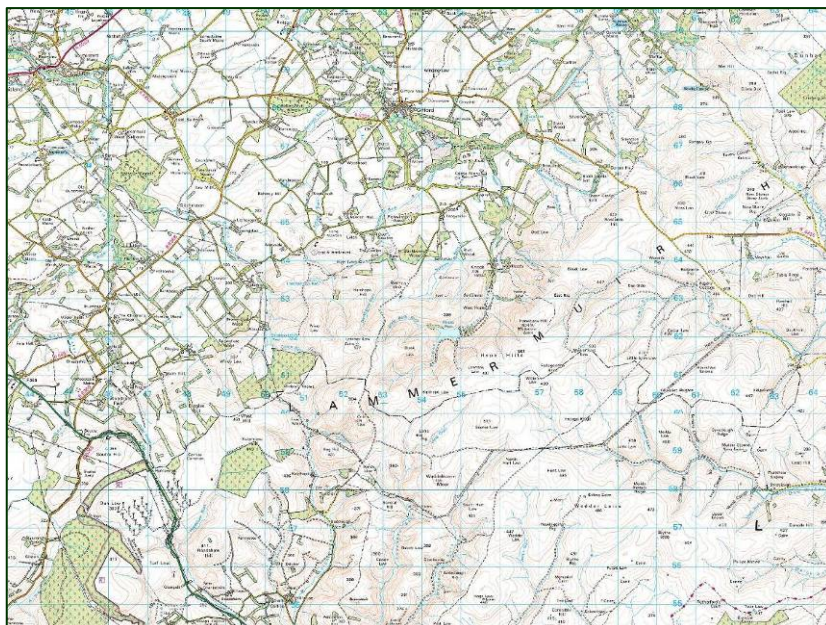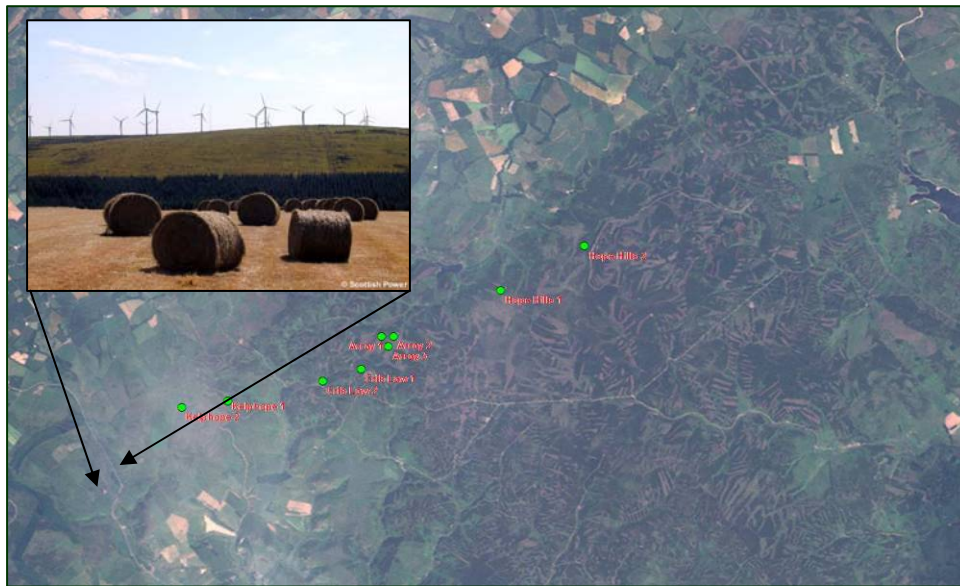
Figure 19   Map and Satellite photo of the Lammermuir Hills and the area east of Dun Law windfarm which was chosen for the main experiments

After some considerable searching a test site was chosen at Dun Law, a fixed-speed, 26-turbine (Vestas V-47) windfarm of 17 MW capacity operated by Scottish Power. The area of deployment was large tracts of grouse moor owned by Hope Estates and is shown on the following map and satellite photograph. It is clear that this is an ideal area as there is almost no habitation apart from occasional gamekeeper and farm cottages.
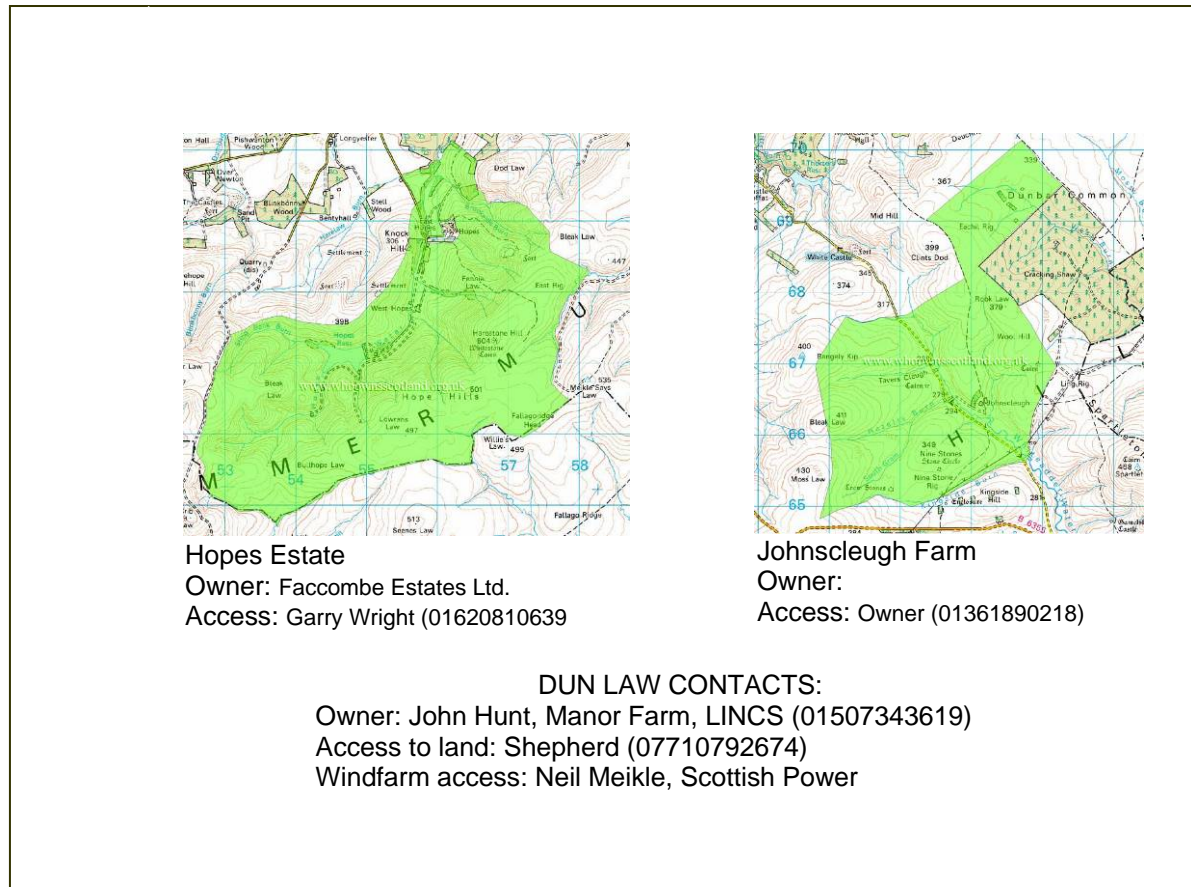
Dun Law Pros and Cons

✓ Virtually Same Geology as Eskdalemuir
Cleaved and Folded Ordovician and Silurian Mudstones and Shales

✓ Huge area of High Moorland with no trees, population (in fact nothing at all!) to cause extraneous background noise

✓ Vestas V47 Wind Turbines which are exactly the same as the Stateline experiment of Schofield

✗ Contract Delay meant Project Start coincided with the start of Grouse Shooting Season!

✗ Peat Bogs

Figure 20   Flooding of seismic sites during the very poor weather of August 2004

We were very fortunate to have excellent cooperation from the estates which owned the Dun Law windfarm site and also Hope Estates who own the majority of the land on which the seismometers were deployed and we are grateful for their assistance especially as the bulk of the work took place during their grouse shooting season.

Hopes Estate
Owner: Faccombe Estates Ltd.
Access: Garry Wright (01620810639

Johnscleugh Farm
Owner:
Access: Owner (01361890218)

DUN LAW CONTACTS:
Owner: John Hunt, Manor Farm, LINCS (01507343619)
Access to land: Shepherd (07710792674)
Windfarm access: Neil Meikle, Scottish Power

Figure 21   Outline of the land holdings and contact details for the owners of the estates on which monitoring took place

Phase 1 – Deployment of Guralp Systems CMG-6TD broadband seismometers.

Figure 22 **CMG-6TD Broad-band three-component seismometer**

This phase consisted of deploying ten CMG-6TD seismometers in shallow pits at distances out to c. 17 Km from the windfarm to provide data showing the vibration caused by Dun Law windfarm and attenuation with distance. Full details of the deployment are described in Appendix A and only a summary is given here.

Site Name	UTM, Coordinates	Sensor Serial Number	Distance from northwest point of Dun Law (m)
Kelphope 2	NT 48954 58867	T6064 & T6121	1391
Kelphope 1	NT 49927 59007	T6123	2362
Crib Law 2	NT 51950 59469	T6083	4425
Crib Law 1	NT 52764 59735	T6091	5242
Array 1	NT 53210 60479	T6087	5939
Array 3	NT 53349 60246	T6132	5981
Array 2	NT 53455 60477	T6179	6175
Hope Hills 1	NT 55739 61515	T6124	8868
Hope Hills 2	NT 57518 62521	T6047	10702
Johnscleugh	NT 63008 66344	T6155	17287

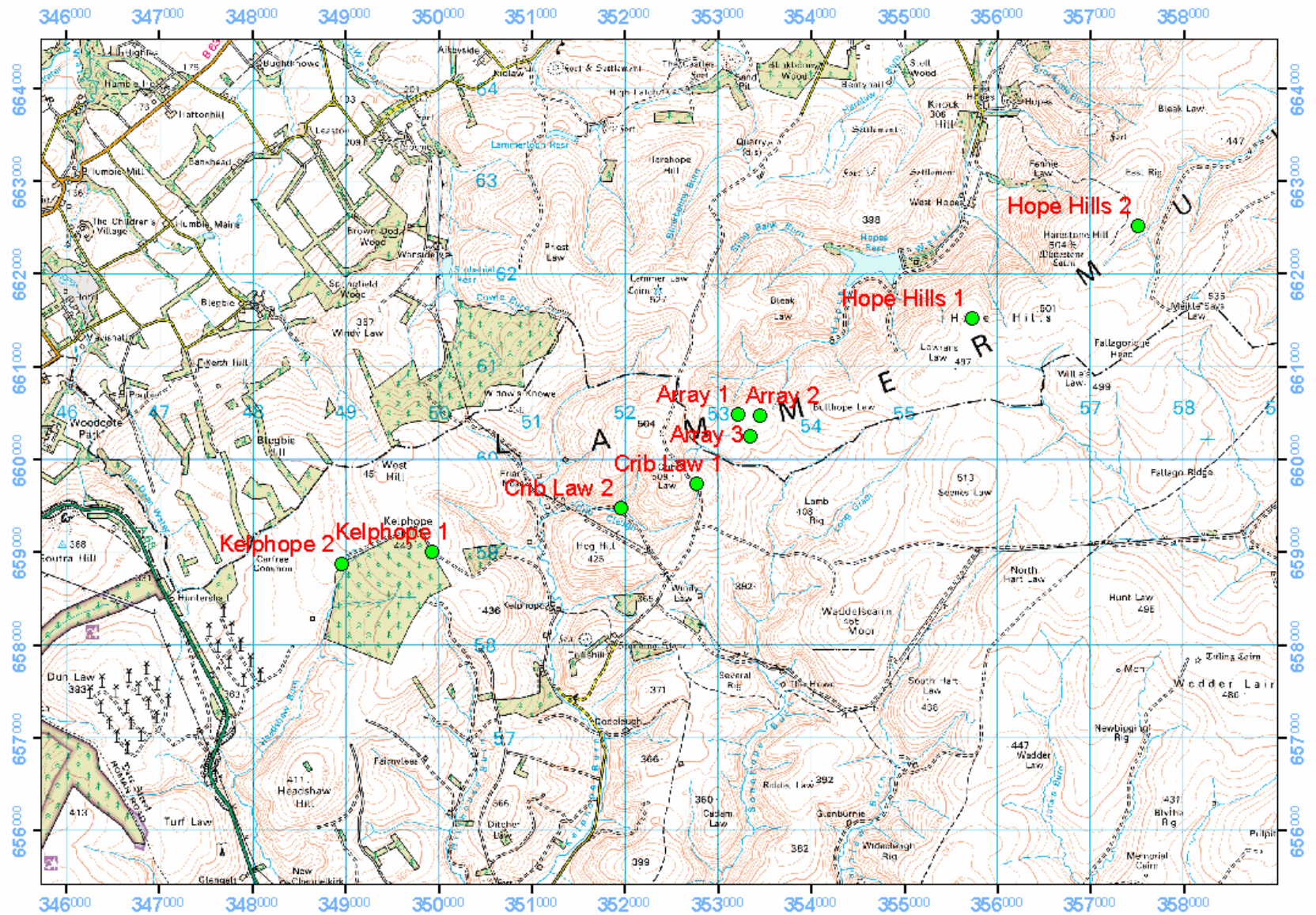Table 3 Locations of the Guralp 6TD seismometer stations

Figure 23 Location of the Seismometer (Guralp 6TD) sites

Expected Spectral Content

The analysis of the data from St Breock Downs showed clear harmonics which were multiples of the blade-passing frequency and therefore also harmonics of the rotation rate. Schofield (2001) has monitored the same type of wind turbine (Vestas V47) as we have here at Dun Law and obtained a particular suite of frequencies. We can therefore predict what principal frequencies we would anticipate from the Dun Law windfarm for a rotation rate of 28.5 rpm. It is clear from previous work that it is the blade-passing frequency which is the dominant excitation of vibrations and the table below shows all possible harmonics up to 10Hz. It should of course be realized that interference between sources may cause beating at sum or difference frequencies of these components which will contribute to the broadening of the peaks. However, our work to date has shown that the blade-passing frequencies are relatively easy to discriminate.

Harmonic (Rotation Rate)	Harmonic (Blade Passing)	Hz
1		*0.48*
2		*0.95*
3	**1**	**1.43**
4		*1.90*
5		*2.38*
6	**2**	*2.85*
7		*3.33*
8		*3.80*
9	**3**	*4.28*
10		*4.75*
11		*5.23*
12	**4**	*5.70*
13		*6.18*
14		*6.65*
15	**5**	*7.13*
16		*7.60*
17		*8.08*
18	**6**	**8.55**
19		*9.03*
20		*9.50*
21	**7**	**9.98**

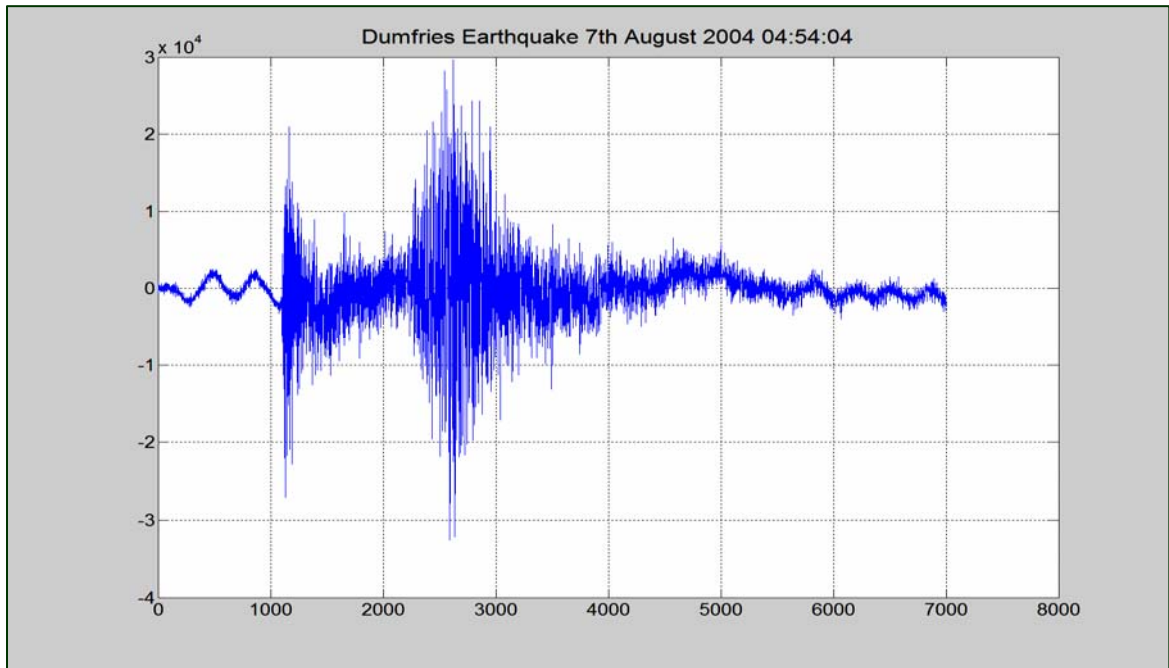Table 4 Blade-passing frequency and its harmonics for a rotation rate of 28.5 rpm

Figure 24   This shows a small earthquake which occurred near Dumfries on the 7th of August 2004, giving useful confirmation that the system was working well

DATE :   7 August 2004
ORIGIN TIME : 04:54 04.7s UTC
LAT/LONG :   55.07° North / 3.67° West
GRID REF :   293.4 kmE / 576.8 kmN
DEPTH :   5.4 km
MAGNITUDE :   2.2 ML
INTENSITY :   3+
LOCALITY :   Dumfries, Dumfries & Galloway

On-Tower Measurements at Dun Law

In order to establish the spectra of the excitation from the turbine towers an experiment was carried as described in detail in Appendix C using accelerometers mounted within Turbine 22 tower as shown on the following map.
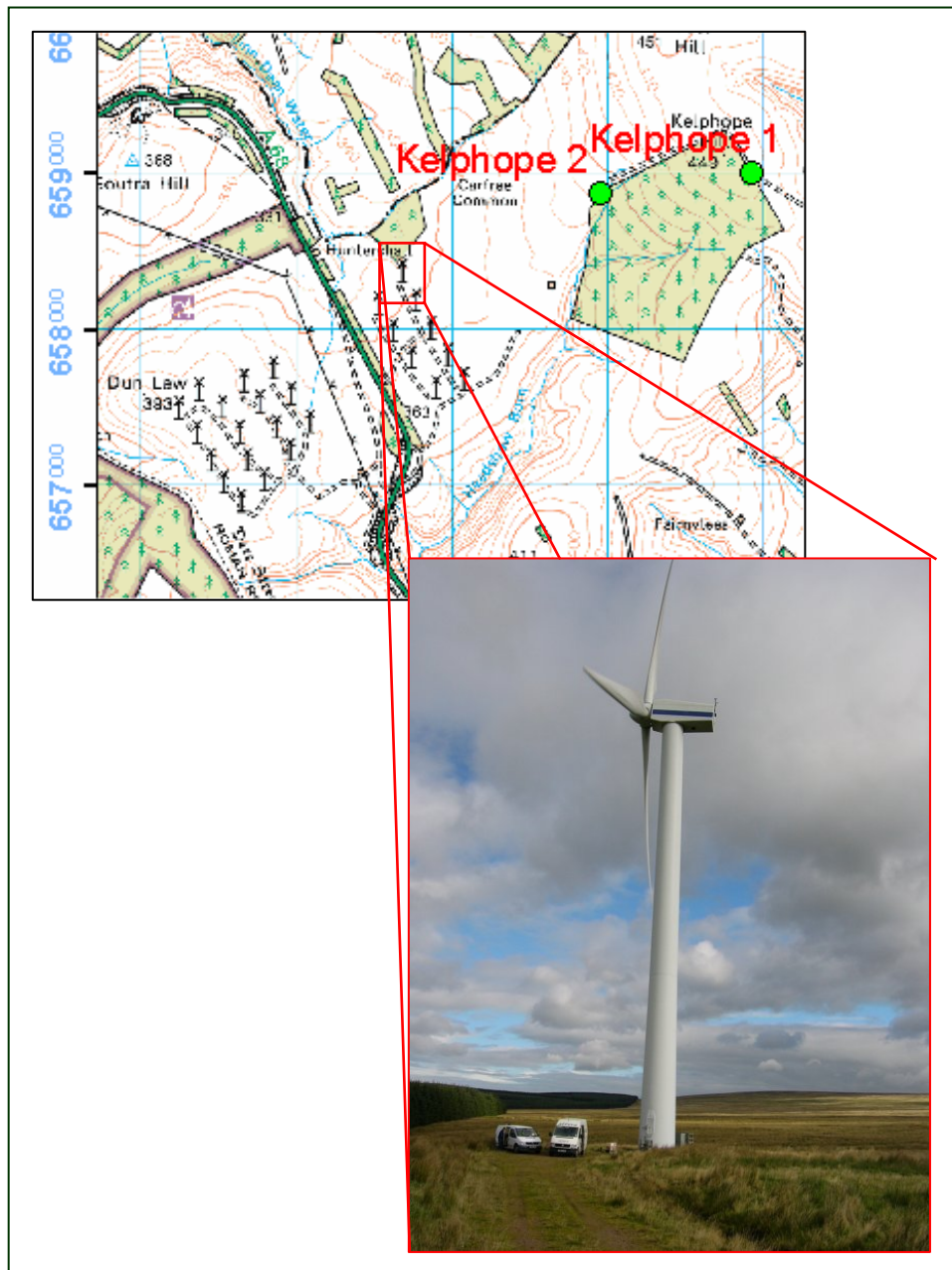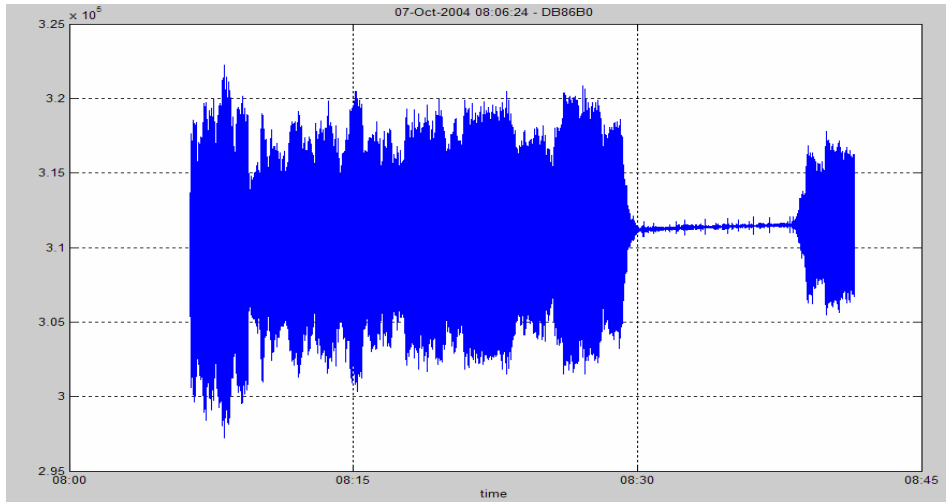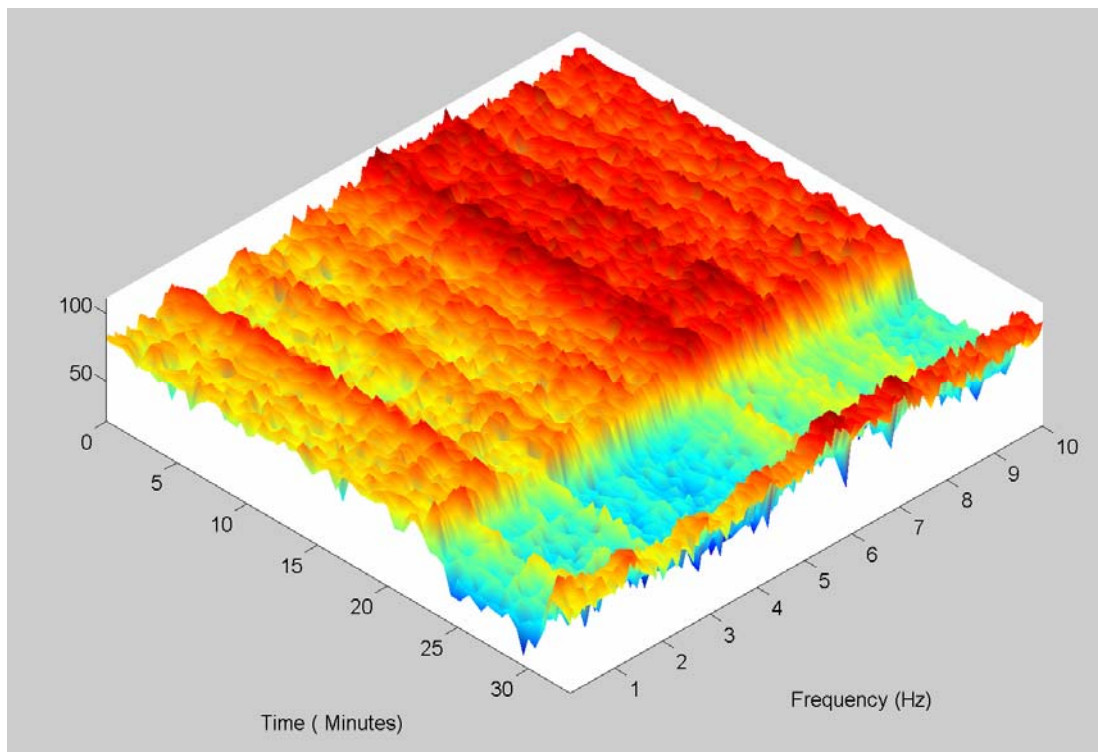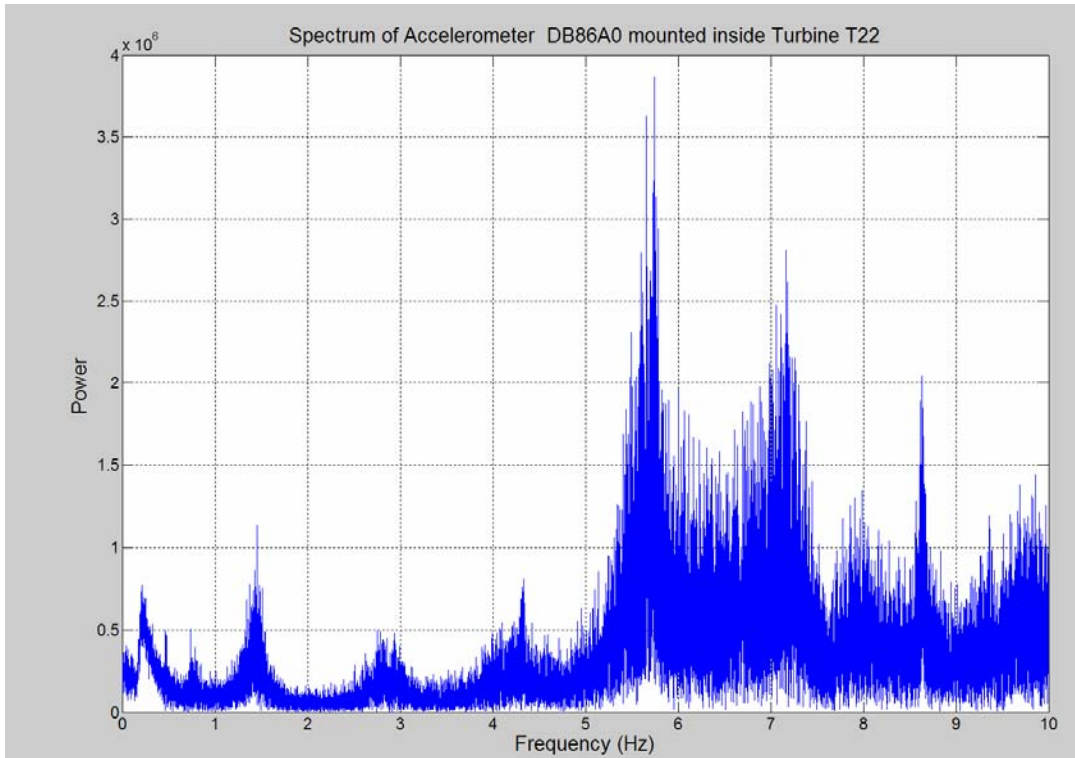

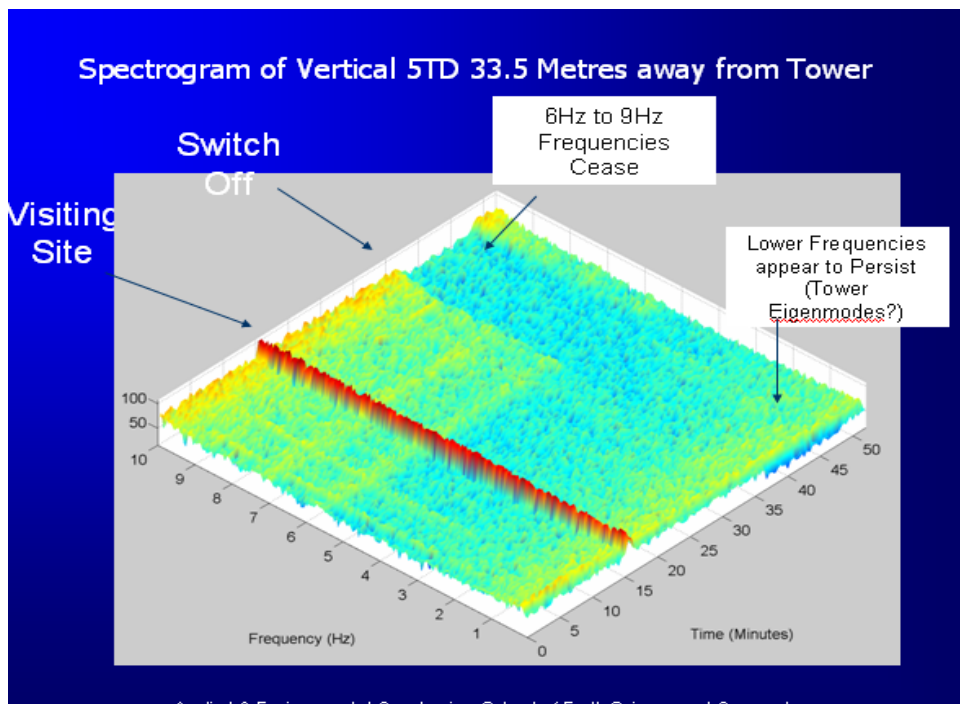Figure 25 Map of Dun Law wind farm and location of Turbine 22

Figure 26 Accelerometer record of DB86AO on Turbine T22 during switch off and back on 7 October 2004

Figure 27   Spectrogram of accelerometer DB86AO during Turbine T22 Switch Off

Figure 28   Blade-passing (1.43 and Harmonics) and structural resonances of Turbine T22

Figure 29   Spectrogram of vertical 5TD accelerometer situated 33.5 Metres away from Tower 22

Figure 26 shows the vibration record recorded on one of the accelerometers clearly showing the drop and rise in amplitude during the switch-off. Figure 27 shows a spectrogram of the signal during this period. A spectrogram is a set of successive frequency analyses through overlapping time windows of a long period of data and this method of display allows the identification not only of individual frequencies but how they change with time throughout an interval such as the switch-off we see here. It is clear that frequencies are occurring close to those predicted in Table 4 and that they cease during the switch-off and then re-appear at switch-on. However, there are low amplitude frequency components which appear to continue across the switch-off and indeed some that appear to be *only* present then. It seems probable that these are related to structural modes of the turbine powers which are excited when the blades are braked and energy has to be dissipated in the tower itself. There is a low frequency peak at c 0.75 Hz which may correspond to the 0.67 Hz peak observed by Schofield.

Figure 28 shows a composite spectrum throughout the interval and significant components at 1.4, 2.8, 4.3, 5.7 Hz and higher can be clearly seen. The broadening of the peaks is due to the complex sequence of events which are composited into this spectrum.

Figure 29 show the spectrogram recorded on a 5-TD strong-motion accelerometer buried 33.5 metres away from the tower and again the switch of and the change in spectra can clearly be seen albeit not so strongly as on the tower itself. The strong feature running across at time, t=18 minutes, is caused by a visit to the site and the opening and closing of the turbine tower door as we checked the system before the switch-off.

We can then, with some confidence, identify peaks at these frequencies observed on more distant seismometer records as having their origin in vibrations generated from Dun Law windfarm.

The software for these Power Spectral Density (PSD) analyses and displays has been written for this project using the MATLAB package and the principal program (Dun_Law_Proc.m) is given in Appendix C. The data have been filtered beneath 0.5 Hz to remove the very strong noise peak which occurs due to wave microseismic noise and which would obscure the analysis because of its dominant amplitude.

Analysis of seismic records from Lammermuir array

More than 40 GBytes of seismic data have been collected during this experiment and only a minute fraction are shown here as examples, or to illustrate particular points of importance. The data are archived at the Applied and Environmental Geophysics Group, Keele University and can be consulted on application and with the permission of the Eskdalemuir Working Group.

19-Sep-2004 - 6123E2 6123N2 6123Z2

Z PSD
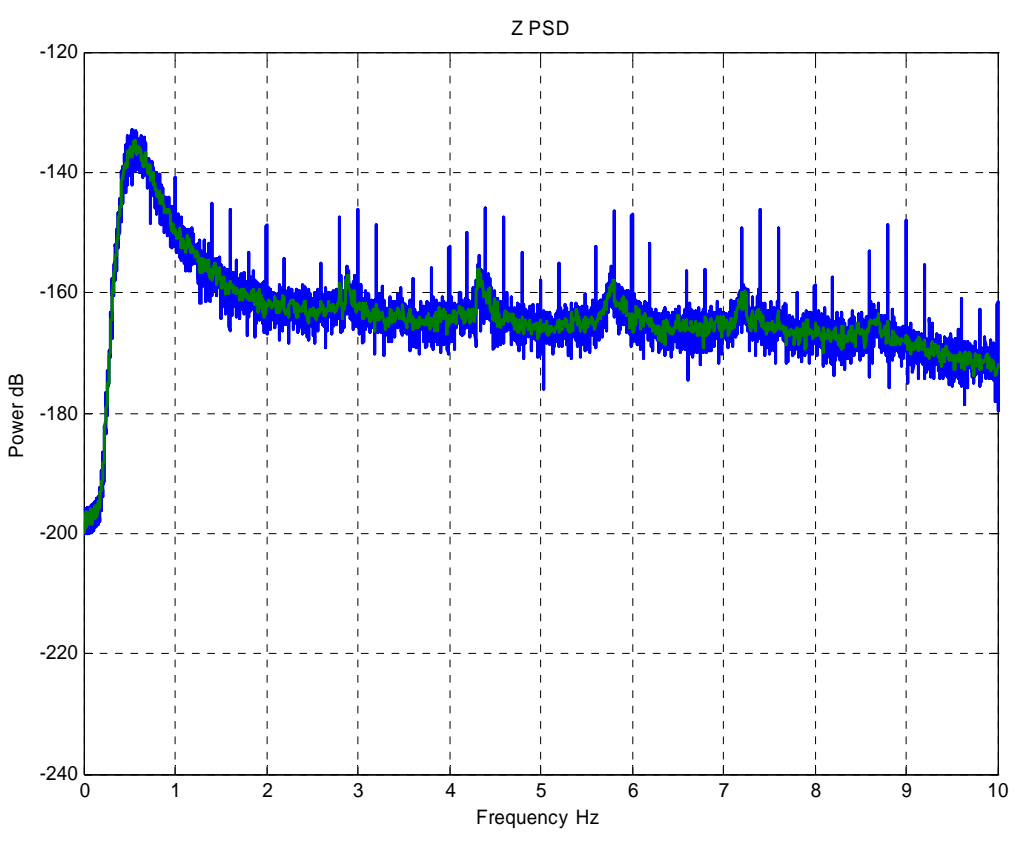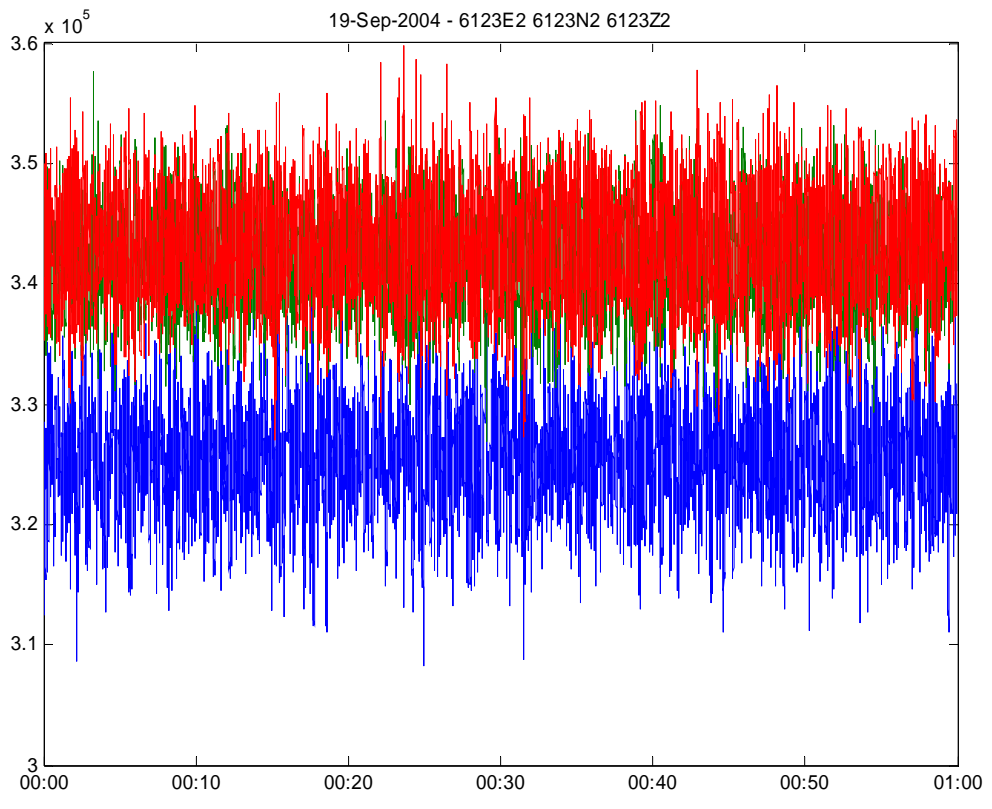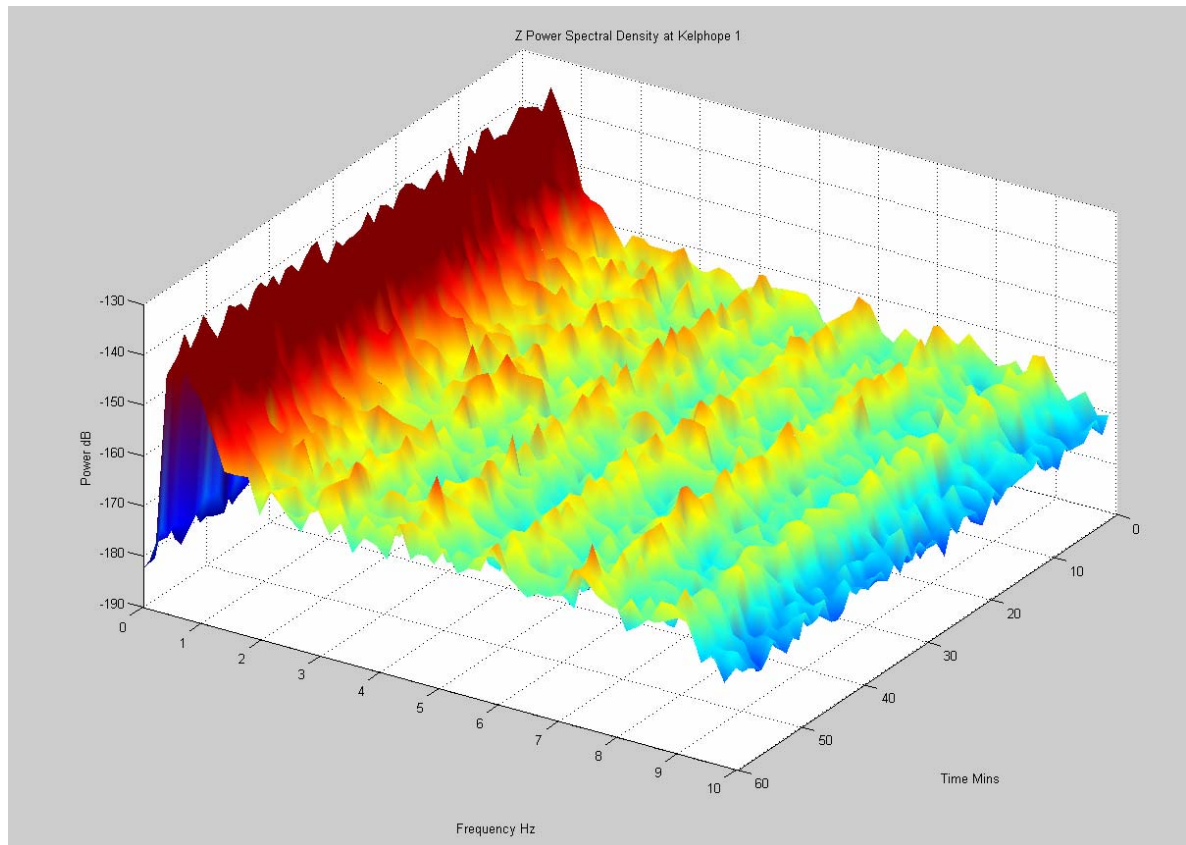
Figure 30   Seismic three-component record, its power spectral density (z-component) and spectrogram at Kelphope 1 on 19 September 2004 between 00:00 and 01:00

It should be noted, that notwithstanding our search for a quiet site away from ambient background noise and the selection of the Lammermuir Hills as an exceptional site, the background noise is still some 20dB greater than Eskdalemuir, confirming how quiet a site EKA really is.

Fig 30 is an example of seismic data for 19 September 2004 between midnight and 01:00 am from Kelphope 1, some 2.4 km away from the nearest point of the Dun Law windfarm and the spectrogram and PSD show the prominent presence of the principal harmonics of 2.8, 4.3, 5.7, 7.1, 8.5 Hz as predicted and as observed in both the on-tower measurements and the infrasound measurements at Kelphope 1. The fundamental blade-passing frequency at 1.4 Hz is not readily apparent but is masked by the rising background noise which climbs sharply below 2 Hz and the averaging process which is employed to give robust estimates of the Power Spectral Density for the spectrograms. However, a narrow band analysis (Figure 31) of part of the data shows that it **IS** present and also demonstrates even more clearly the principal harmonics. Figure 32 shows a similar narrow band spectrum from Crib Law 2 some 4.4 km away during the same interval
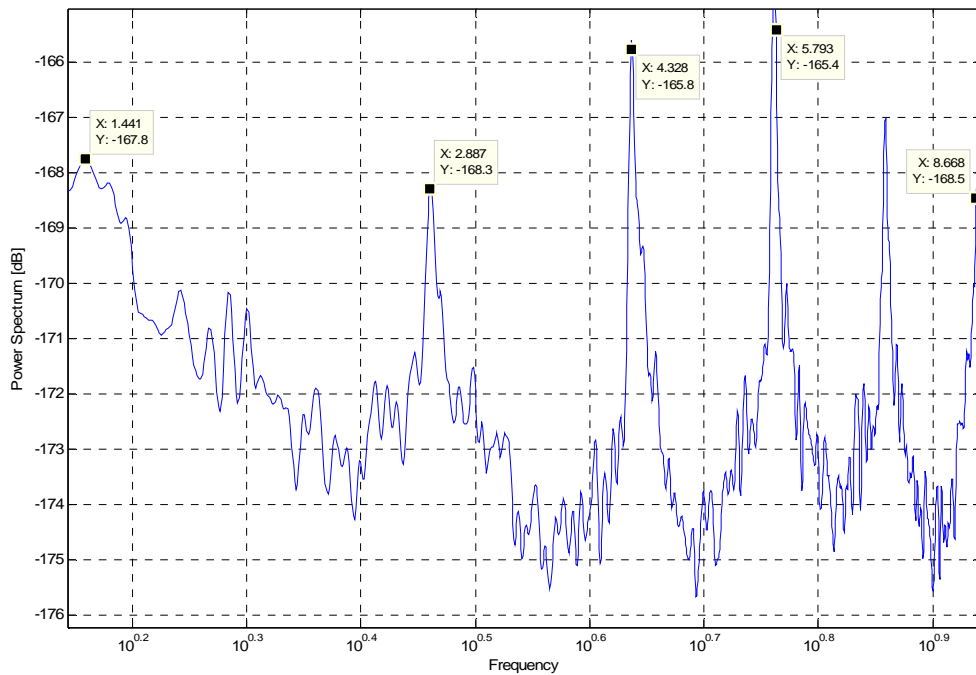
**Figure 31   Narrow-band spectral analysis of part of the seismic data from 19 September at Kelphope 1 showing the 1.4 Hz and higher harmonics of the blade-passing frequency.**
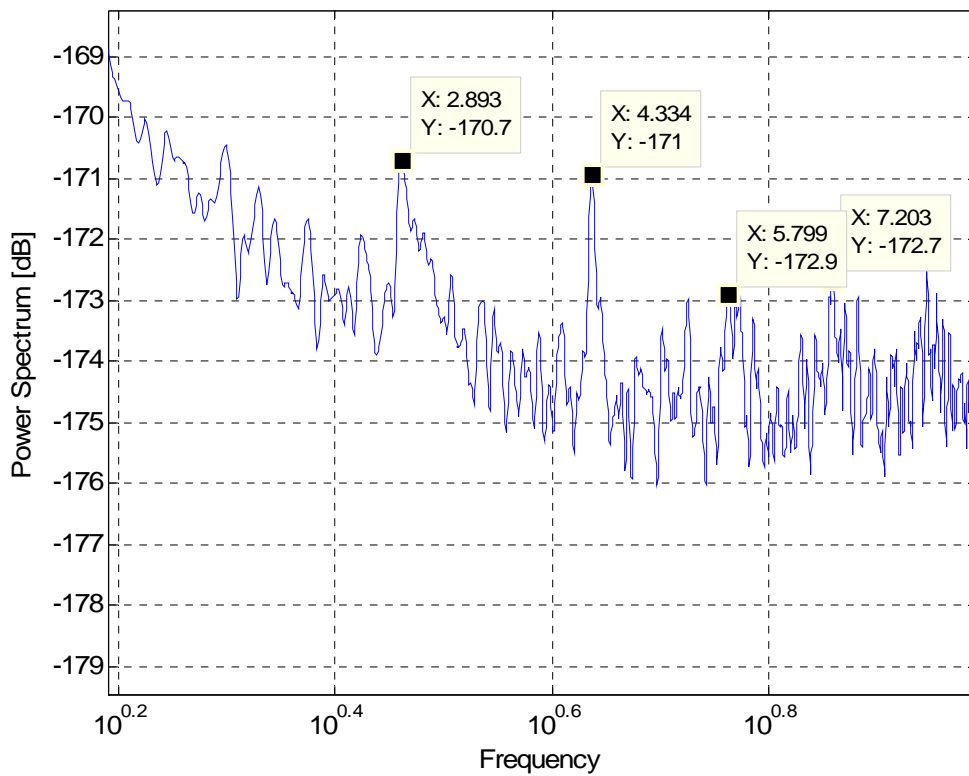
Figure 32   Narrow-band spectral analysis of part of the seismic data from 19 September at Crib Law 2 (4.4 km) showing the 2.8 Hz and higher harmonics of the blade-passing frequency

Fig 33 shows the seismic record and spectrogram recorded at Array 3, some 6 km away from Dun Law and again the 5.7, 7.1 and 8.5 Hz components can all be clearly seen throughout the whole duration of the record. The data have been rotated into principal components with the X-component radial to the longitudinal axis of the array and the Y-component tangential to the longitudinal axis and the z-component vertical. After this rotation, the energy is largely confined to the X and Z-components suggesting that that it is propagating as vertically polarised P-SV (Rayleigh) waves.
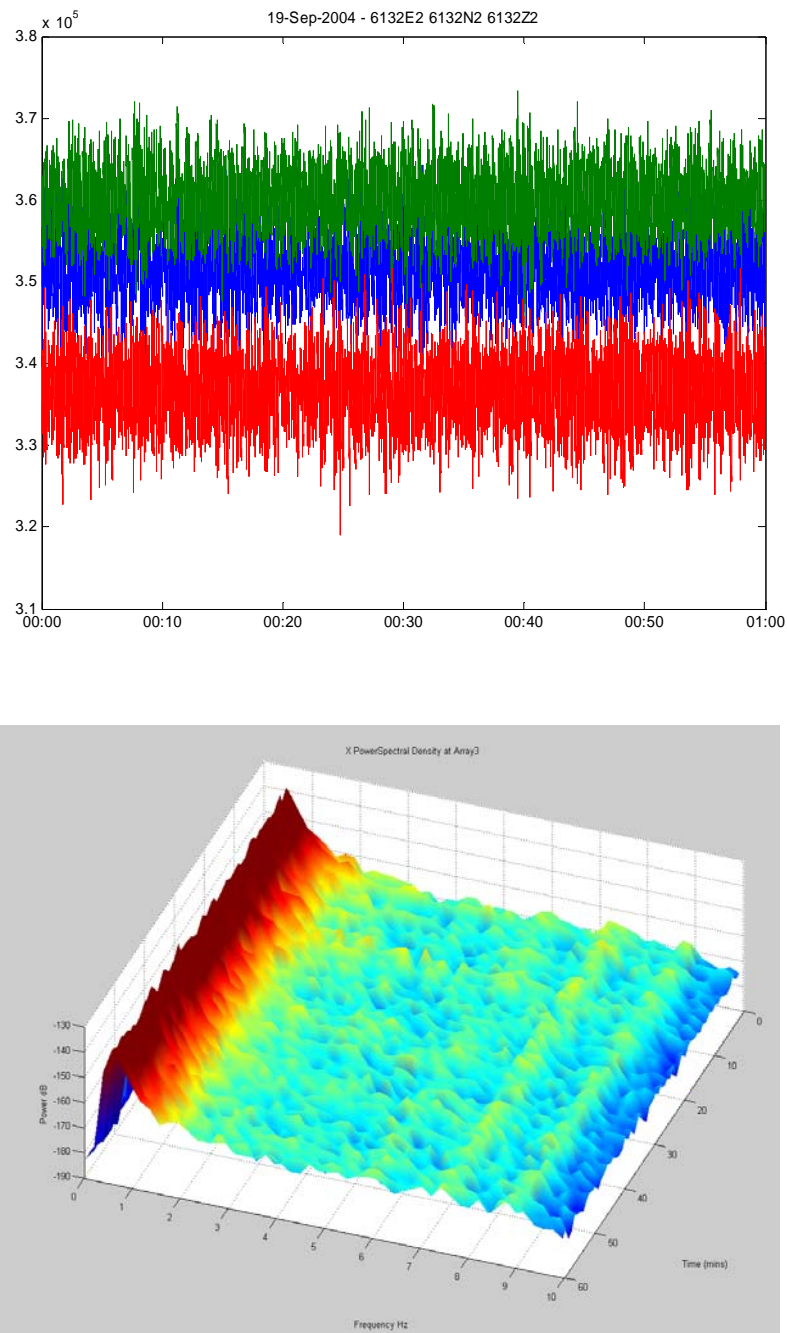
Figure 33   Seismic three-component record and spectrogram at Array 3 on 19 September 2004 between 00:00 and 01:00

These are simply examples from a very large data set which demonstrate clearly the presence of harmonic components which we associate with the Dun Law windfarm and which can be identified on many of the seismometers throughout the 6 month monitoring period. This confirms the previous work of Styles (1996) and Schofield (2001) that wind farms do produce discernible harmonic signals which can be detected over considerable distances.

While it becomes more difficult to discern the individual harmonic components with greater distance because of the ambient background noise it should not be considered that they then become unimportant as they are contributing to the level of ambient noise in the region between 1 and 10 Hz which is the critical discrimination band for forensic seismology and that is why they may lead to degradation of the discrimination capabilities of EKA at Eskdalemuir. It is therefore critically important to establish the mode of propagation and therefore attenuation characteristics of the microseismic noise. The polarisation is a very strong indication that we are dealing with Rayleigh waves (commonly known as 'ground-roll') rather than coupled infrasound.
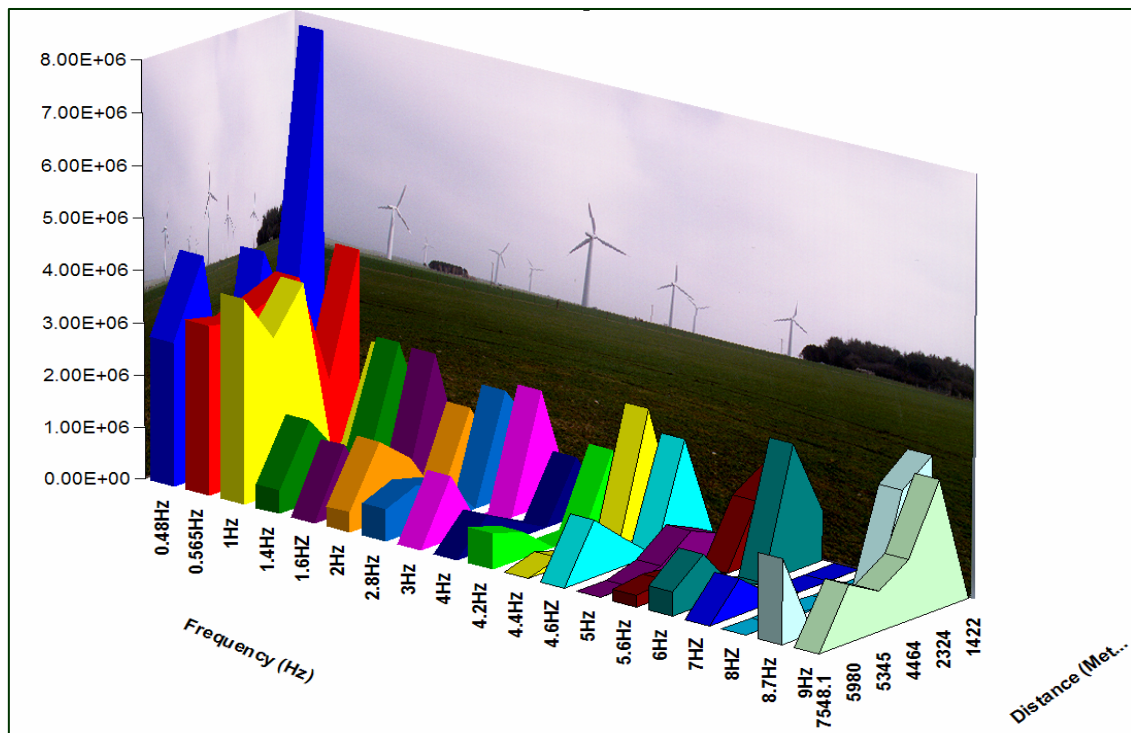
Figure 34   Attenuation of principal harmonic components with distance away from Dun Law

Figure 34 shows a composite plot of the attenuation of various harmonic components with distance away from Dun Law. While it is clear that the amplitude does decay with distance, there appears to be a dip at middle distances which may be due to coupling differences at different seismometer sites which preclude establishment of a definitive decay law from this plot.

Figurse 35 to 38 show a sequence of spectra and spectrograms obtained from Kelphope 1, c 2.4 km from Dun Law over a range of wind conditions on 1st and 2nd of October 2004.

Extremely Low wind speed, no production:

Date:	01.10.2004
Time:	04:00 to 05:00
Average wind speed:	3.46ms^{-1}
Average wind direction:	206.67°
Average production:	-4.5 kW!

It is clear that when wind speeds are close to zero and there is no production then the normal harmonic components we associate with Dun Law cannot be seen. Enigmatically there appear to be frequencies of 4 and 6.7 Hz which we have not seen before and at present are unexplained.

Low wind speed, low production:

Date:	01.10.2004
Time:	06:00 to 07:00
Average wind speed:	4.58ms^{-1}
Average wind direction:	221.33°
Average production:	1826.8 kW

When the windfarm starts to generate at low wind speeds, considerable microseismic signals can be detected km. Clear harmonic components can be seen including the fundamental at 1.4 Hz but there appears to be considerable side bands to the frequencies. It may be that these are due to the turbine slewing and intermittently operating in the low wind conditions prevailing at this time

Moderate wind speed, moderate production:

|	
Date:	02.10.2004
Time:	00:00 to 01:00
Average wind speed:	7.29ms^{-1}
Average wind direction:	245.67°
Average production:	9100.9 kW

When the windspeed and production rise clear harmonic signals stabilize and present for the full period although some other frequencies can be seen on the

narrow band spectra they are not obvious on the more robust power spectral density spectrograms probably because of the averaging of spectra which takes place to achieve stability of spectral estimates.

High wind speed, full production:

Date: 02.10.2004
Time: 11:00 to 12:00
Average wind speed: 11.189ms^{-1}
Average wind direction: 254.67°
Average production: 16920.8 kW

In the regime of high wind speed and production we see very well developed harmonic components with far fewer sidebands. It is clear from this sequence (and further shown in later work) that power in the harmonic components increases as wind speed and associated production increase which is what would be expected for seismically generated and propagating signals.
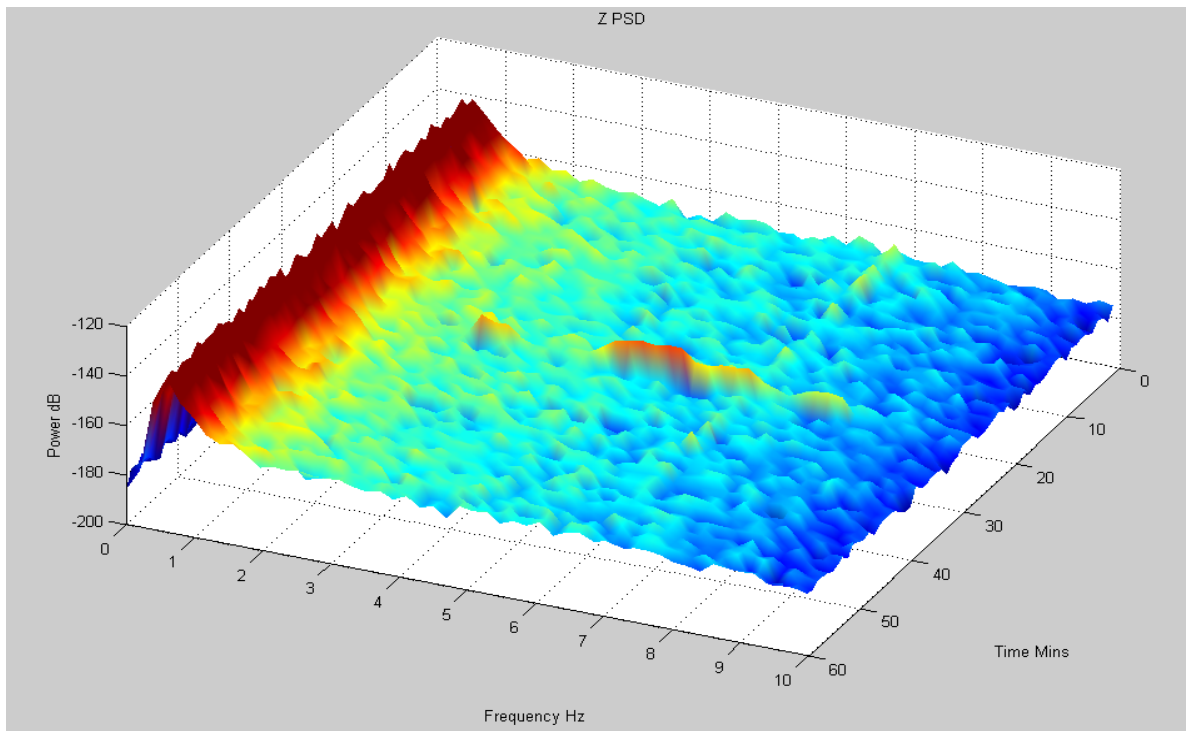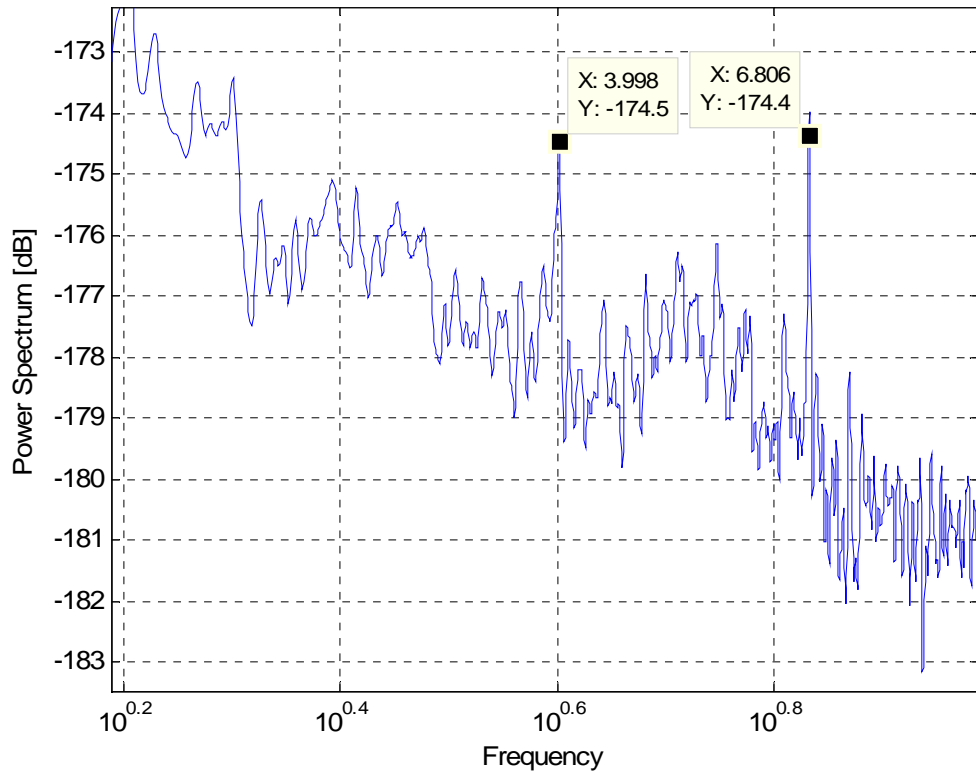
Figure 35 **Kelphope 1 on 1/10/2004, 04:00 to 05:00, very low wind speed**
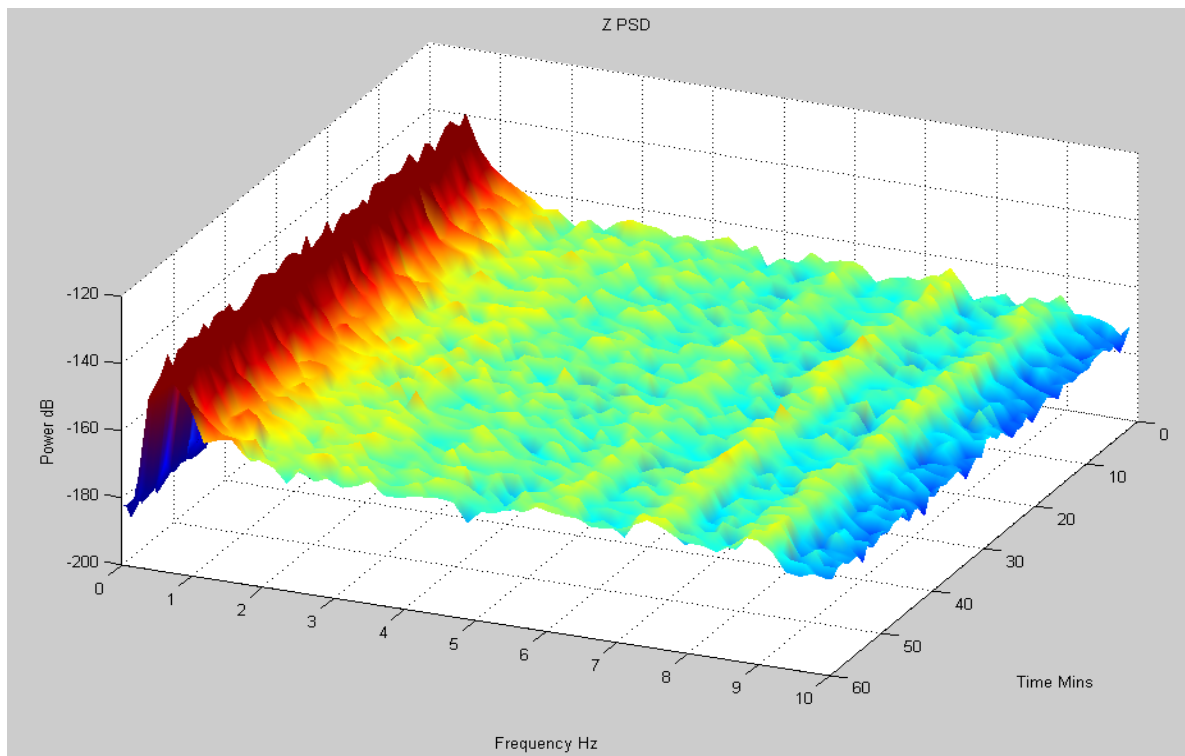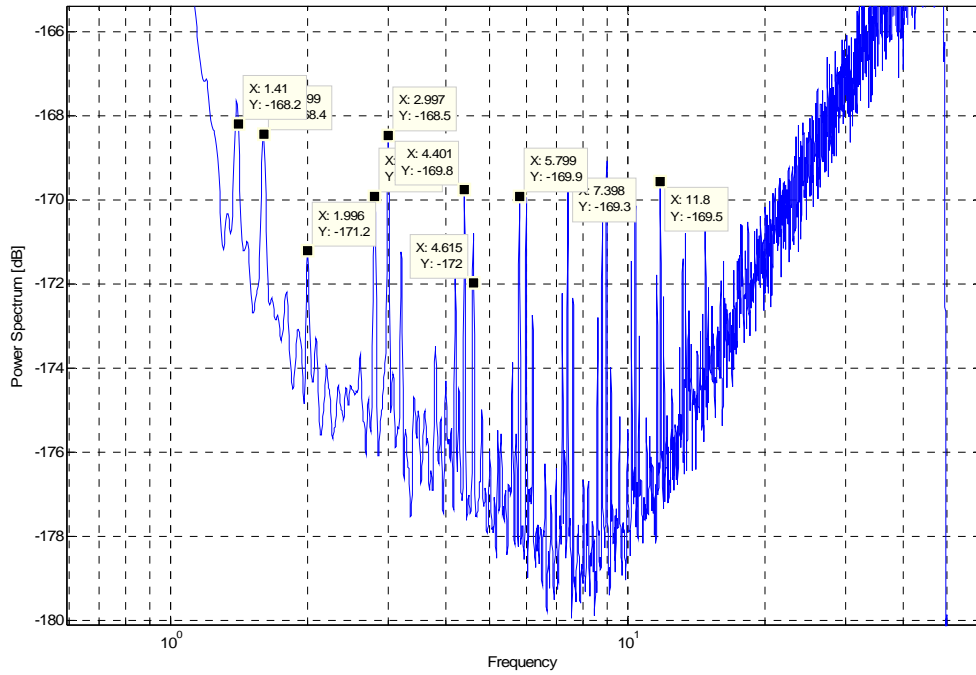
Figure 36   Kelphope 1 on 1/10/2004, 06:00 to 07:00, low wind speed

Figure 37   Kelphope 1 on 2/10/2004, 00:00 to 01:00, moderate wind speed
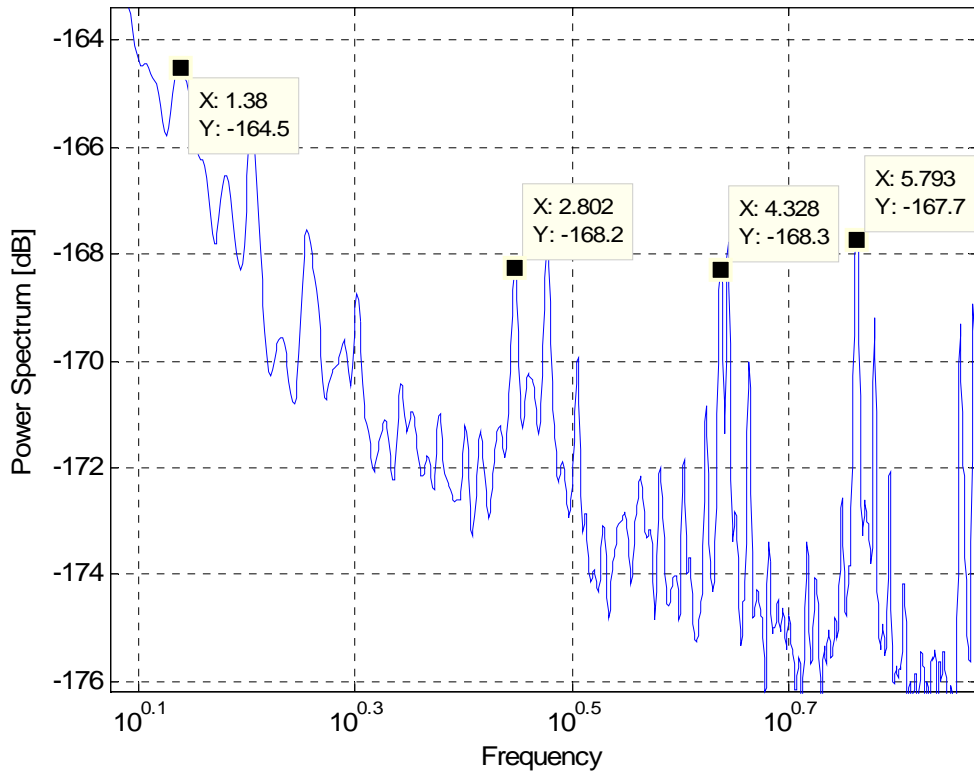
Figure 38   Kelphope 1 on 2/10/2004, 11:00 to 12:00, high wind speed

Vibration from variable speed wind turbines

Future wind farm developments are much more likely to be of variable speed design rather than the usual fixed-speed machines which most wind farms use now. 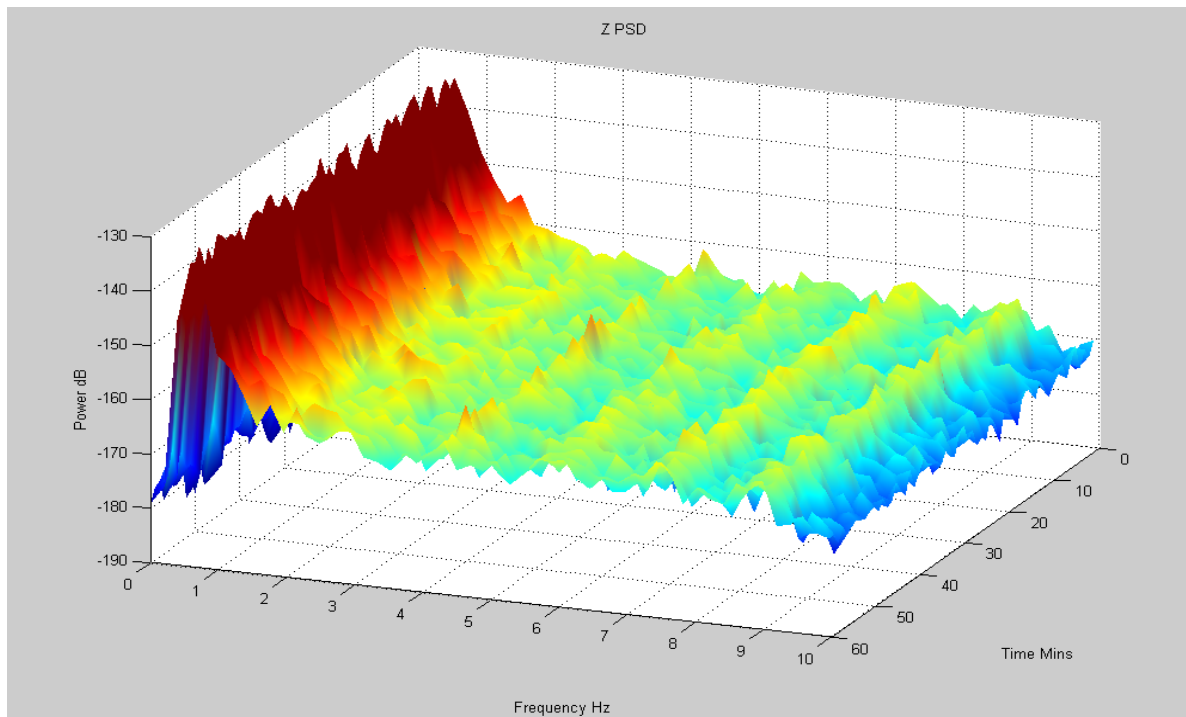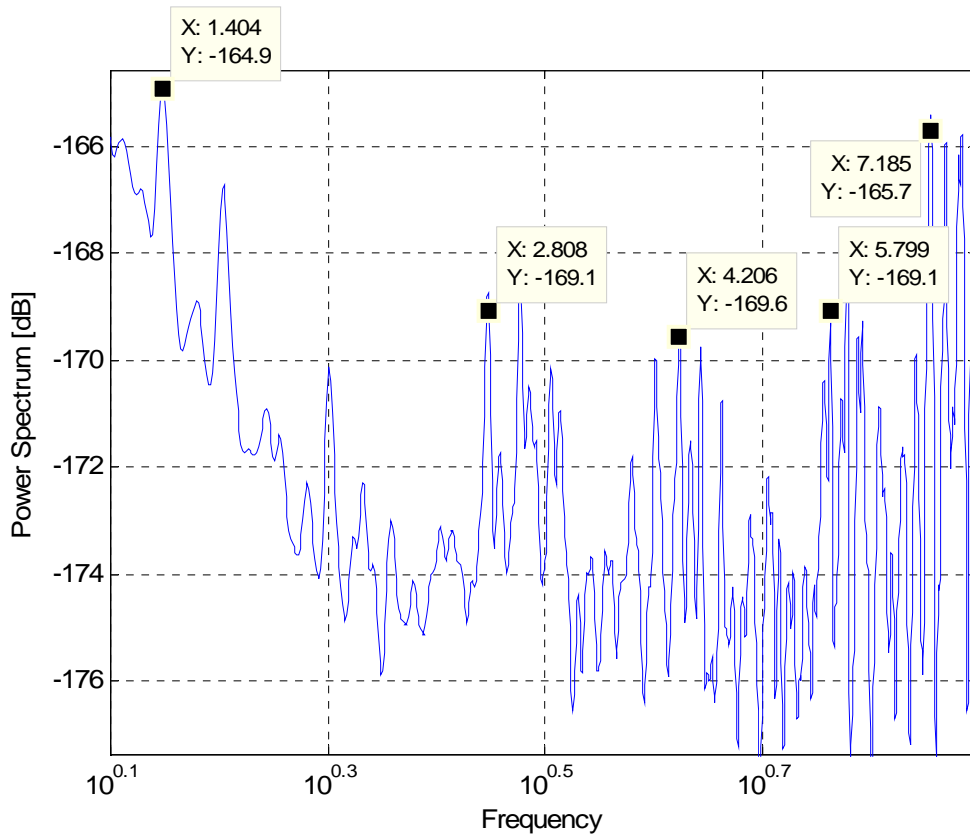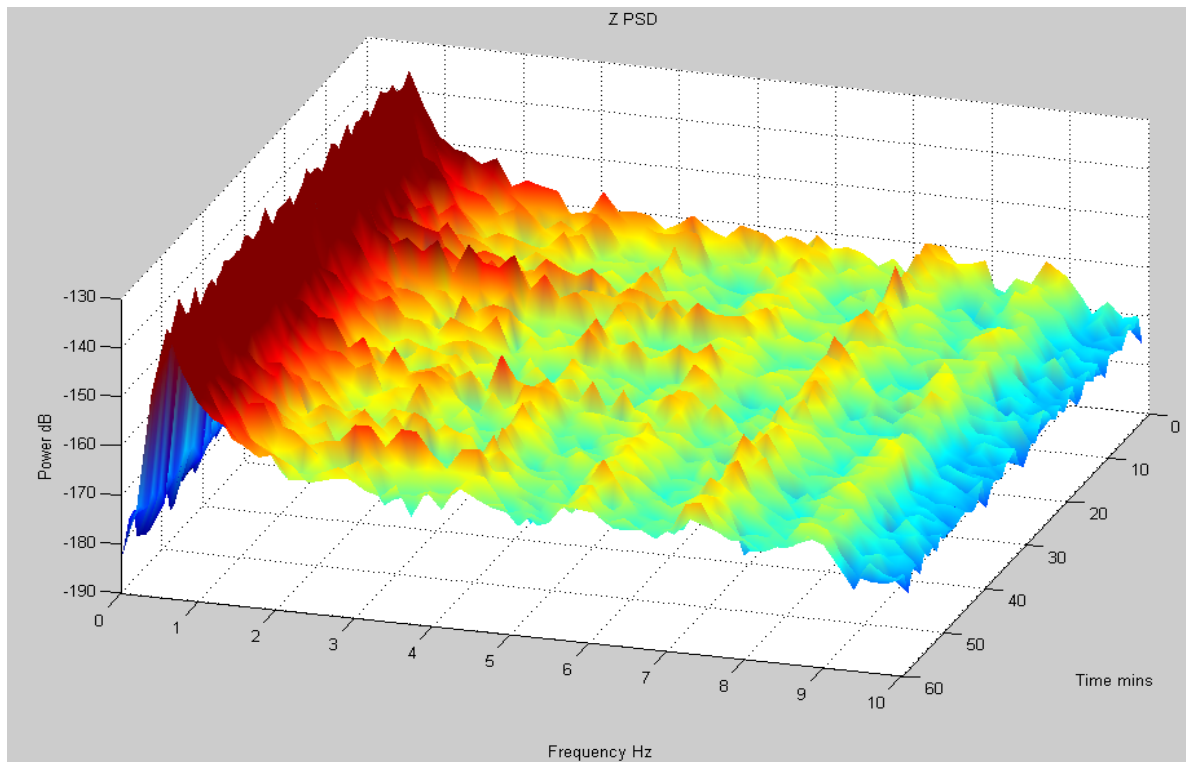Most of this study has concentrated on the fixed speed machines but we have a limited amount of data from Crystal Rig which is quite close to the most distant seismometer at Johnscleugh. Crystal Rig is a 20 turbine, 50 MW Variable Speed windfarm operated by Fred Olsen Renewables located at NT678678 but is likely to be considerably extended in the future with an additional 5 2.5 MW turbines.

While we were not able to obtain permission to go onto the Crystal Rig site we were located within a few kilometers. Figure 39 shows the spectrogram of two components (not decomposed into principal components as the software is optimized for Dun Law monitoring). However we can see strong harmonic components which are mostly concentrated between 5 and 9 Hz and to be rather broader than those we see from a fixed wind speed as might be expected as the turbines can find their own rate of rotation.

These frequencies appear to be quite stable and as they also fall into the band which is of interest for Eskdalemuir detection will be considered in the same way as the fixed speed machine harmonics and form part of the analysis.
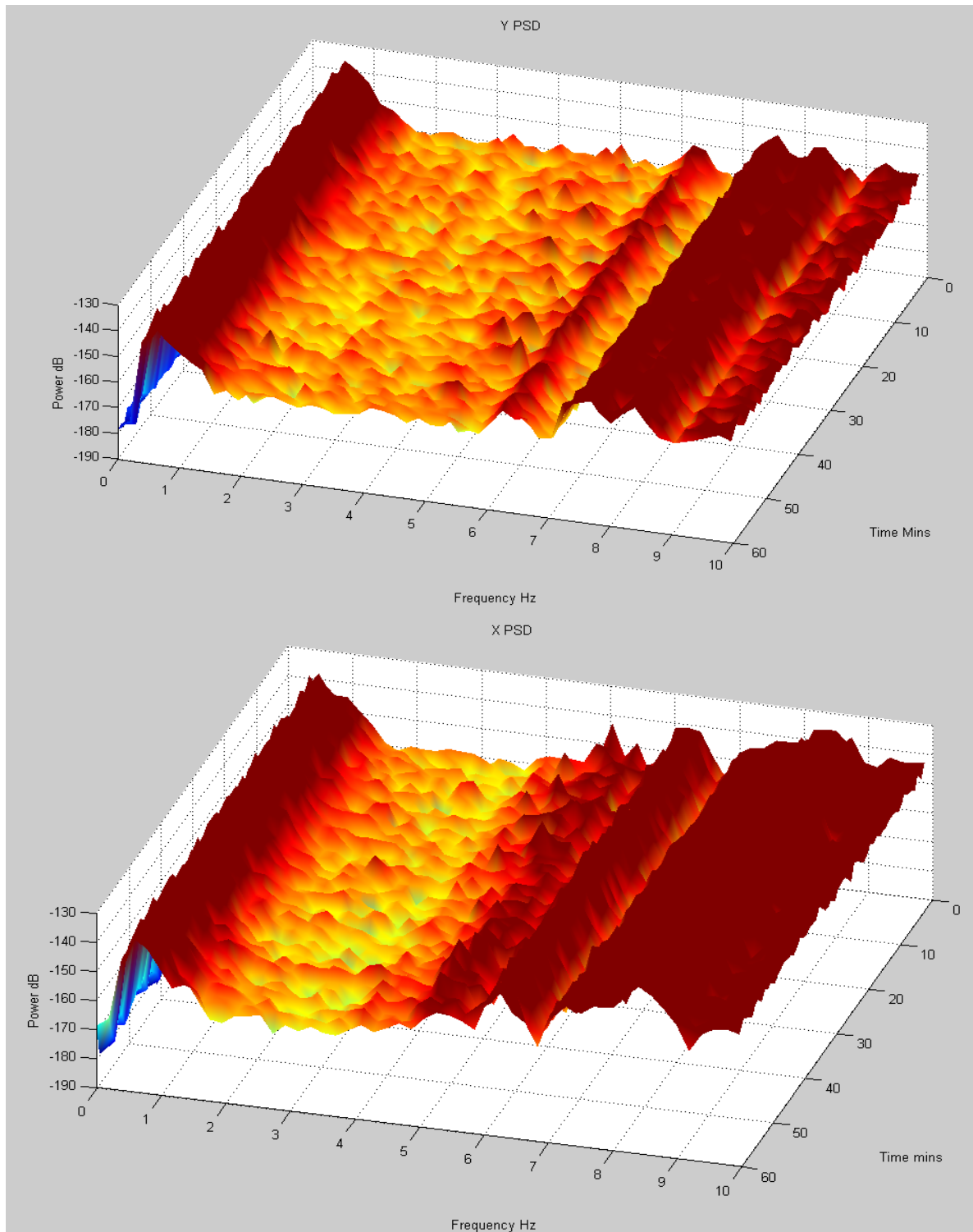
Figure 39 Spectrograms of Crystal Rigg as recorded at Johnscleugh on the 5th November 2004 from 00:00 to 01:00

Phase 2 – Infrasound Measurement using MB2000 Microbarometers.

Figure 40 **DASE MB2000 Microbarometer**

Full details of the deployment are described in Appendix 2 and only a summary is given here

Phase 2 – Deployment of Infrasound sensors

Deploying microbarometers co-located with Phase 1 seismometers to quantify infrasound from windfarms. Co-location of infrasound and seismic sensors will allow us to determine whether infrasound couples with the ground as seismic signal. The Infrasound equipment was on loan courtesy of Professor Sergio Barrientos and Mr. John Grant, of the CTBTO, Vienna and Dr David McDonald of the Canadian Geological Survey

Equipment:

4 Département analyse, surveillance, environnement (DASE) MB2000 microbarometers with 4 ORION portable data loggers on loan from the CTBTO.

MB2000:
Measures small variations of atmospheric pressure and also those generated at large distances.
Sensitivity of output is 1MV/Pa.
Frequency response is 0.0001 to 40Hz (filtered output is 100s to 27Hz).
Electronic noise is less than 2mPa rms (0.02~4Hz).
Can be deployed with weather/environmental monitoring equipment.

ORION:
Field portable seismic data logger.
Data recorded to removable disk cartridge.
Can operate in continuous recording mode.
Timing referenced to UTC by an internal GPS receiver.

Deployment locations:

DATE:	20.09.2004
LOCATION:	Infrasound 1
GRID REFERENCE:	NT 53333 60478 (bisects seismic Array 1 & Array 2)
SENSOR:	WB1103
DATALOGGER:	Orion number 0190

DATE:	20.09.2004
LOCATION:	Infrasound 2
GRID REFERENCE:	NT 53280 60363
SENSOR:	WB1107
DATALOGGER:	Orion number 0190

DATE:	20.09.2004
LOCATION:	Infrasound 3
GRID REFERENCE:	NT 53415 60368
SENSOR:	WB1146
DATALOGGER:	Orion number 0139

DATE:	21.09.2004
LOCATION:	Kelphope 1 Infrasound
GRID REFERENCE:	NT 49931 59031
SENSOR:	WB1144
DATALOGGER:	Orion number 0192
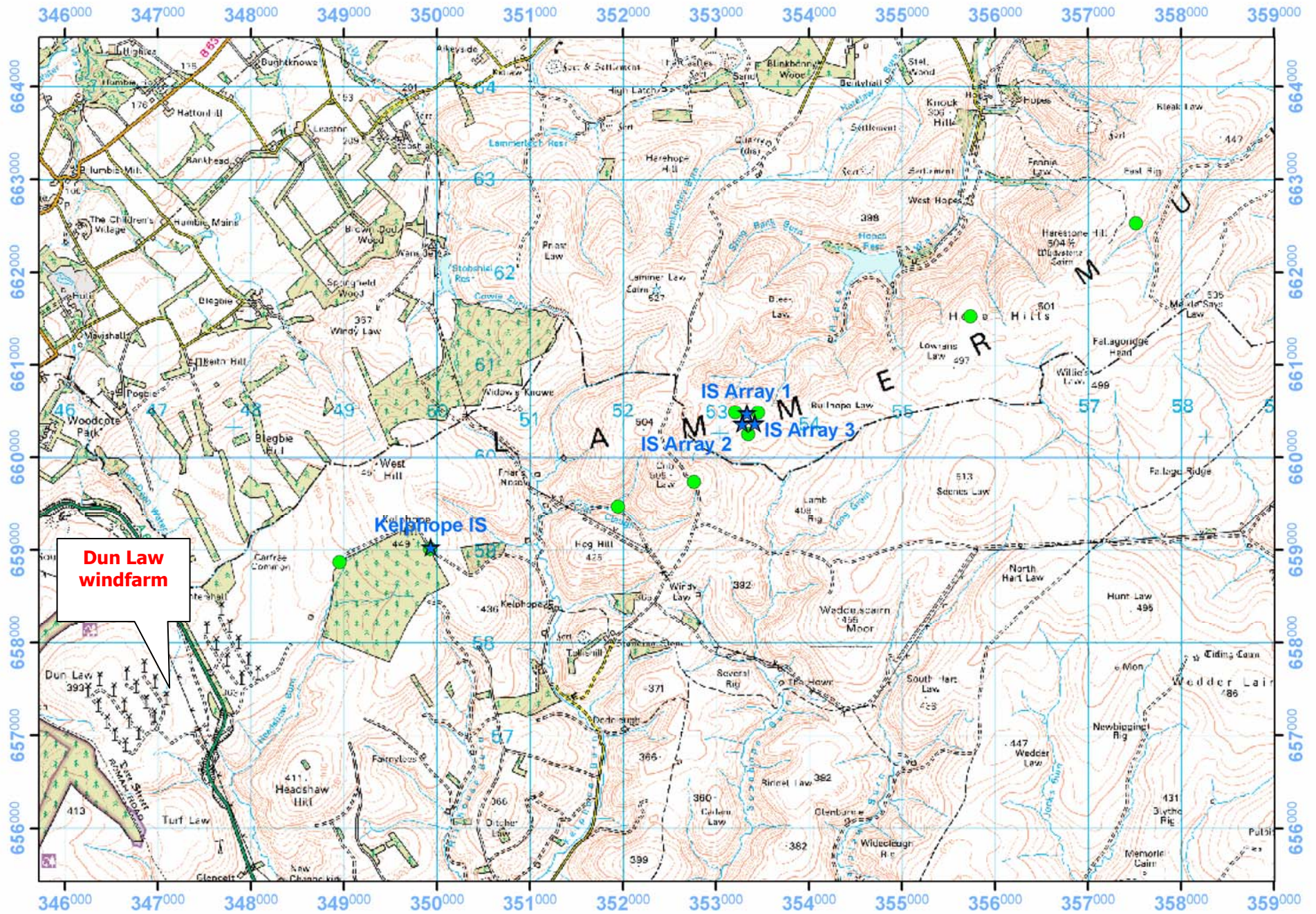
Figure 41: Infrasound deployment locations (seismic stations in green).
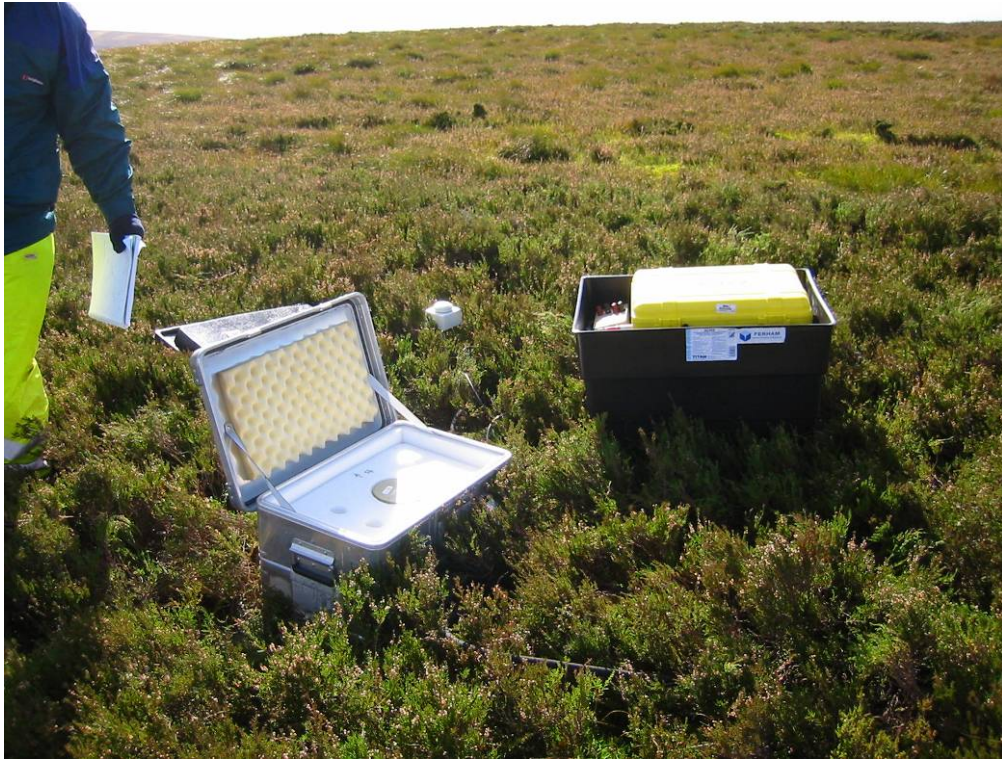
Figure 42.   MB2000 (in metal box), ORION datalogger (yellow box) and battery deployment at an infrasound site.
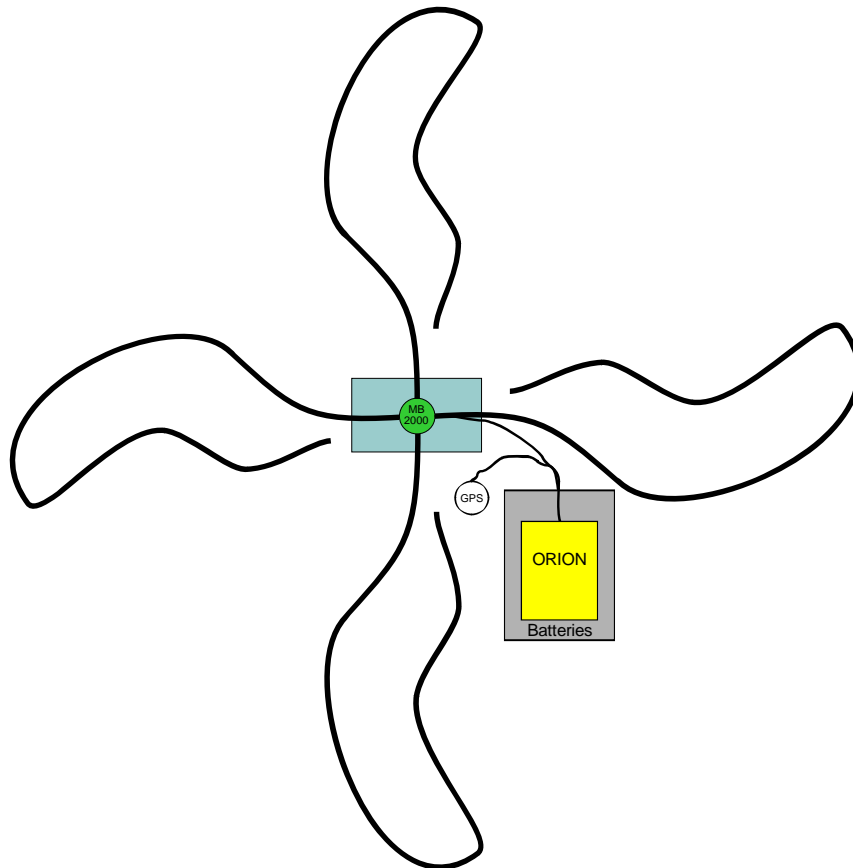
Figure 43.   Plan view of Infrasound deployment showing the leaky hoses used to attenuate high frequency barometric noise

Infrasound Results and their significance

The infrasound equipment was more difficult to maintain than the seismic systems due to the very high power drain and the poor weather which made the solar panels less effective than planned and data coverage is patchy. However, the most optimal infrasound records during a range of wind speeds were recorded over 3 of the 4 stations from 01/10/2004 to 03/10/2004 and they show some very important aspects of the study. The operational stations were: Kelphope Infrasound, IS Array 1 and IS Array 2. The results are shown in the following sequence of spectrograms (Figures 44 to 55) recorded over the same range of variable wind conditions as the microseismic records analysed and discussed previously.

Extremely Low wind speed, no production:

Date:	01.10.2004
Time:	04:00 to 05:00
Average wind speed:	3.46ms^{-1}
Average wind direction:	206.67°
Average production:	-4.5 kW
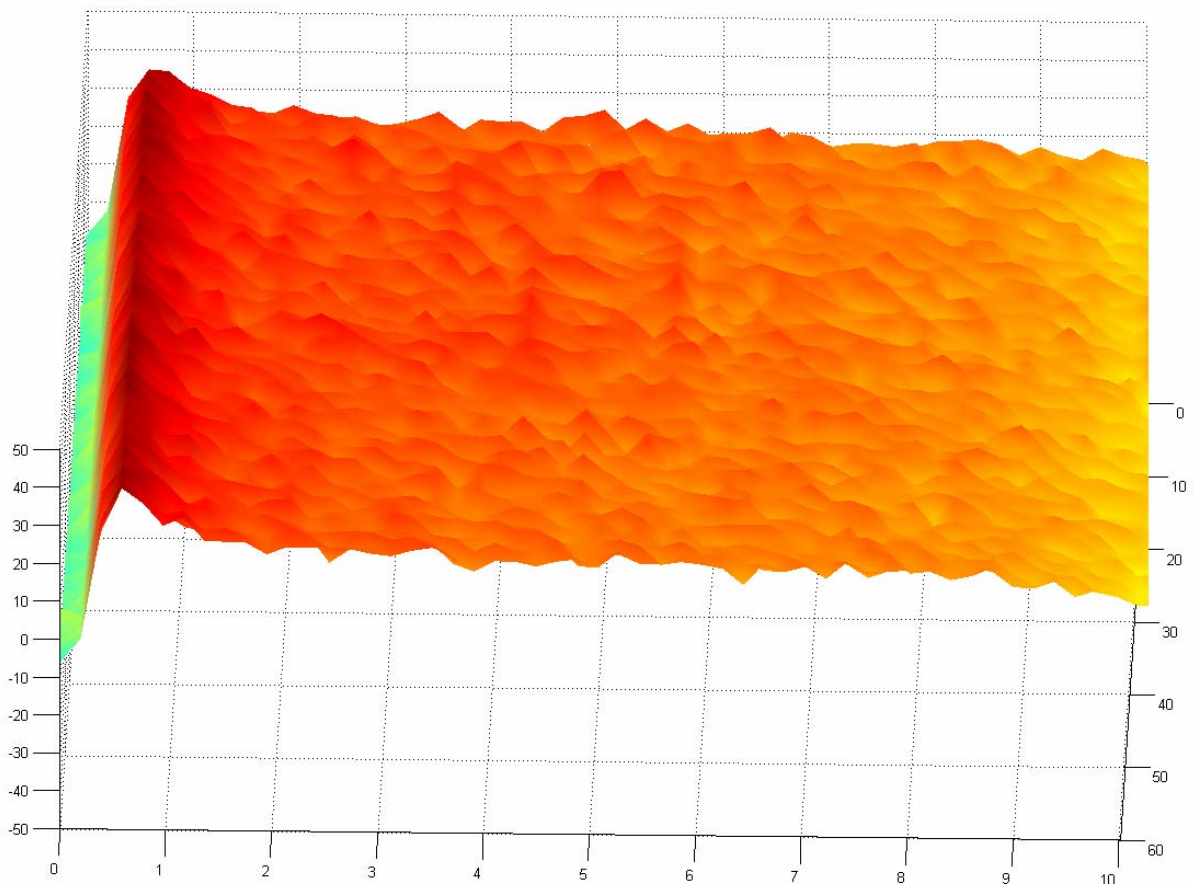
Figure 44.   Data recorded at Kelphope 1 Infrasound, 01/10/2004 04:00 to 05:00.
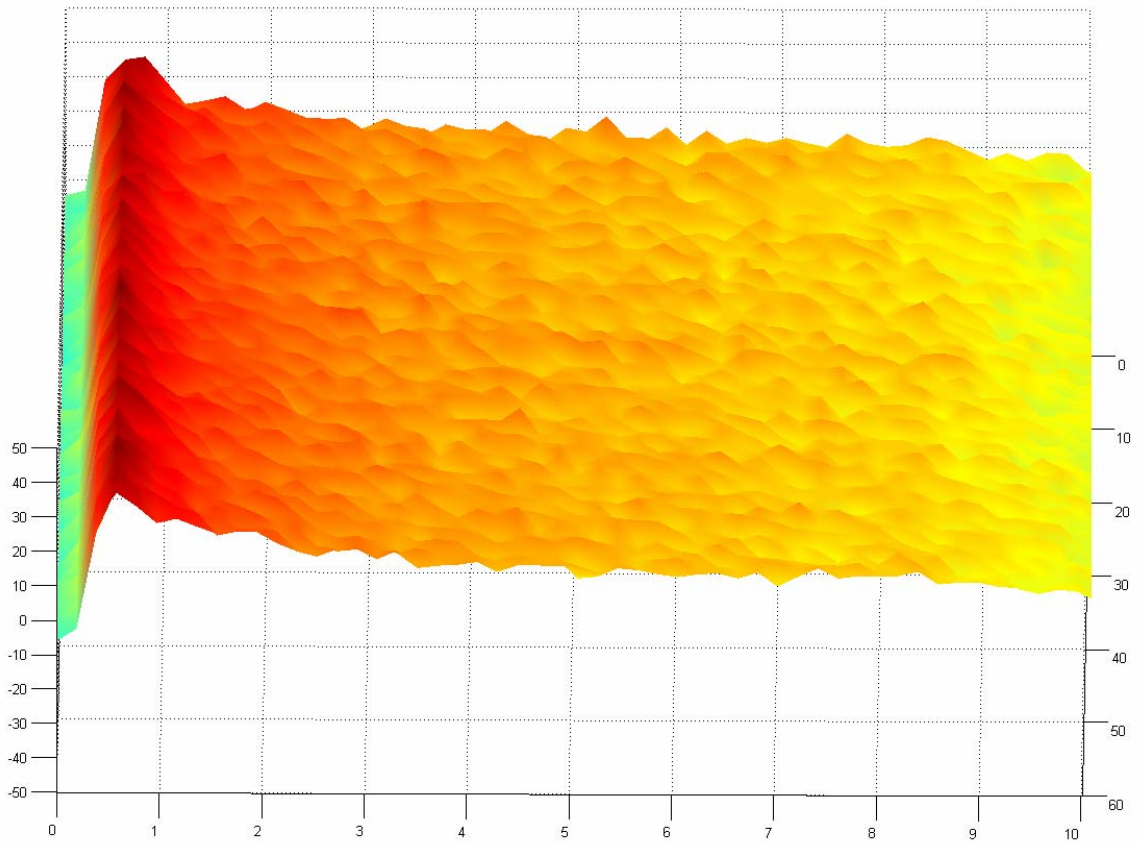
Figure 45.   Data recorded at Array 1 Infrasound, 01/10/2004 04:00 to 05:00.

Figure 46.   Data recorded at Array 2 Infrasound, 01/10/2004 04:00 to 05:00.

Low wind speed, low production**:**

Date: 01.10.2004
Time: 06:00 to 07:00
Average wind speed: 4.58ms^{-1}
Average wind direction: 221.33°
Average production: 3041.8 kW
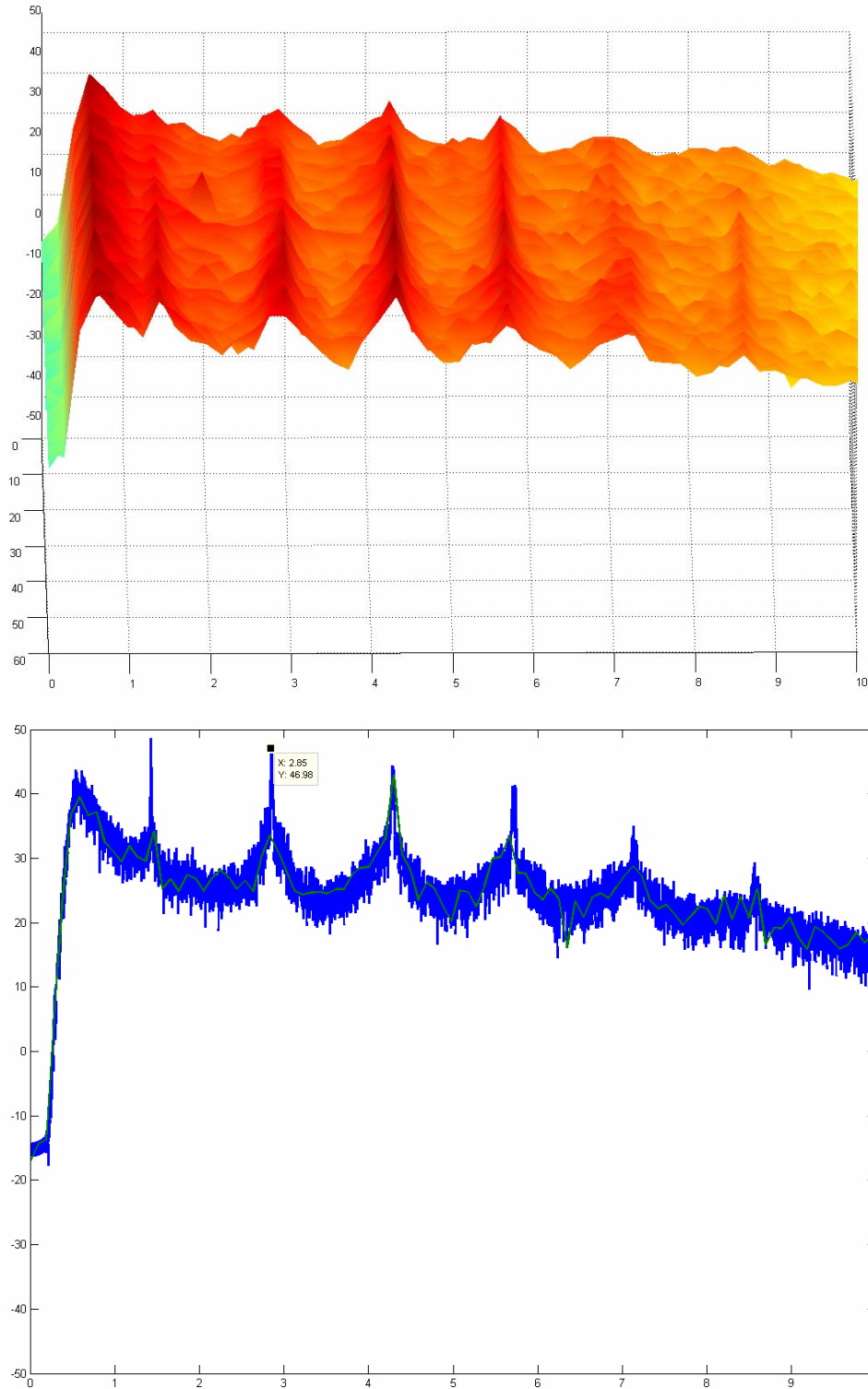
Figure 47. Data recorded at Kelphope 1 Infrasound, 01/10/2004 06:00 to 7:00.
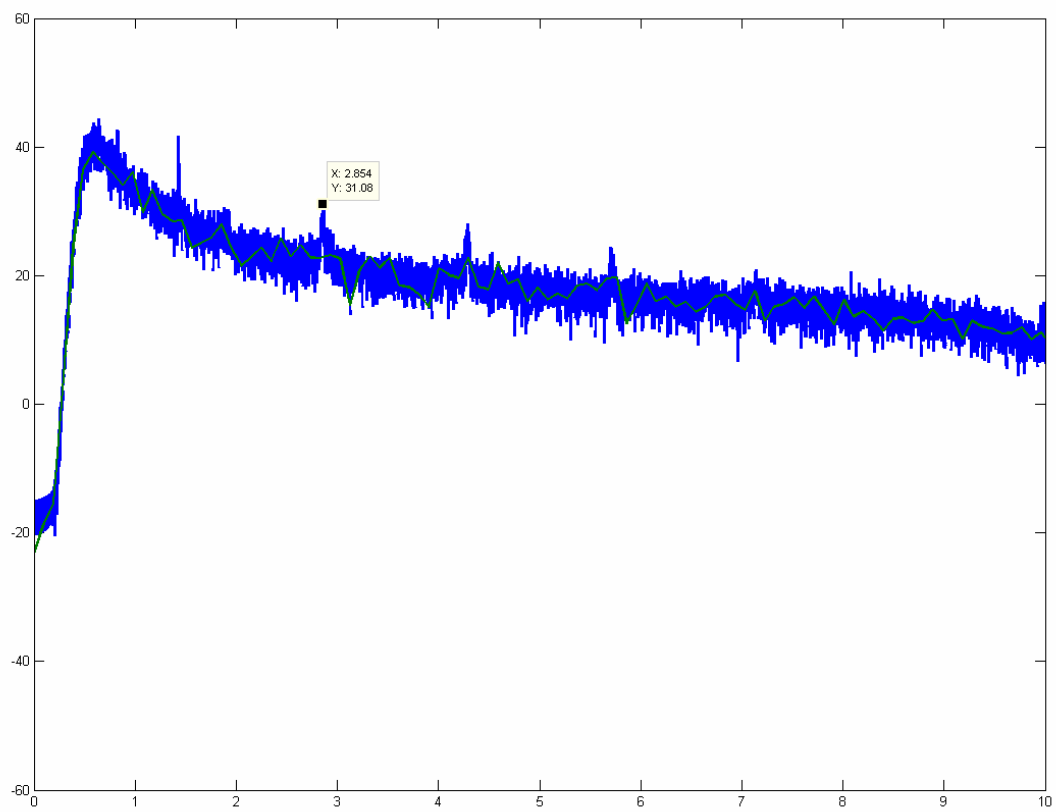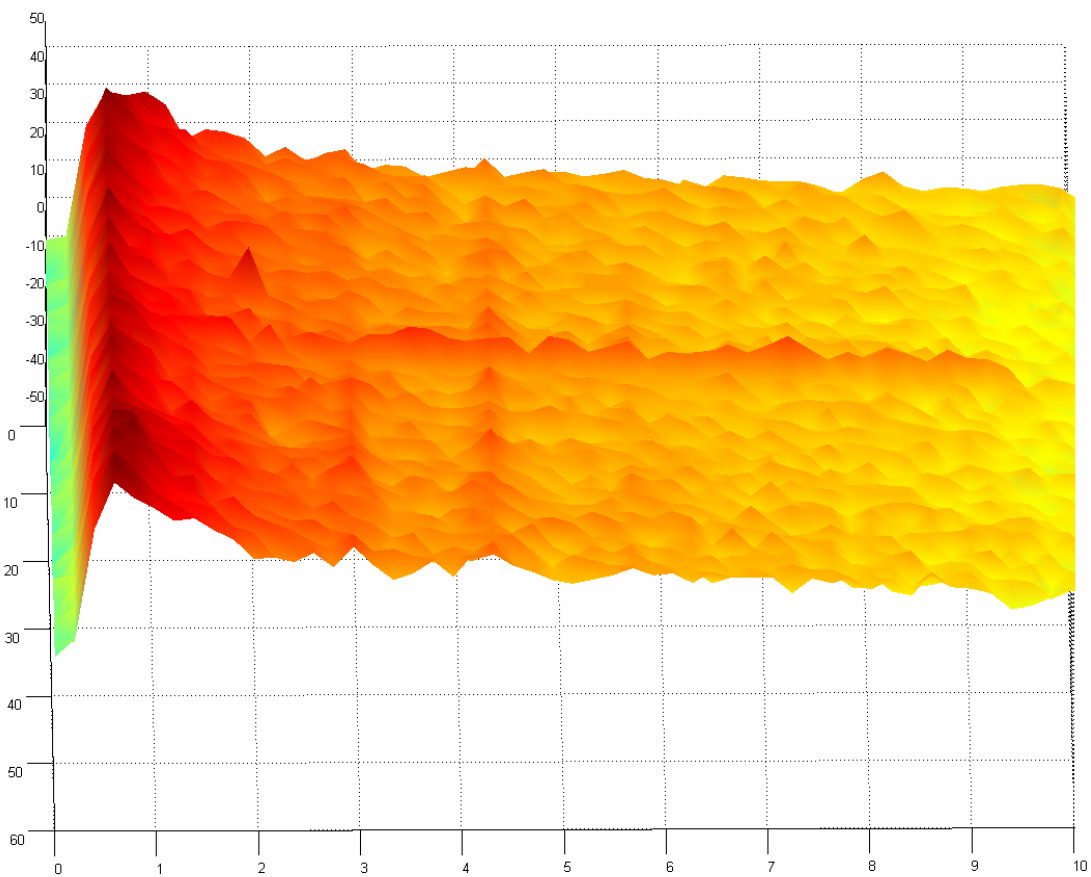
Figure 48.   Data recorded at Array 1 Infrasound, 01/10/2004 06:00 to 7:00.
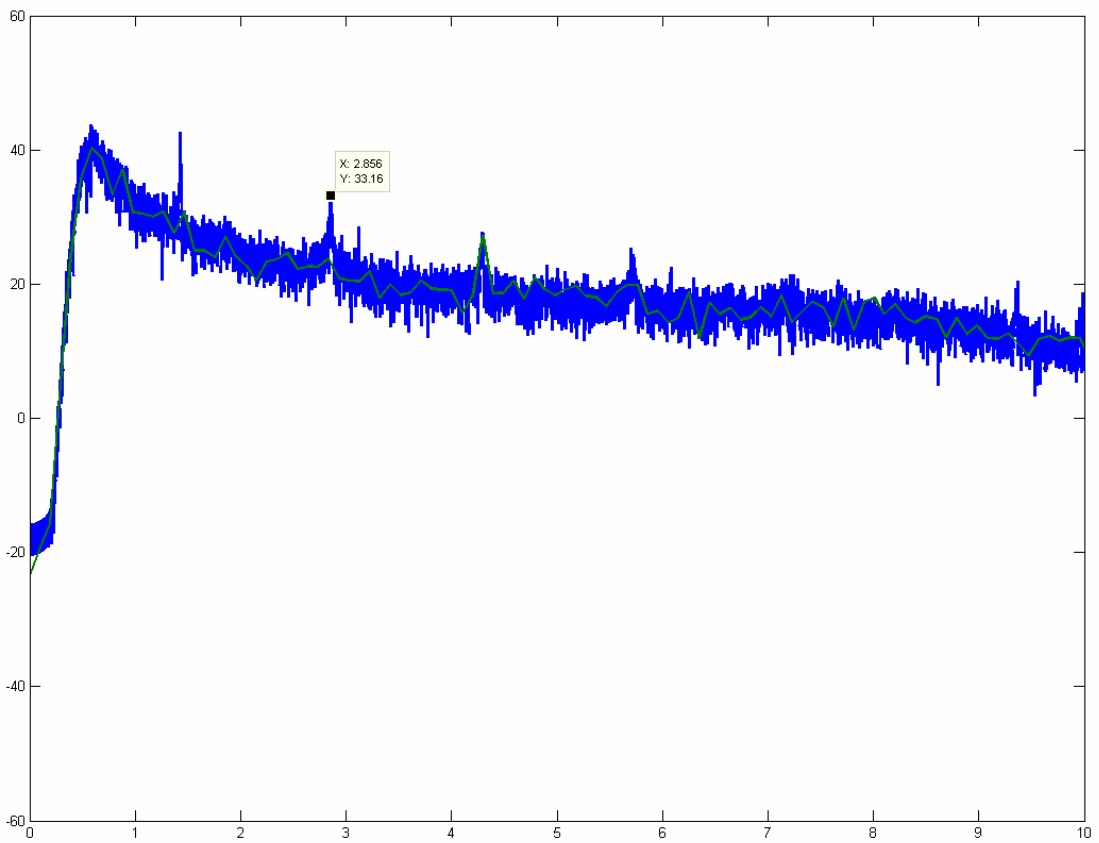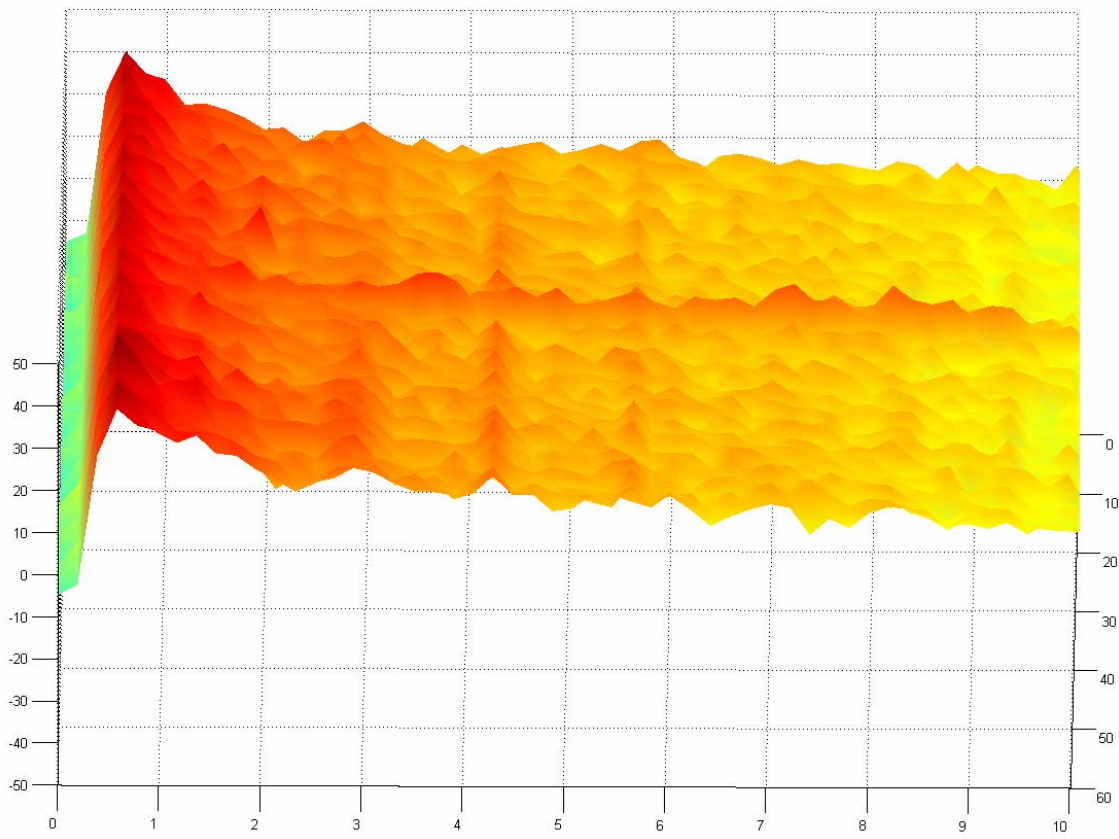
Figure 49.   Data recorded at Array 2 Infrasound, 01/10/2004 06:00 to 7:00.

Moderate wind speed, moderate production:
Date: 02.10.2004
Time: 00:00 to 01:00
Average wind speed: 7.29ms^{-1}
Average wind direction: 245.67°
Average production: 9100.9 kW
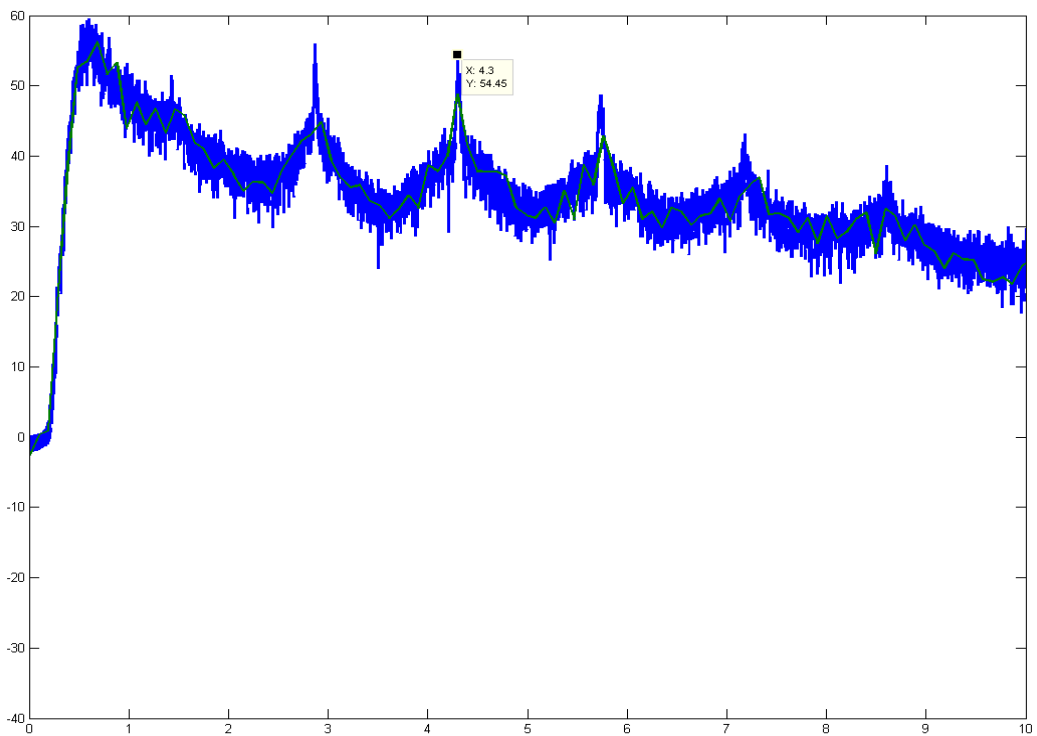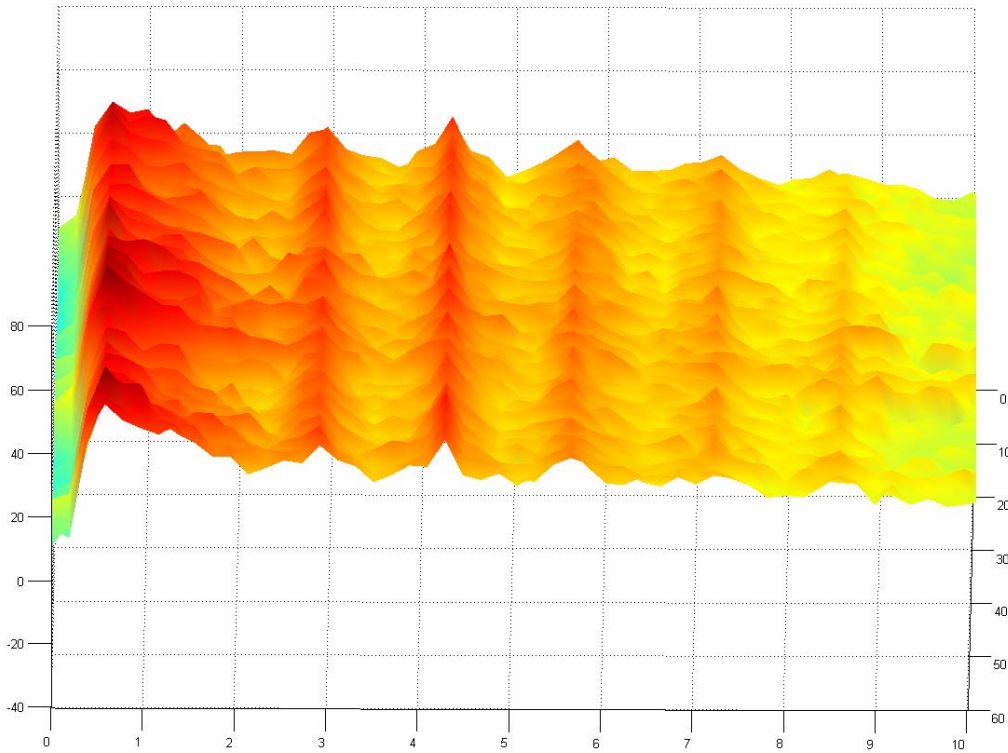
Figure 50. Data recorded at Kelphope 1 Infrasound, 02/10/2004 00:00 to 01:00.
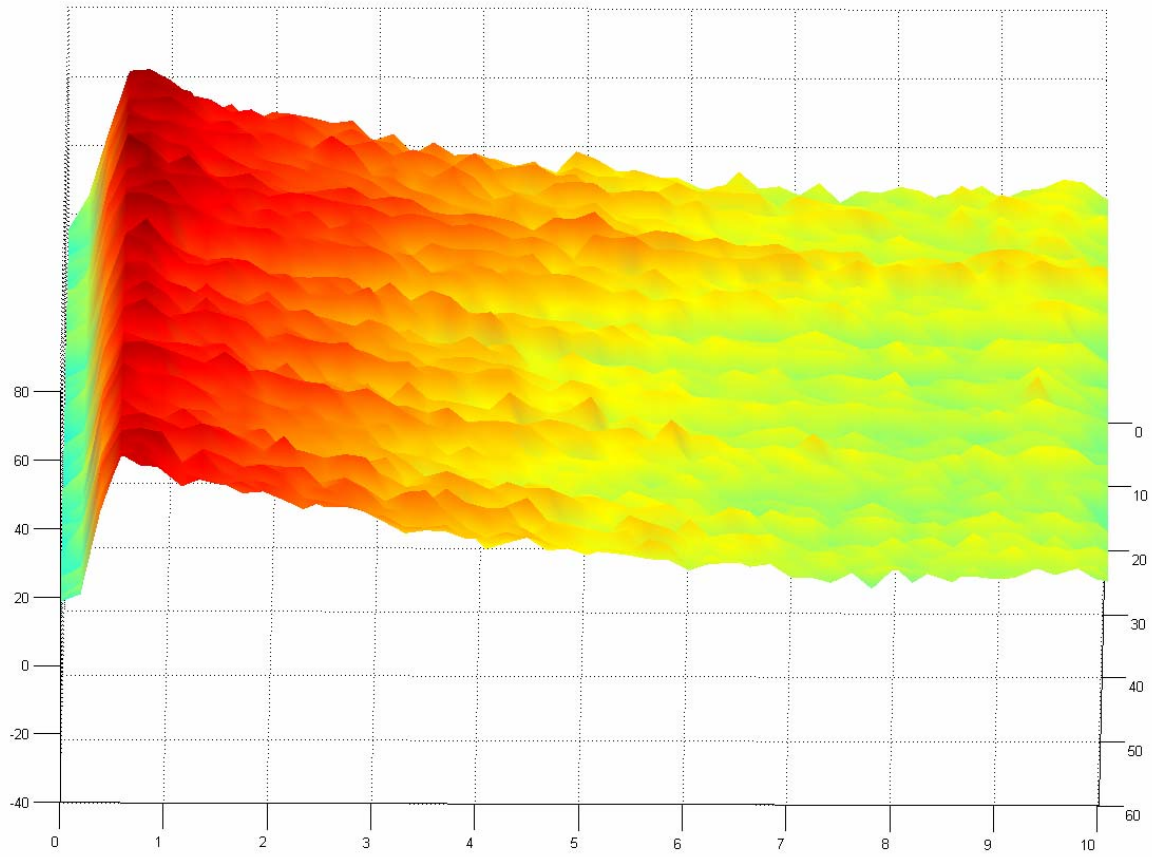
Figure 51. Data recorded at Array 1 Infrasound, 02/10/2004 00:00 to 01:00.
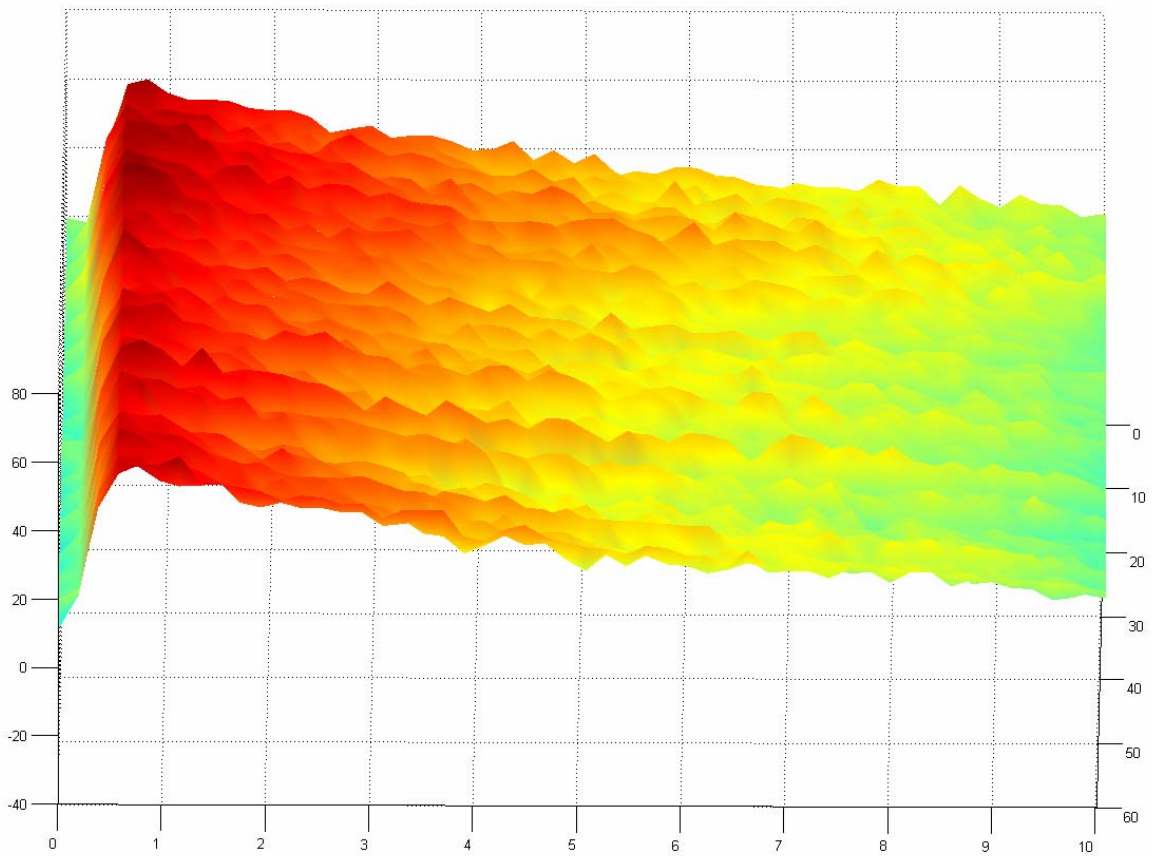
Figure 52. Data recorded at Array 2 Infrasound, 02/10/2004 00:00 to 01:00.

High wind speed, full production**:**

Date:	02.10.2004
Time:	11:00 to 12:00
Average wind speed:	11.189ms^{-1}
Average wind direction:	254.67°
Average production:	16920.8 kW
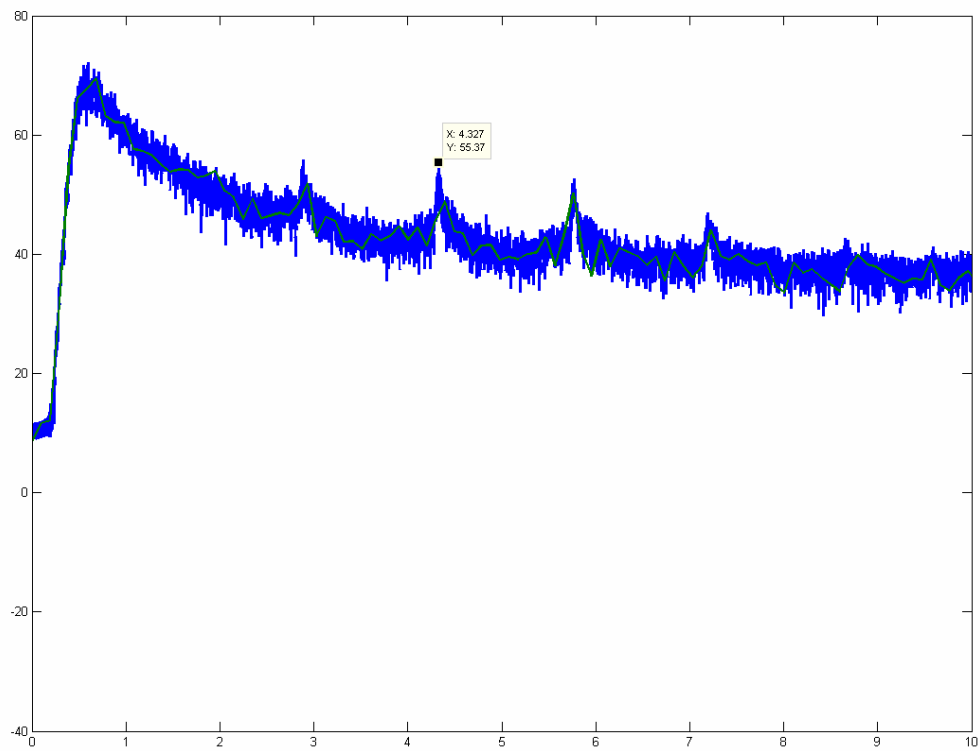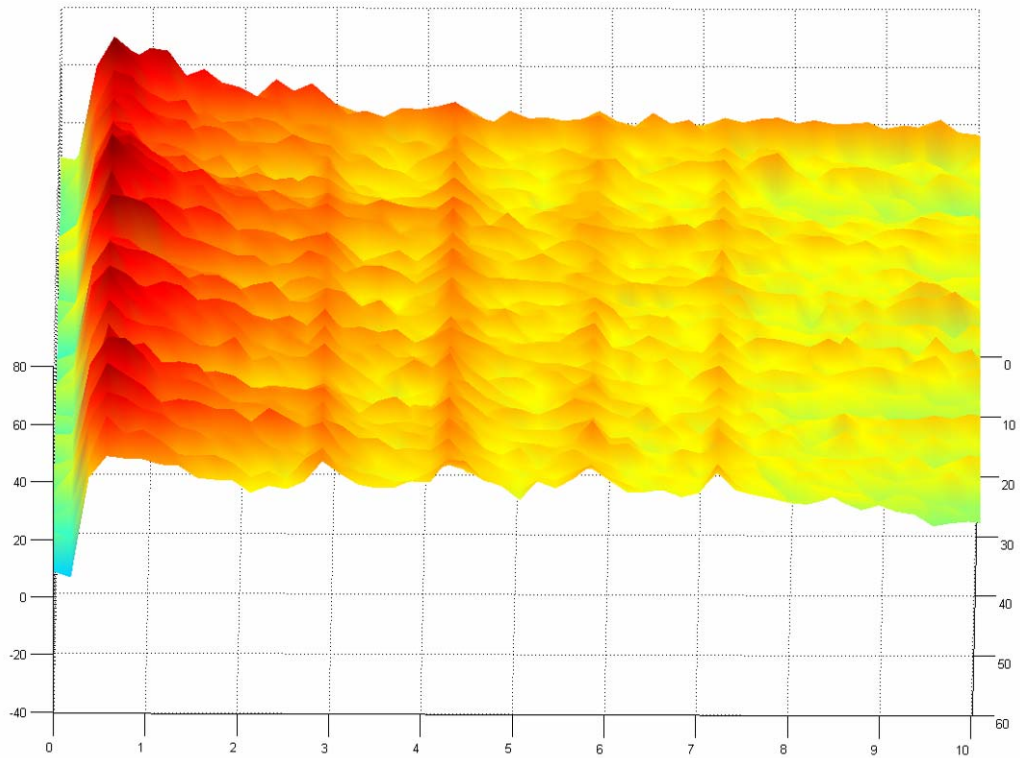
Figure 53. Data recorded at Kelphope 1 Infrasound, 02/10/2004 11:00 to 12:00.
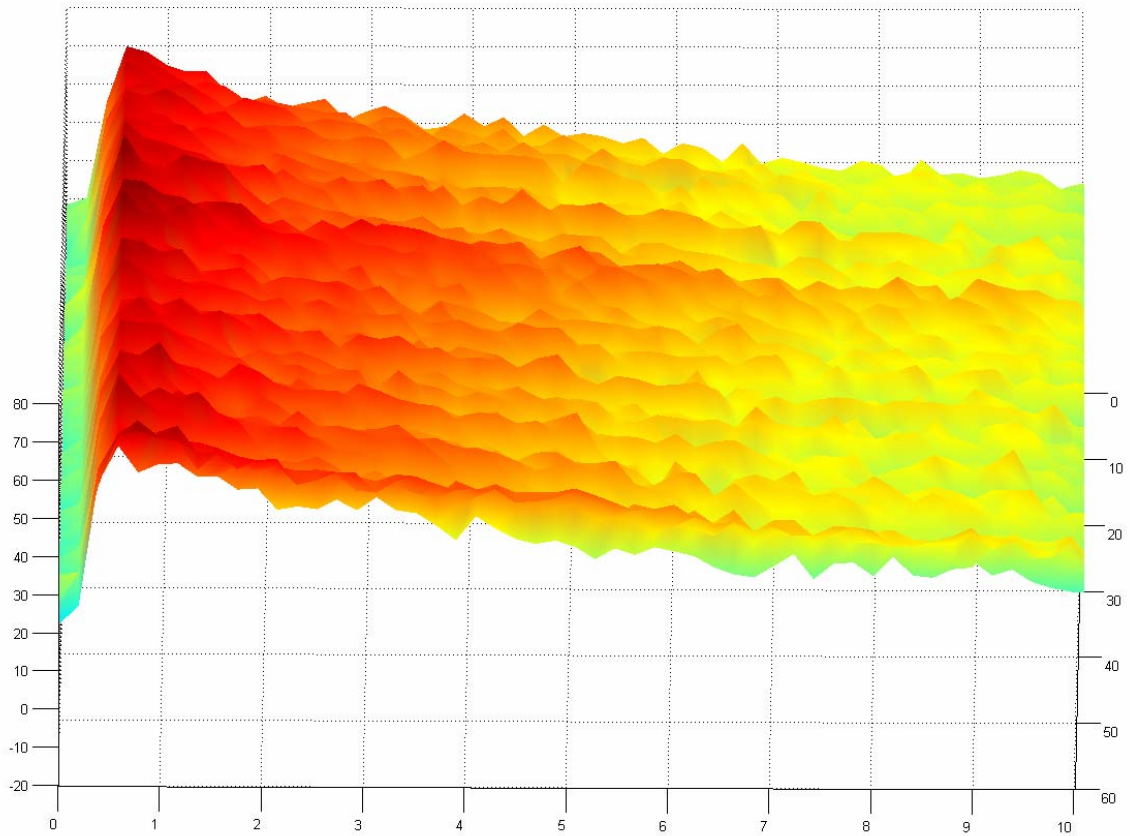
Figure 54. Data recorded at Array 1 Infrasound, 02/10/2004 11:00 to 12:00.
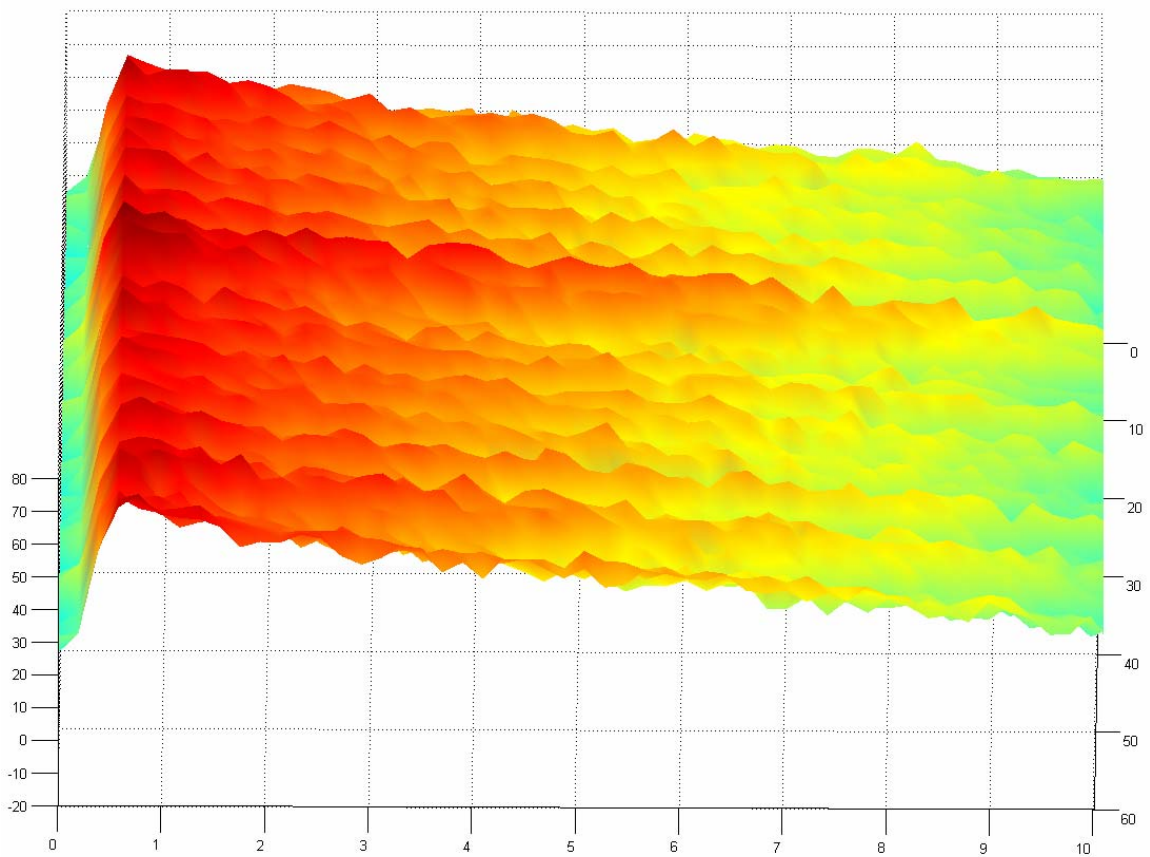
Figure 55.   Data recorded at Array 2 Infrasound, 02/10/2004 11:00 to 12:00.

<u>Extremely Low wind speed, no production</u>**:**

Date: 01.10.2004
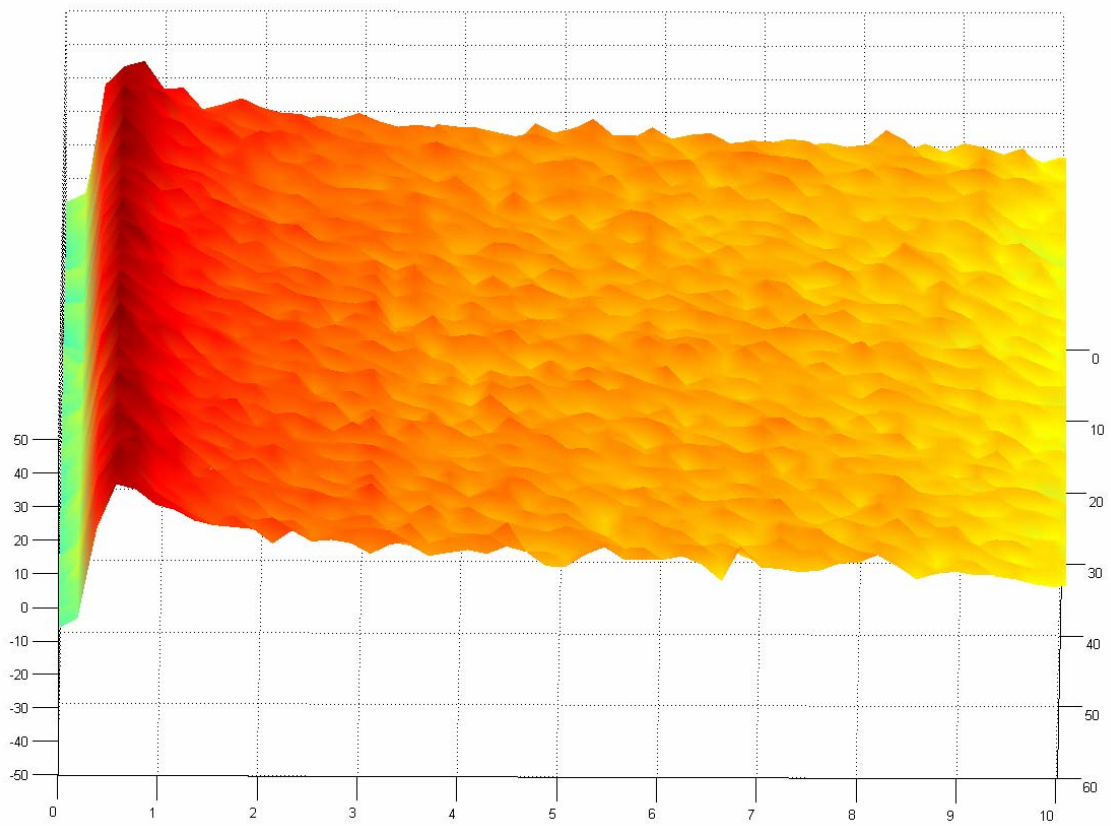Time: 04:00 to 05:00
Average wind speed: 3.46ms^{-1}
Average wind direction: 206.67°
Average production: -4.5 kW

It is clear that when wind speeds are close to zero and there is no production then no infrasound signals can be seen on any of the detectors as would be predicted.

<u>Low wind speed, low production</u>**:**

Date: 01.10.2004
Time: 06:00 to 07:00
Average wind speed: 4.58ms^{-1}
Average wind direction: 221.33°
Average production: 1826.8 kW

When the windfarm starts to generate at low wind speeds, considerable infrasound signals can be detected at all stations out to c 10 km. Clear harmonic components which are the second multiple and up of 1.4 Hz (the blade-passing frequency) can be seen although interestingly and somewhat enigmatically the blade-passing frequency itself is not so strongly detected

<u>Moderate wind speed, moderate production</u>**:**

Date: 02.10.2004
Time: 00:00 to 01:00
Average wind speed: 7.29ms^{-1}
Average wind direction: 245.67°
Average production: 9100.9 kW

When the windspeed and production rise clear signals can be seen on Kelphope 1 at c 2 km but the signals are not so well detected at the more distant array.

<u>High wind speed, full production</u>**:**
Date: 02.10.2004
Time: 11:00 to 12:00
Average wind speed: 11.189ms^{-1}
Average wind direction: 254.67°
Average production: 16920.8 kW

When the windspeed and production rise then while it is possible to see the harmonics at Kelphope they are not detectable at all on the more distant array at 10 km.

This is a very significant observation and indicates that infrasound signals from windfarms only appear to propagate efficiently to the more distant parts of the array during relatively calm conditions when turbulence associated with high wind velocities is not present.

This is in marked contrast to the microseismic signals observed during exactly the same period which grow in amplitude and power as the wind speed and energy production increase. While it is apparent that infrasound signals can clearly be detected at considerable distances away from a windfarm in the right conditions and may have an importance in this regards, they CANNOT be the primary source for the ground vibrations we measure on buried seismometers as there is an inverse relationship with windspeed and weather conditions for the two phenomena and they cannot therefore be causally related.

This confirms what was suggested earlier, that the vibrations experienced on seismometers situated at considerable distances from farms propagate through the ground as high frequency Rayleigh waves and not through the air, and as such must obey the propagation modes and attenuation and absorption laws for geological materials and not air.

ON-Tower monitoring of a variable speed wind farm

A variable speed site was made available at Ardrossan, a 12 turbine 24 MW windfarm operated by Airtricity in order for us to carry out on-tower monitoring there and we are grateful for their very helpful cooperation.

12 Vestas V80
24 MW
Airtricity
Latitude 55 41 09
Longitude 04 48 26
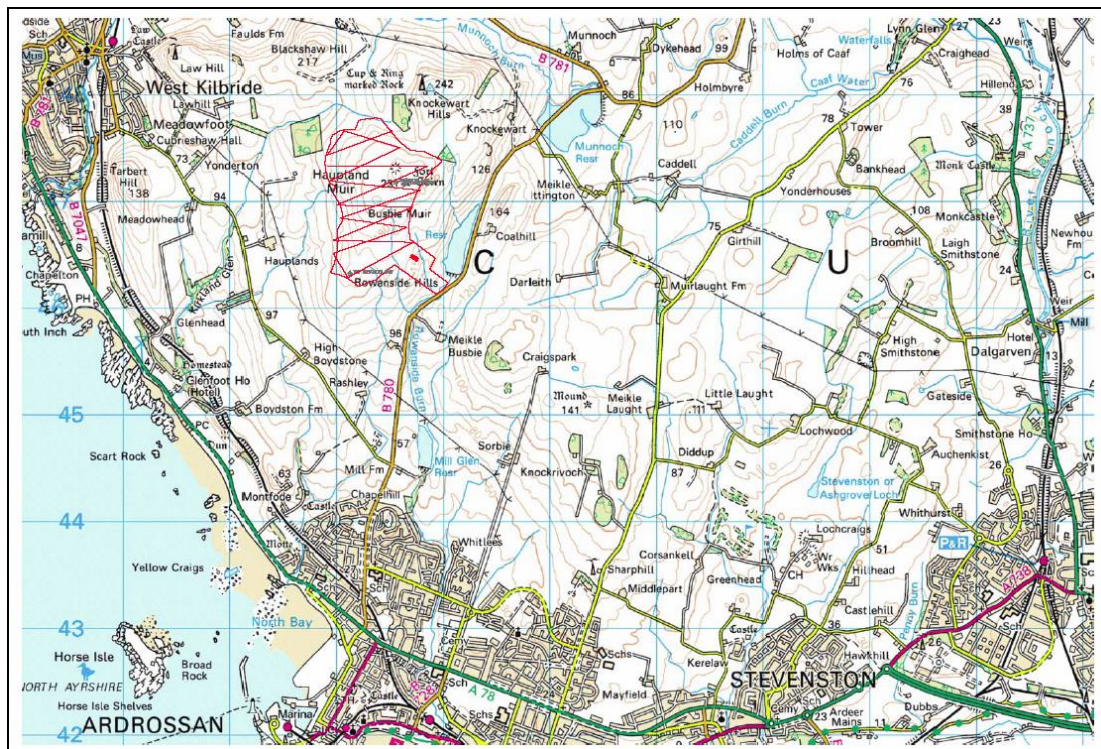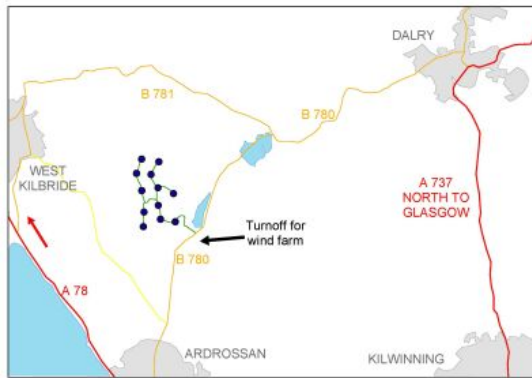
Figure 56 Location of Ardrosssan variable speed windfarm

The Güralp CMG-DM24S12AMS acquisition and monitoring system with 6 CMG-5U accelerometers was deployed on wind turbine 1 on 2/11/2004 and on Turbine 7 on 9/12/2004 , in each case a 1 CMG-5TD digital output strong motion accelerometer buried at a distance between from each turbine. Locations of the site and the turbines are shown in figures 56 and 57. Details of the deployment and sequence of shutdown of these experiments are given in Appendix C.

Accelerometers were attached to the tower along North South East and West azimuths and also mounted vertically as described in Appendix 3. A rapid shut down and sequential switch on was carried out and the spectrograms for both phases are shown in Figures 58 and 59.

As these are variable speed turbines we should not expect to obtain quite such distinct harmonics as we might measure at a fixed speed windfarm as has already been shown from Crystal Rig. However, it is very clear that we do have remarkably persistent spectral peaks which do not appear to change much during the 90 minutes of this experiment. They form bands which are very pronounced between 3 to 5 Hz and between 6 to 9 Hz but there are distinct spectral peaks even within these bands. They disappear as soon as the farm is switched off, re-appear for the short time that turbine 7 and then 6 are on individually and then reappear gradually as the sequential switch-on occurs as described in the tables beneath the spectrograms.

Measurements close to the turbines allow us to clearly see the fall and subsequent rise in power but because there is a considerable disparity in distance to the individual turbines does not allow us to assess quantitatively how the signal sums as extra turbines are included.

In order to address this we have selected the 4.5 Hz band on the Kelphope1 station (2.4 km) during the Dun Law switch-off experiment and have calculated the power change during the switch off and on. The signals from this station were filtered to remove all other components and the rms power was calculated through the duration of the switch off. These are shown in Figure 60 (lower figure).

It is clear that as the number of turbines increases the power increases but it does not scale linearly with power (i.e. the final signal is not 26 times as large as the l with a single turbine.

Schofield (2001) suggested that the power should scale as $\sqrt{N}$ and this seems to be the case as in fact it is approximately 4 to 5 times as much, which is close to what we would anticipate for 26 turbine ($\sqrt{26}=5.1$).
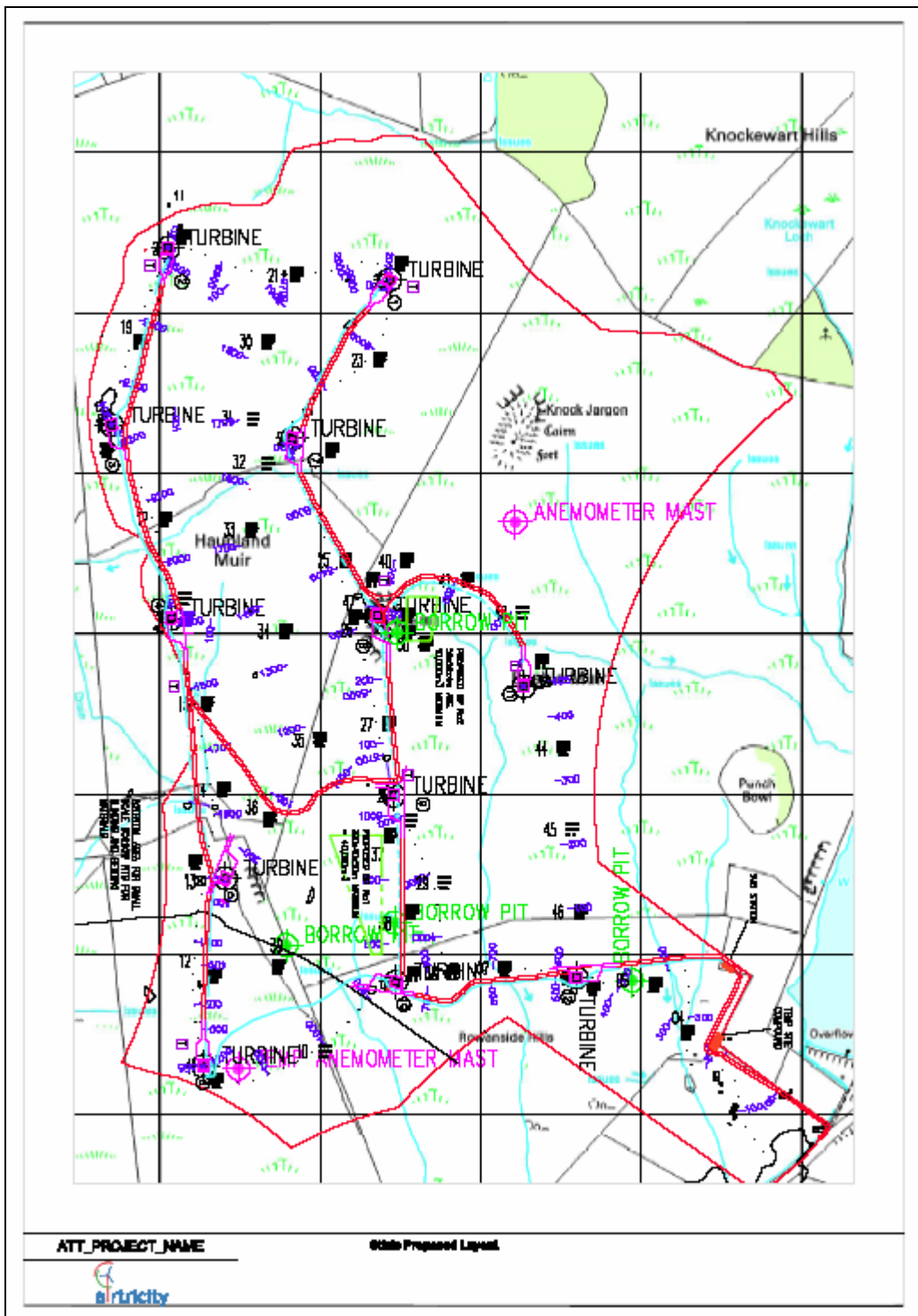
Figure 57 Map of the Turbine Locations at Ardrossan
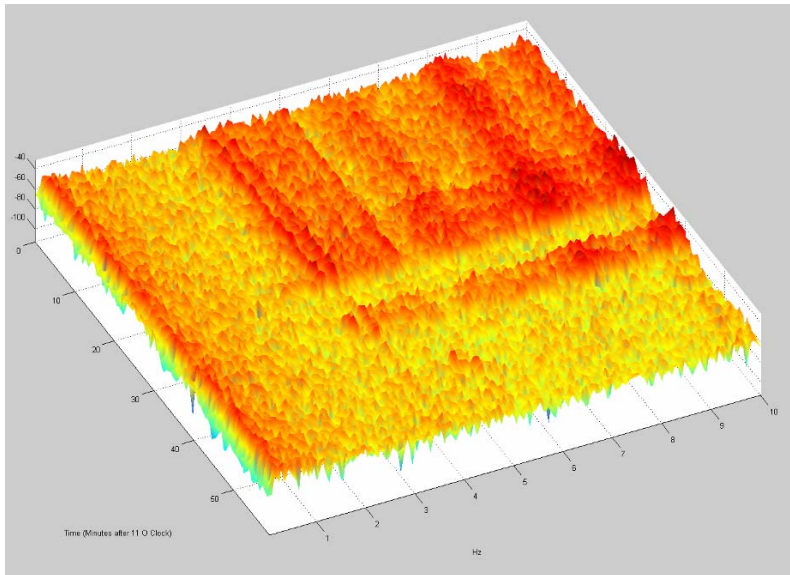
11.25	All
11.30	All Off
11.35	7
11.40	All Off
11.45	6
11.50	6,10
11.55	6,10,12

12.00	6,10,12,5
12.05	6,10,12,5,9
12.10	6,10,12,5,9,11
12.15	6,10,12,5,9,11,8
12.20	6,10,12,5,9,11,8,4
12.25	6,10,12,5,9,11,8,4,3
12.30	6,10,12,5,9,11,8,4,3,2
12.35	6,10,12,5,9,11,8,4,3,2,7
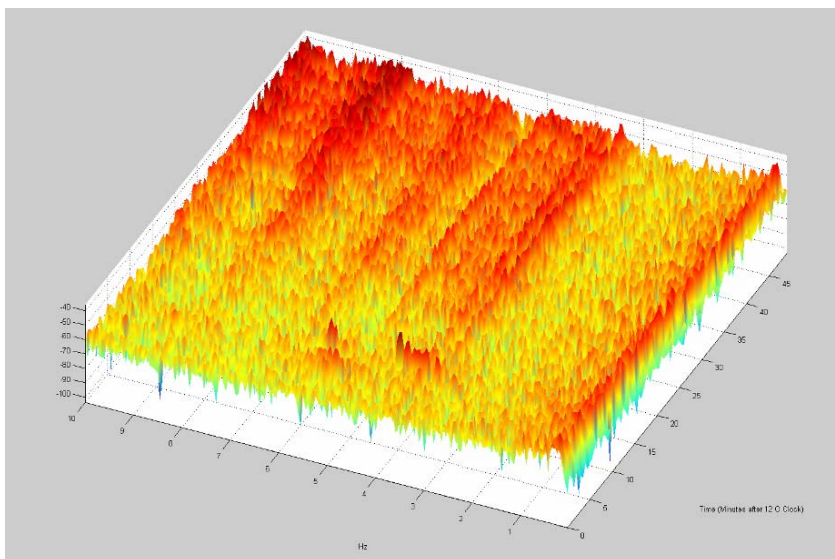
Figure 58   Spectrograms of the switch of and switch on at Ardrossan on 9/12/2004
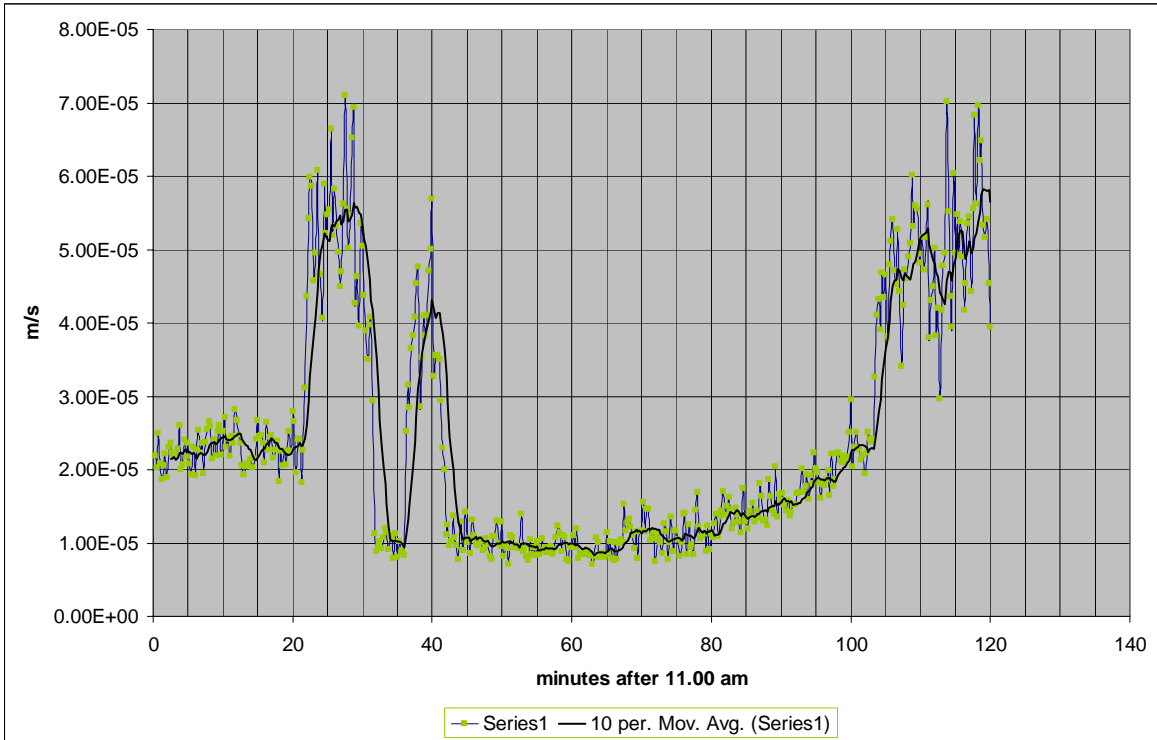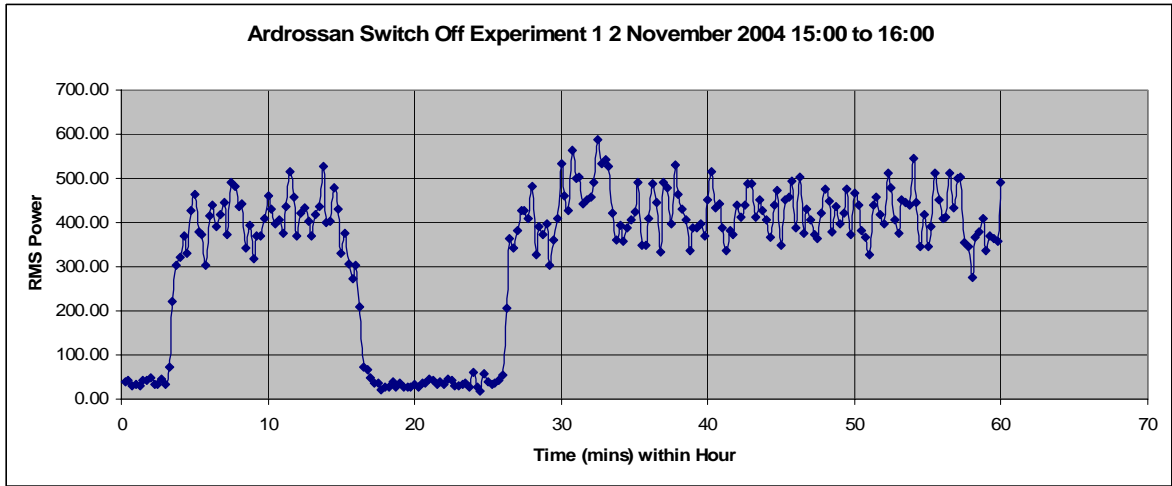
Figure 59   Ardrossan Switch Off and On,
         2 /11/2004 15:00 to 16:00   (top) and
         9/12/2004, 11:00 to 13:00 (bottom)

Dun Law Switch Off and On , 7/102004, 09:00 to 10:00

Dun Law Switch Off 3/11/2004 , 11:00 to 12:00

Power in 4.5 Hz Band During Dun Law Switch Off
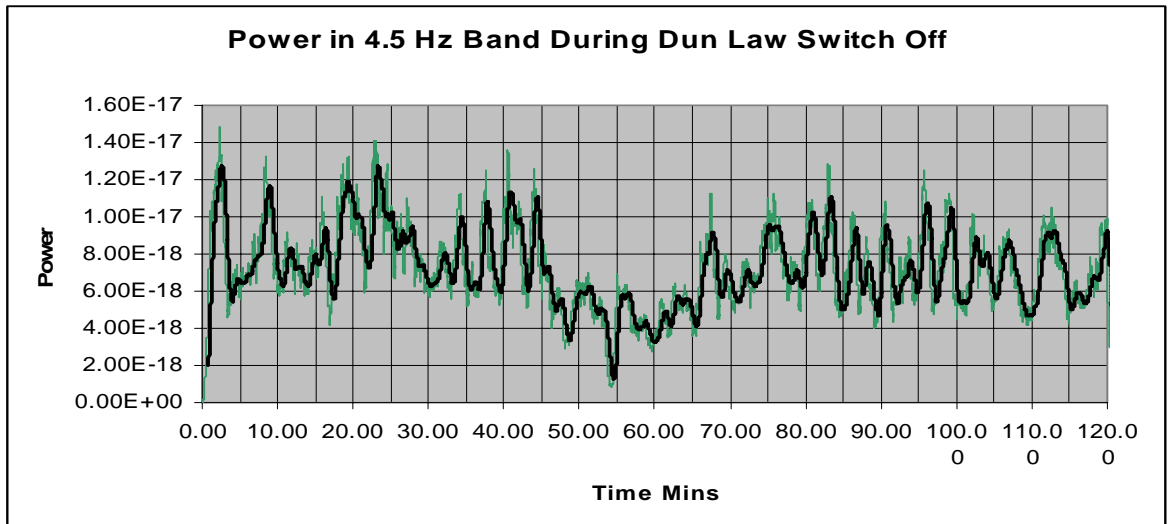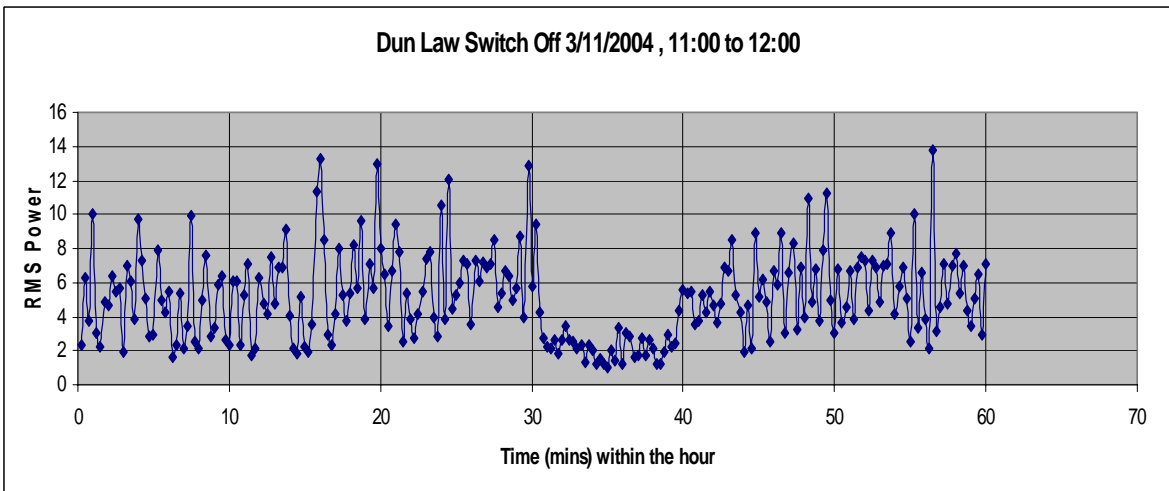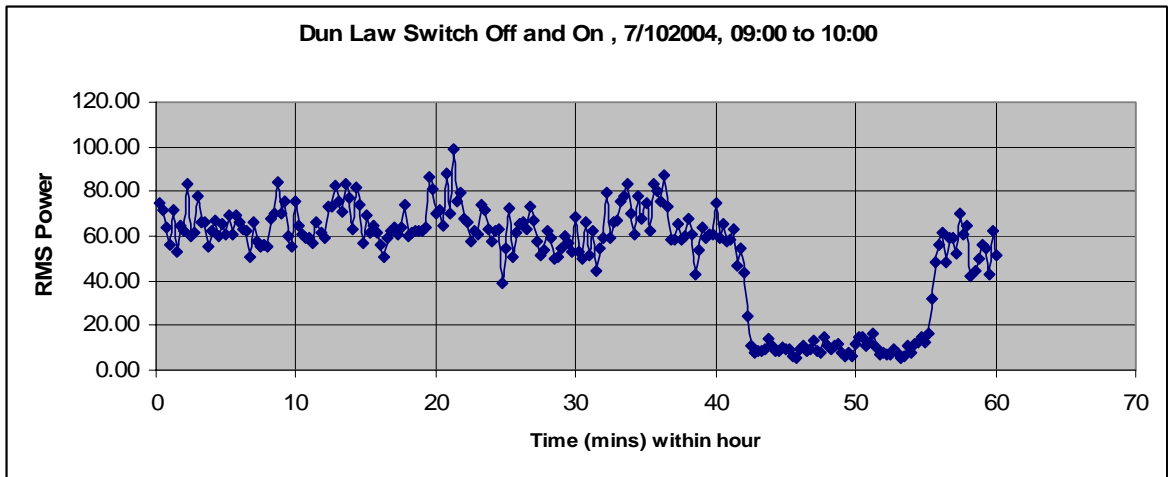
Fig 60   Switch Off at Dun Law on 7/8/2003 Top and Bottom and 3/11/2004 (middle)

We now have sufficient information from the monitoring and analysis of microseismic, infrasound and on-tower monitoring to develop a solution to the problem of what level of vibration is permissible at Eskdalemuir, how does wind farm vibration propagate and attenuate and what is the permissible number and distribution of wind farms and turbines in the Southern Uplands. We first propose a mathematical model for the system following Bowers (2004) and then address the points of interest as a series of important questions with the answers derived from this study.

Mathematical Model of Wind Farm Noise Propagation

In order to evaluate the nature and properties of noise propagation from windfarms we postulate the following mathematical model

The seismic displacement amplitude spectrum, $U(\omega, r)$ at angular frequency ω, of a single wind turbine operating at distance r, from the recording station is given by the following convolutional mathematical model:

$$U(\omega,r) = S(\omega)G(r)B(\omega,r)P(r)$$

where,

S(ω) represents the source spectrum,
P(r) is a frequency-dependent receiver-site effect,
G(r) represents geometrical spreading, $G(r) = r^{\eta}$
B(ω, r) is the attenuation
v=seismic velocity

$$B(\omega,r) = \left(\exp\left(\frac{-\omega r}{2Q(\omega)v} \right) \right)$$

For Cylindrical Spreading (seismic surface waves)

$$\eta = -0.5$$

Therefore the amplitude of the signal from a single turbine at a distant location, A_{far}, is related to the amplitude at a location closer to the turbine, A_{near}, by the following equation (the 1/sqrt(r) with linear attenuation model), where:

$$A_{far} = A_{near} \sqrt{R_{near}/R_{far}}\; e^{-\frac{\pi f (R_{near} - R_{far})}{Qv}}$$

R_{near} and R_{far} are the distances from the source to the near and far locations, respectively,

Q is a factor giving the non-geometrical attenuation of the wave with distance travelled i.e. absorption of energy within the rock as the seismic wave does work to vibrate the particles of the material.

f is the frequency of the signal ($\omega = 2\pi f$)

This formula is applicable to surface waves radiating out from the source uniformly. Localised inhomogeneties may cause some focussing of the energy but this is not predictable in a generalised model and is unlikely to significantly affect the conclusions.

Question 1:   Do Fixed and Variable speed wind turbines generate detectable vibrations

Answer: Yes

➢ We have clearly shown that both fixed speed and variable speed wind turbines generate low frequency vibrations which are multiples of blade passing frequencies and which can be detected on seismometers buried in the ground at significant distances away from wind farms even in the presence of significant levels of background seismic noise (many kilometres).

➢ Some of these are non-stationary at very low wind speeds where we clearly see variation in frequency over long and short timescales and we postulate that these are generated by the interaction between the blades and the towers. There are other frequencies which are stationary and we postulate that these are caused by normal modes of vibration of the towers

➢ We have clearly shown that wind turbines generate low frequency sound (infrasound) and acoustic signals which can be detected at considerable distances (many kilometres) from wind farms on infrasound detectors and on low-frequency microphones (Hayes pers. comm.)

Question 2:   How does energy propagate from the Wind Turbine to a receiving SEISMIC Station?

● as Infrasound travelling through the air for the near zone where

$$G=r^{-1} ?$$

or

● as Seismic Surface Waves travelling through the ground (cylindrical spreading), where
$$G=r^{-1/2} ?$$

Note: At greater distances where the atmosphere acts as a waveguide infrasound may also have a cylindrical dependency on r

Answer

➢ It travels to the seismometer as seismic surface waves, because, we can examine co-located seismic records and infrasound records at the same times and show that it is clear that infrasound energy propagation is optimal in quiet wind conditions where stable atmospheric conditions prevail and that the amplitude DECREASES as the wind speed (and turbulence) increase.

- Conversely, Seismic Amplitude INCREASES with wind speed as the energy of the turbines increases

- Clearly there CANNOT be a casual relationship between the seismic amplitude and the infrasound if they have different behaviours with wind speed.

- N.B. However, it is also clear that low-frequency sound waves can be detected at considerable distances away from a wind farm under the right atmospheric conditions.

Question 3: **If we have a wind farm of N turbines, how does the seismic amplitude increase as compared to 1 turbine?**

Answer

- We have shown it varies as the square root of N and this is to be expected because the turbines are not all in phase and neither are they operating at exactly the same frequency because of the slight possible variations in rotation speed and also wind conditions across the farm. There is also a possible 10% variation in speed (Optislip) which will cause broadening of the spectral peaks. They are quasi-random sources and therefore add as √N

- Therefore 100 turbines are 10 times as noisy as 1, not 100 times

Question 4: If we have N wind farms, how does the seismic amplitude increase as compared to 1 windfarm?

Answer:

- For similar reasoning as given previously for individual wind turbines, individual wind farms will not be in phase with each other and so they will add in QUADRATURE

- $v_{tot} = \sqrt{(v1^2 + v2^2 + v3^2 \ldots + vn^2)}$

Question 5: **How will wind speed and direction affect the vibrations?**

Answer: The following graph (Figure 2) shows the variation of seismic power with windspeed and direction. Although there is some variation with wind direction there is a clear increase with windspeed within the operational region (up to c 15m/s)
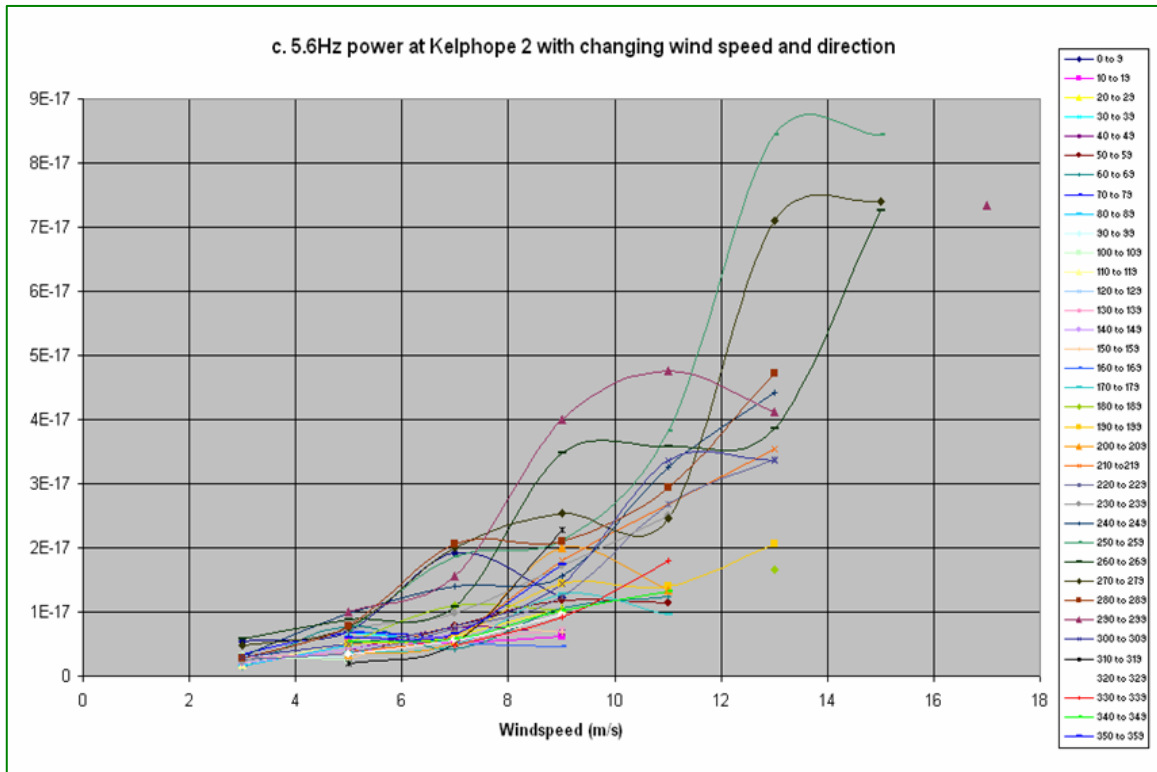
Figure 61   Variation of Seismic vibration power with windspeed at Kelphope 2

Question 6   How does ground vibration vary with electrical power?

Figure 3 show fits of power law variations to the power against windspeed plot and the average of the exponents

Start (Deg)	End (Deg)	Exponent
50	59	1.7287
190	199	1.522
200	209	2.1154
210	219	2.48
220	229	1.8473
230	240	1.7908
240	249	1.7073
250	259	2.316
260	269	1.5667
270	279	1.7399
280	289	1.8642
290	299	1.6351
300	309	1.7712
330	339	2.8986
	mean	1.927371
		0.37715
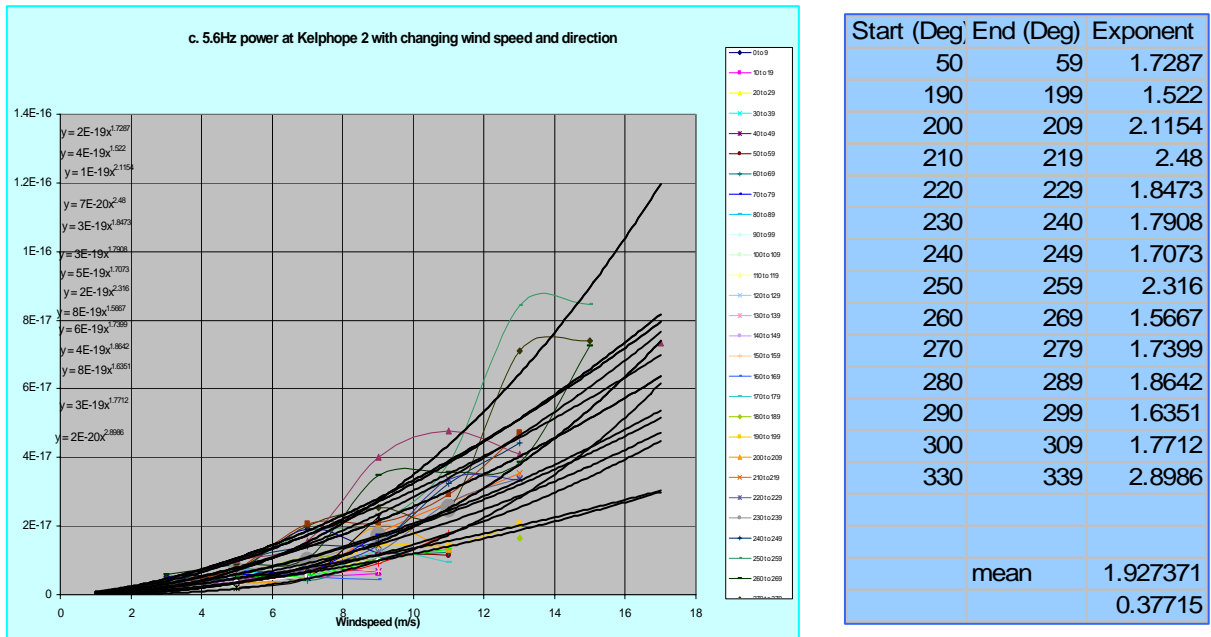
Figure 62   Seismic power v windspeed and the best fit power law for each azimuth

From this we note that:

$$\text{Seismic power} \propto \text{windspeed}^{1.93}$$
$$\text{Seismic amplitude} \propto \text{windspeed}^{0.96}$$

Therefore we conclude that seismic Amplitude is proportional (nearly) to windspeed. Electrical Power is very nearly proportional to windspeed in the operational band (5 to 15 m/s) and so seismic amplitude is approximately proportional to electrical power as can be seen from Figure 4
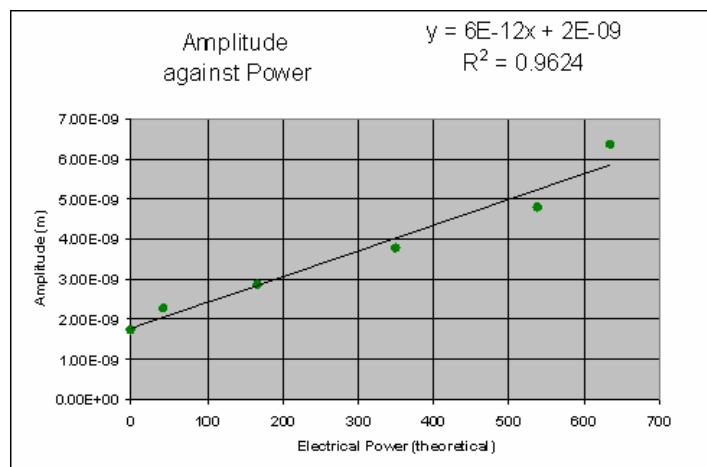
Figure 63   Seismic Amplitude against Electrical Power at Kelphope 2

Question 7:   **How will changes in Wind Turbine Power Capacity and Design change the Vibrations?**

➢ In our propagation model, vibration is proportional to power based on the above evidence and we have further evidence from Ardrossan, Crystal Rig and Dun Law that this is the case

However, at present, foundations are designed for maximum stability without (we presume) regard to seismic coupling. Changes in foundation design and dynamic damping strategies may be able to reduce this linear relationship. It will be possible to measure and assess (model) this for new foundation designs and tower structures. **If** a developer can demonstrate that a new foundation design or active damping results in a lower source noise level than assumed in this report and if this can be verified by modeling AND measurement then the calculations of permitted capacity and position can be changed to reflect this.

Question 8:   **How are we setting the threshold for permitted vibration at Eskdalemuir?**

Notes:

1   In order to assess the effect of wind farm vibration on the detection capability we have selected the 4 to 5 Hz band which is very quiet at Eskdalemuir and therefore ideal for discrimination of nuclear events. This is also a frequency band which is very efficiently generated by the wind turbines we have observed in this experiment and previously (St Breock Downs) and also by Schofield (2001) and therefore liable to interfere with the operation of the array. (N. B. this band attenuates FASTER than lower frequency bands)

2   Even though the strictest possible interpretation of the CTBTO agreement would mean NO increase in threshold is acceptable we have taken the view that an increase equal to the present observed ambient displacement in this band is acceptable without seriously compromising the detection capability of the array.

3   Therefore we are proposing that the **NOISE BUDGET** for Windfarms in the Southern Uplands of Scotland is equal to the windy day rms median noise level as measured at Eskdalemuir.

4   The **NOISE BUDGET** is the **TOTAL** additional noise which all windfarms in the southern uplands of Scotland will be allowed to generate in addition to the present noise at Eskdalemuir

Question 9   **What IS the statistical nature of background noise at Eskdalemuir?**

Initial short-term estimates by Bowers (AWE) suggested that the median level was 0.25 nm, but re-analysis of data from Eskdalemuir over a much longer time period for noisy conditions has given the following histogram. The median level of the nose is 0.336 nm and this has been taken as the noise budget which will be permitted for aggregate wind-farm noise for the region centred on Eskdalemuir.
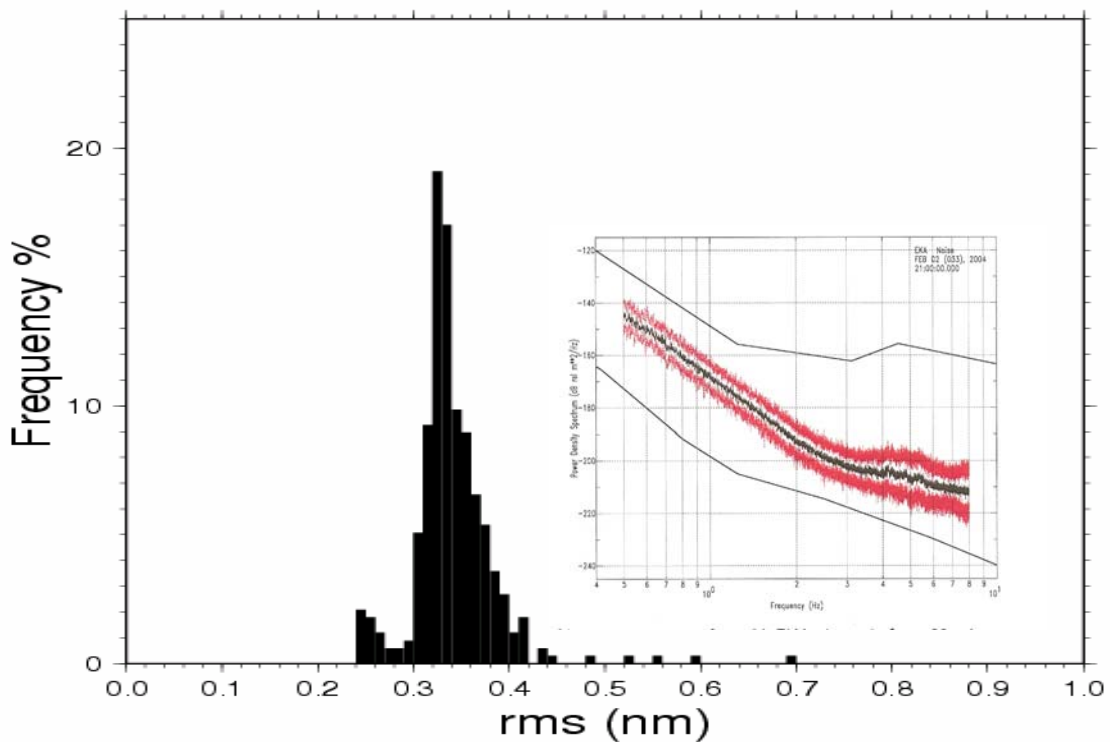
Figure 64   **Seismic background noise levels at Eskdalemuir for 330 half hour data sets. Inset shows the power spectrum of the mean at 20 EKA channels for one of the 30 minute samples at high wind speeds (25 knots) compared to the noise models of Petersen(1994)**

Question 10   **How does changing the amount of power we are prepared to accept as an additional load on Eskdalemuir affect its detection capability?**

If the average band-limited noise power of the (N=20) seismometers comprising EKA is σ_n^2, then we can define the allowable power (σ_w^2) of seismic signals generated by wind turbine as:

$$\sigma_w^2 = x\sigma_n^2$$

where x is a constant multiplier which we wish to set.

We can assume that σ_w^2 can be considered random because in general the wind turbine seismic signals will be generated by a range of windfarms of varying design of variable (mostly) and or fixed speed, location operating under different local wind conditions at a variety of azimuths and distances from EKA. A question has been posed as to what difference azimuth makes to the sensitivity of Eskdalemuir to wind farm vibration but except for a few specific directions at a few specific frequencies this effect can be ignored.

The rms noise level, D after beam forming can be considered a measure of the detection threshold of the array. If the noise power σ_n^2 is random then

$$D_o = \sqrt{\frac{\sigma_n^2}{N}}$$

In the presence of seismic power from windfarms the rms noise level becomes

$$D_1 = \sqrt{\frac{\sigma_n^2 + \sigma_w^2}{N}}$$

And the ratio of the degradation of the EKA detection threshold due to wind turbine signals therefore becomes

$$\frac{D_1}{D_0} = \sqrt{1+x}$$

The preliminary recommendation of Styles (2004) considered the value of x to be ≤1 (ie equal ambient and windfarm noise), giving $D_1/D_0 \leq \sqrt{2}$ (≈1.4).

This can be transformed into an estimate of the degradation of the detection threshold in terms of seismic yield, W in kilotonnes, using a standard magnitude-yield relationship such as

$$m_b = b + a\log_{10} W$$

Where typically a=0.75 and b=4.45 for East Kazakhstan.

Therefore,

$$\frac{W_1}{W_0} = (1+x)^{1/2a}$$

The consequence of this for detection thresholds are shown in figure 6:
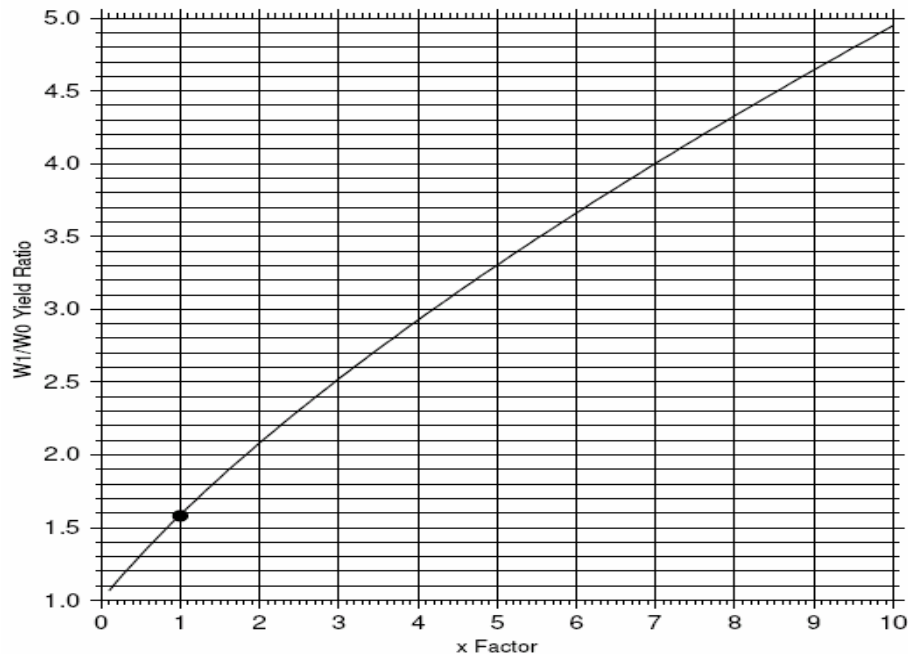
Figure 65   Yield detection ratio (relative to present capability) as a function of additional windfarm generated background noise

> ➤ At present EKA can detect 100 Tonnes of conventional explosive detonated in Kazakhstan (Equivalent to a magnitude 3.8 Mb Earthquake)

> ➤ The suggestion that x=1 , i.e. equal ambient and wind turbine power, will mean that 160 Tonnes will be the minimum detectable at times when the noise rises to the permitted level of equal power from ambient noise and windfarms

> ➤ If we permit more windfarm noise than ambient (say twice as much) then the threshold would be c 200 Tonnes of explosive which I consider to be too prejudicial to the capabilities under the CBT agreement

Question 11   What is a realistic figure for percentage utilisation of a wind farm?

It is clear from discussions with the BWEA that a group of windfarms considered together rarely, if ever, operate at maximum rated power and that for much of the time they operate at considerably less than rated power. This has significant implications for the expectation value of the wind turbine generated vibration levels. The following production data were kindly provided by Sgurr Energy on behalf of the BWEA.

2   WIND FARM PRODUCTION DATA

Data from four ScottishPower wind farms have been used for this study, the details of which are listed Table 1.

Wind Farm	Turbine	Number of Turbines	Turbine Rating (kW)	Site Capacity (MW)
Beinn an Tuirc	Vestas V47	46	660	30.36
Dun Law	Vestas V47	26	660	17.16
Hagshaw Hill	Bonus 600kW	26	600	15.60
Hare Hill	Vestas V47	20	660	13.20

Table 1: Wind Farm Details

Table 5   Production Data for Current Windfarms 1 July 2004 to 30 September 2004
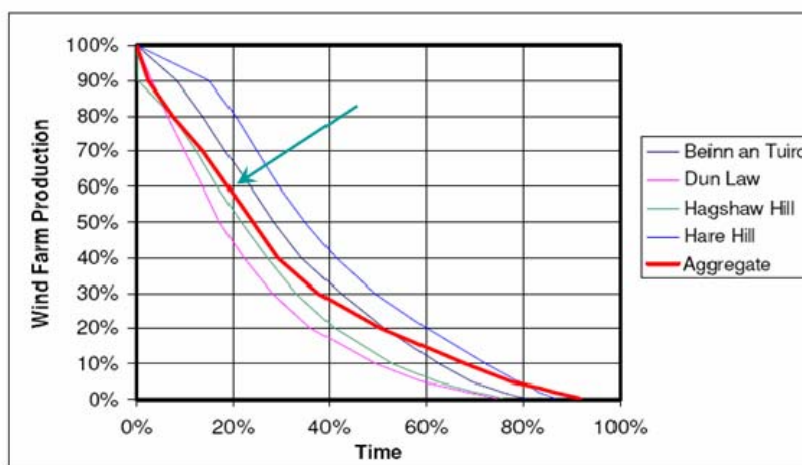
Figure 1: Production Duration Curve

Figure 66   Plot of Production against percentage of time that level is exceeded

Normalised Production	Percentage of Time Normalised Production Exceeded				
	Beinn an Tuirc	Dun Law	Hagshaw Hill	Hare Hill	Aggregate
0.50%	80.3%	74.7%	75.8%	86.6%	92.0%
1%	78.4%	72.2%	73.9%	85.3%	89.8%
2%	75.8%	68.4%	70.0%	83.3%	86.4%
3%	73.6%	65.2%	67.1%	82.0%	83.6%
5%	69.6%	59.6%	62.4%	79.3%	78.0%
10%	62.5%	49.4%	53.1%	72.4%	67.9%
20%	51.4%	36.1%	41.0%	60.0%	50.6%
30%	42.4%	28.3%	33.2%	49.4%	37.8%
40%	34.3%	22.3%	27.3%	41.3%	29.3%
50%	28.6%	17.5%	21.6%	34.9%	24.2%
60%	23.7%	13.7%	16.7%	29.6%	19.0%
70%	18.6%	10.1%	12.5%	25.0%	13.8%
80%	13.8%	6.5%	7.7%	20.7%	7.6%
90%	8.3%	3.3%	0.3%	15.1%	2.4%
100%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 2: Wind Farm Details

Table 6 Production Statistics

It is clear from these tables and figures that Production exceeds 60% Capacity only about 20% of the time

Question 12   **What is a realistic Production level which is not exceeded too often?**

➢ **Proposal :**

- **We accept that for 20 % of the time averaged over a year, seismic amplitude levels may exceed the permitted threshold set at Eskdalemuir of 0.336 nm**

  - NB These will also correspond to days on which the Eskdalemuir Array is less effective because of microseismic noise.

- **This is equivalent to accepting that windfarm electrical power production exceeds 60% of rated capacity only 20 % of the time over a year**

- **This is implemented by scaling the predicted seismic amplitude levels which are calculated on RATED capacity, by 60%**
  - NB This accepts that amplitude is linearly related to power which is what we have used in the model.

Prediction of the levels of vibrations which may be generated by single and multiple windfarms around Eskdalemuir.

With the answers to these questions determined, we can now build a mathematical model based on the theoretical attenuation model proposed earlier, of the seismic sources and the propagation of vibrations from individual and multiple windfarms. We can then compare these individually and in aggregate to the NOISE BUDGET of 0.336 nm rms at Eskdalemuir. The windfarms which we have included in this calculation are those which have been given consent or are already in planning as recognised by the Ministry of Defence Safeguarding Department.

i   We can predict, using the model developed, the vibration level for a given wind farm by knowing its number of turbines, power and distance and test it against the noise budget.

ii   We can place a particular windfarm and then see how this affects the permitted distribution of other windfarms

iii   We can predict the maximum possible number and hence total generating capacity at any particular distance from Eskdalemuir

The parameters which are used in the model are as follows and represent best estimates of the appropriate values.

Parameters

- F=4.5 Hz (mid-point of the passband)

- Q=50 (Determined by MacBeth and Burton, 1986, 1987 for southern Scotland and Bowers pers. comm. for Eskdalemuir)

- Velocity (c)=2000 (From Eskdalemuir)

- Noise Budget= 0.336 nm (median noisy day value for Eskdalemuir)

- Percentage utilisation which is only exceeded 20 % of the time = 60%

- The displacement at r=1 km is calculated at 24 nm rms equivalent for the Stateline Windfarm of 399 Vestas, 0.66 MW, V47 turbines which is calibrated against vibration levels measured throughout this experiment of 5.5 nm at Kelphope 2 (1.3 km) and 2.6 nm at Kelphope 1 (3.1 km) at Dun Law (26 Vestas, 0.66 MW, V47 turbines) and levels of 30nm at 720 meters for Stateline (Schofield 2001).

Figure 8 shows the centroids of windfarms with consent or in planning at 1st March 2005
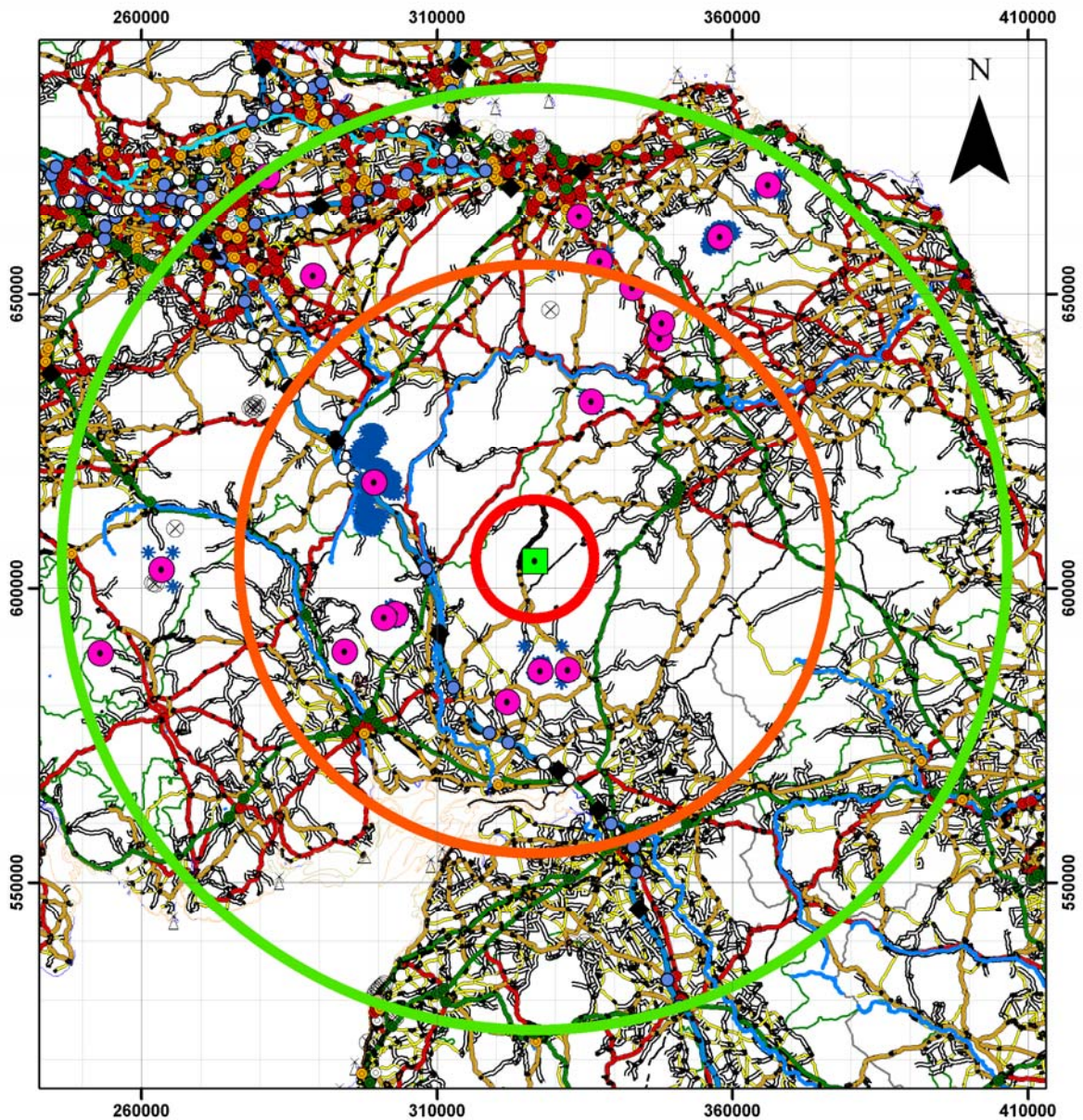
Figure 67. Distribution of windfarms and their centroids with respect to Eskdalemuir (Circles are at 10 km, 30 km and 50 km)

Table 4 shows the individual levels and the total generating capacity and aggregate seismic noise which we predict will be generated by windfarms in planning or having obtained consent.

Attenuation of Displacement in the 4.5 Hz Band as a Function of Number of Turbines, Power and Distance											
TOTAL GENERATING CAPACITY			1657.1							Noise threshhold in 1.5 to 4.5 Hz Band	
TOTAL NOISE			0.307							0.336	
										24	
Windfarm	N (Number of Turbines)	Power (per Turbine)	r (km)	Total Power (MW)	Attenuation with Distance	N-Ratio	P_Ratio	Total Scaling Factor	Amplitude (nm)	Scaled by 60% to reflect Utilisation	EXCEEDS <20% of time (ie 60% power)	Noise Power(nm2)
Stateline (Ref)	399	0.66	0.71	263.34	1.23645	1.000	1.000	1.23644823	29.6748	17.8049	ref	FROM Stateline
KELPHOPE2	26	0.66	1.3	17.16	0.84064	0.255	1.000	0.214589995	5.1502	3.0901	ref	FROM KELPHO
KELPHOPE1	26	0.66	3.1	17.16	0.42207	0.255	1.000	0.107742194	2.5858	1.5515	ref	FROM KELPHO
Stateline (Ref)	399	0.66	18	263.34	0.02131	1.000	1.000	0.021311589	0.5115	0.3069	ref	
EWE HILL	22	2.30	18.9	50.6	0.01831	0.235	3.485	0.014985552	0.3597	0.2158		4.66E-02
CLYDE	173	3.00	30.04	519	0.00301	0.658	4.545	0.008998851	0.2160	0.1296		1.68E-02
HARESTANES	71	3.00	27.38	213	0.00459	0.422	4.545	0.008797356	0.2111	0.1267		1.60E-02
MINSCA	17	2.50	24.97	42.5	0.00675	0.206	3.788	0.005278918	0.1267	0.0760		5.78E-03
CARLESGHILL	5	1.75	19.63	8.75	0.01621	0.112	2.652	0.004811735	0.1155	0.0693		4.80E-03
MINNYGAP	15	2.00	25.32	30	0.00639	0.194	3.030	0.003752921	0.0901	0.0540		2.92E-03
DALSWINTON	16	3.00	35.31	48	0.00132	0.200	4.545	0.001197797	0.0287	0.0172		2.98E-04
MINCH MOOR	12	2.00	38	24	0.00087	0.173	3.030	0.000456049	0.0109	0.0066		4.31E-05
MIDDLE HILL	12	2.00	28.7	24	0.00372	0.173	3.030	0.001954133	0.0469	0.0281		7.92E-04
HALKBURN	20	2.00	42.97	40	0.00040	0.224	3.030	0.000274094	0.0066	0.0039		1.56E-05
SELL MOOR	19	2.00	45.44	38	0.00028	0.218	3.030	0.000183203	0.0044	0.0026		6.96E-06
TODDLE BURN	26	2.31	48.9	60	0.00016	0.255	3.497	0.00014616	0.0035	0.0021		4.43E-06
FALAHILL	15	1.75	51.72	26.25	0.00011	0.194	2.652	5.49815E-05	0.0013	0.0008		6.27E-07
BLACK LAW	62	2.30	60.94	142.6	0.00003	0.394	3.485	3.67534E-05	0.0009	0.0005		2.80E-07
AFTON RESERVOIR	41	2.76	63.21	113	0.00002	0.321	4.176	2.54967E-05	0.0006	0.0004		1.35E-07
FALLAGO RIDGE	67	2.00	63.04	134	0.00002	0.410	3.030	2.42814E-05	0.0006	0.0003		1.22E-07
BROADMEADOWS	25	1.40	58.73	35	0.00004	0.250	2.121	1.97834E-05	0.0005	0.0003		8.12E-08
CRYSTAL RIG PHASE	40	2.50	74.81	100	0.00000	0.317	3.788	4.074E-06	0.0001	0.0001		3.44E-09
TORRS HILL	2	2.50	75.21	5	0.00000	0.071	3.788	8.58584E-07	0.0000	0.0000		1.53E-10
SITE 9	4	0.85	79.27	3.4	0.00000	0.100	1.288	2.26631E-07	0.0000	0.0000		1.07E-11
												0.3067

Table 7   **Predicted total noise aggregate for all Windfarms currently consented or in planning. The total generating capacity of 1.6 GW has a total aggregate noise level below the limit of 0.336 nm.**

An alternative way of looking at this is to consider the total generating capacity which would be permissible at any given distance from Eskdalemuir and this is shown in Figures 9 and 10 for a notional turbine power of 2 MW where we assume that NO turbines lie closer than each calculated distance.

Permitted Rated Electrical Power at a given Distance from Eskdalemuir
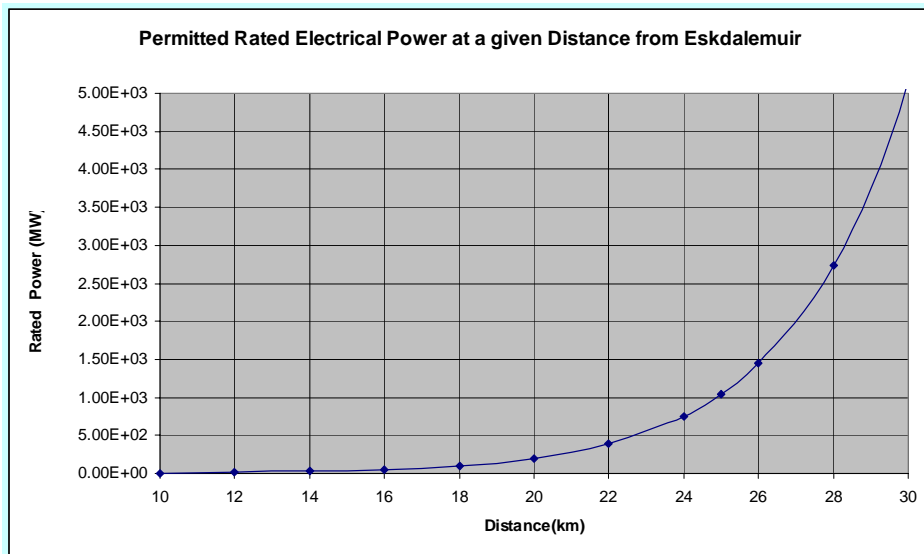
Figure 68   Total permissible generating capacity at distances from 10 to 30 km from Eskdalemuir. Note that the 1 Gigawatt level is at 25 km and that this presumes that NO turbines lie closer than this distance.

Permitted Electrical Power at a given Distance from Eskdalemuir
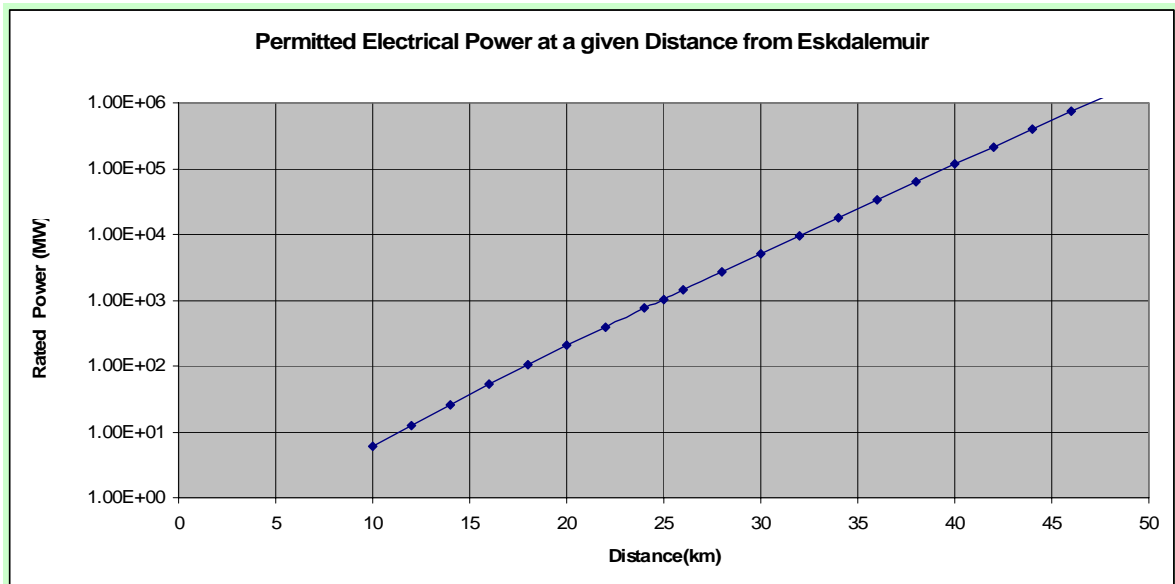
Figure 69   Total permissible generating capacity as a function of distance from Eskdalemuir from 10 to 50 km:

Note 1   The 1 Gigawatt level is at 25 km and this presumes that NO turbines lie closer than this distance.

Note 2.   Note the enormous increase in capacity which can be tolerated at distances greater than 45 to 50 km.

Conclusions

At present there are no current, routinely implemented vibration mitigation technological solutions which can reduce the vibration from wind turbines. Technologies which are helpful in the reduction of vibration from mechanical systems **do** exist and in the long-term and at some additional cost it should be possible for manufacturers/developers to modify/augment these for application to wind turbines to reduce the levels of vibration transmitted into the ground.

However, the following conclusions are based on **current** turbine designs as built.

1 This analysis allows us to define an exclusion zone of 10 km within which **NO** windfarm/turbine development is acceptable

2 We recommend that in order to optimise total energy generation, it would be inadvisable to permit any additional windfarms of **current** design to be permitted within 17.5 km of Eskdalemuir as these will effectively sterilise the whole region from generating additional capacity.

3 It allows us to calculate that presently consented and planned windfarms as defined in Table 4, will not exceed the limit of 0.336 nm for approximately 80% of the time and that during the remaining 20% of the time where they **might** exceed the limit, the ambient background noise at Eskdalemuir will also be higher than the median value and as discrimination will be sub-optimal during these periods of higher windspeed this is acceptable.

4 Beyond 50 km, we do not anticipate that **ANY** reasonable windfarm development will have an impact on the detection capabilities of Eskdalemuir.

5 There is some limited headroom for additional capacity with currently available turbine designs **if** it is required, up to the aggregate noise level of 0.336 nm, but we would strongly recommend that in order to maximise the energy generation capability this takes place at distances greater than 25 km from Eskdalemuir. The algorithms developed here will permit this to be assessed.

References

Bache, T. C., Marshall, P. D. and Young, J. B., 1986, High frequency seismic noise characteristics at the four United Kingdom-Type arrays. Bull. Seis. Soc. Amer,, 76, 601-616.

Bowers D., (2004), Effects of known and foreseeable noise interference on seismic arrays, AWE Report No. 763/04 (M52/2), 1-27

Brisbourne, A. & Horelston, A. 2004. Seis-Uk Cmg_6td Intrumentation: Recommended Fieldwork Procedures, Version 2.1. Seis-Uk, Leicester University.

Elliot J., Bowers, D. and Selby N., 2004, Correlations between seismic noise and wind speeds and directions at the Eskdalemuir array, AWE Report (in prep),

Güralp Factsheet. 2004. Cmg-6td Digital Output Broadband Seismometer. Güralp Systems Limited.

Güralp Operator's Guide. 2004. Cmg-6td Digital Output Broadband Seismometer. Güralp Systems Limited.

Legerton, M.L., Manley, D.M.J.P, Sargent, J.W, Snow, D.J, Styles, P. "Low frequency noise & vibration levels at a modern wind farm". Proceedings of Inter-Noise 96 p. 459-462. Liverpool 1996.

MacBeth, C. and Burton, P.W., 1986. Propagation of 0.7- 2.5Hz Rayleigh waves in Scotland, Geophys. J. Roy. Astr. Soc., 84, 101 - 120.

MacBeth, C. and Burton, P.W., 1987. Single station measurements of high frequency Rayleigh waves in Scotland, Geophys. J. Roy. Astr. Soc., 89, 757-797.

Manley, D. M. J. P. and Styles, P., (1995), Infrasound Generated by large sources, Proc. Inst. of Acoustics, Vol. 17, 239-246

Manley, D. M. J. P., Styles, P., and Scott, J., (2002), Perceptions of the public of Low Frequency noise, Journal of Low Frequency Noise, Vibration and Control., 21, 1, 37-44.

Peterson, J., 1993. Observations and modelling of seismic background noise, US Geological Survey Open File Report 93-322.

Rushforth, I., Styles, P., Manley , D J. M. P. and Toon, S. (1999), Microseismic Investigation of Low Frequency Vibrations and their possible effects on Population , Journal of Low-Frequency Noise, Vibration and Active Control , 18, (3), 111-121

Rushforth, I, (2002), Microseismic Investigation of Infrasonic Environmental Noise and Vibration, Unpublished PhD thesis University of Liverpool.

Rushforth I. , Moorhouse, A and Styles P., (2002) A Case Study of Low Frequency Noise Assessed using DIN 45680 Criteria, Journal of Low Frequency Noise and Vibration, V21, No4, 181-198.

Rushforth I., Moorhouse A. and Styles P., (2003) An Integrated Acoustic/Microseismic Approach to Monitoring Low Frequency Noise & Vibration – A Case Study, Building Acoustics, V10, no 1, 77-95

Schofield R., (2001), Seismic Measurements at the Stateline Wind Project, LIGO T020104-00-Z

Snow D.J. (1997). Low frequency noise and vibrations measurements at a modern wind farm, ETSU W/13/00392/REP.

Styles P. (1996), Low-Frequency Wind Turbine Noise and Vibration: ETSU/POWERGEN, Contract Number 503922, 22pp

Trodd, H., (1998) Variation in Amplitude of Seismic Noise at Eskdalemuir Array, AWE Internal Technical Note /97/DFS/AG/391 HT052.

Vella, G., Rushforth, I., Mason, E., Hough, A., England, R., Styles, P., Holt, T., and Thorne, P. (2001) Assessment Of The Effects Of Noise And Vibration From Offshore Windfarms On Marine Wildlife, Department of Trade and Industry, Energy Technology Support Unit (DTI/ETSU) report w/13/00566/REP.

Appendix A

Deployment of Microseismic Equipment

Microseismic and infrasound monitoring of low-frequency noise and vibration from windfarms.

Phase 1 – Deployment of Guralp Systems CMG-6TD broadband seismometers.

Figure A1   Guralp CMG 6TD broadband three component seismometer

Phase 1 – CMG-6TD deployment:

Deploying CMG-6TD seismometers from the windfarm out to distances of c. 20km I order to provide data showing the vibration caused by Dun Law windfarm and it's attenuation with distance.

Equipment:

9   Guralp Systems CMG-6TD broadband seismometers were hired from SEIS-UK. The CMG-6TD is a 24bit digital output broadband sensor configured at 30s to 100Hz. Each system consists of:

- Low-power lightweight sensor with internal digitiser and 3 or 4 Gbyte solid state memory.
- Low-power external GPS antenna.
- Breakout box and firewire cable for communication and data extraction whilst the instrument is buried.
- Lacie disks – portable USB/firewire hard-drives for rapid data extraction in the field.
- Power supply – 1 x Solarex SX20M Solar Panel with regulator and integral stand.

The systems are designed for rapid field deployment and servicing which serves our purpose well. Total power consumption is less than 1W with GPS cycling, so instrumentation can be deployed with 1 solar panel and an 85AH 12V battery for long periods. Units can be installed without any user interaction, and data can be transferred in the field. Data extraction time of 3Gbyte is around 12 minutes.

Deployment Procedure:

What follows is a description of the procedure for field deployment of the Guralp CMG-6TD seismometers (after Brisbourne & Horleston, 2004) in a manner appropriate for this project.

1.   Sink a cylindrical hole to circa 80cm depth, making sure it is wide enough to insert the seismometer with bag etc.
2.   At approximately 1m distance from the seismometer pit, dig a further hole to house the water tank which will hold the battery, regulator, breakout box, data cable and GPS cable.
3.   Make a level base with sand at the bottom of the seismometer pit, make sure the breakout box and data cables are connect to the 6TD, bag the seismometer with data cable attached and fasten the top.
4.   Insert the seismometer into the pit packing sides with sand.
5.   Run breakout box and data cables from the seismometer pit to the battery pit through a trench approximately 10-15cm deep.
6.   Place battery in battery box, in battery pit.
7.   Place GPS c. 1m from battery pit, not in the same direction as the seismometer, with a clear sky view. Bury cable in a trench to battery pit, again 10-15cm deep.

8. Repeat with solar panel, burying the cable between the panel and the battery pit.
9. Connect the GPS antenna to the breakout box.
10. Connect the battery to the "Battery" port on the regulator, followed by the solar panel.
11. Connect "Load" from the regulator to the breakout box "power".
12. 6TD should start up with previously programmed configuration.
13. Connect Palm via serial lead to the breakout box.
14. Launch **Shout** software and proceed as follows:
    a. Set baud rate of 19200 and use "probe" to detect the instrument.
    b. Tap the sensor ID to enter configuration.
        i. Use "Fetch" to obtain current configuration.
        ii. Use "Apply" to force any changes.
        iii. GPS cycle is in minutes (not hours) and should be set to 0 for continuous recording.
    c. Tap "streams" to examine velocity/mass output and status stream
15. Open **ptelnet** for command line entries.
    a. On entering **ptelnet** tap "On" followed by the macro "ctrl-s" forcing ptelnet to interpret data from the 6TD
    b. When ptelnet is ready the OK prompt appears with the sensor ID and "Command mode" message.
    c. Using the macro *showflash* note the last flush chip and last write chip.
    d. Check for GPS fix with macros *ok-1* followed by *.fix*.
    e. Ensure that the battery and breakout box are bagged, all connections are made, the solar panel is charging and all cables are secured and sketched.

Figure A2   Field deployment of CMG-6TD sensors.
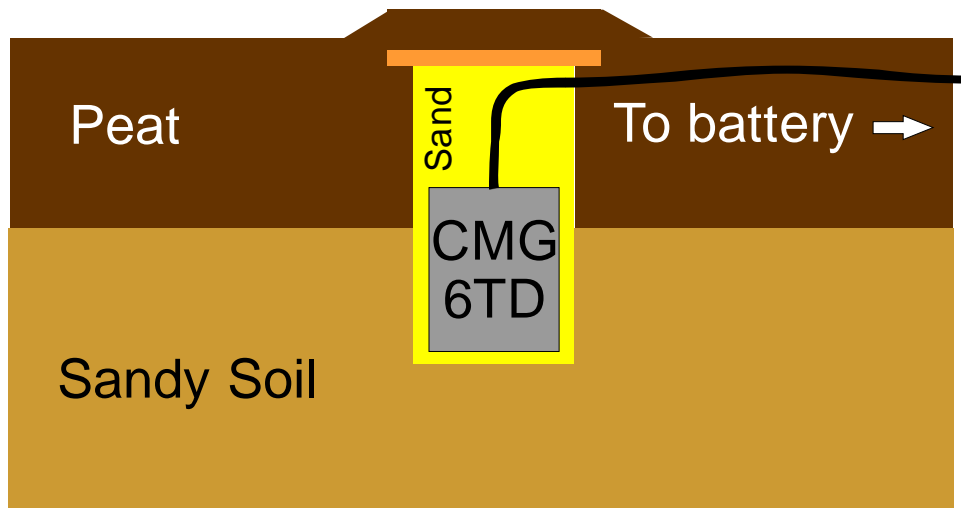
Figure A3   Cross section of typical CMG-6TD deployment

Data Storage and extraction:

When powered the 6TD unit is always recording data to the solid state memory. The data is extracted in the field by copying to a 40GB Lacie disk, via firewire.

The 6TD memory is set as a circular buffer, so when full, the oldest data are overwritten. Due to the length of time the instruments were operating, servicing and data download had to be carried out in the field before the oldest data was overwritten. Recording at 100 samples per second (sps) a 6TD will record circa 50Mbytes a day, which means the disk will fill in around 55 days (allowing 10%). Noisier sites will fill the disk more rapidly due to poor performance of the data compression algorithm. Data are transferred from the 6TD to the Lacie disk in the field via a firewire link. Full 3GB transfer takes around 12 minutes.

Servicing in the field follows the procedure below:

1. Connect the firewire cable from the 6TD to the Lacie.
2. Connect power to the Lacie.
3. Connect Palm to breakout box and open **ptelnet** (followed by "on" and "ctrl-s").
4. In **ptelnet**:
    a. Take the last GPS sync time (.*fix* command).
    b. Check the disk free space using the *dir* command.
    c. Enter "*flush*" at the terminal, the Lacie LED will flash red and hex numbers are spooled to the terminal if working correctly. Flush only downloads data recorded since the last successful flush.
    d. Check the disk free space using the *dir* command.
5. In **Shout**:
    a. Check Mass positions.
    b. In *streams* check velocity offsets Z, N and E.
    c. Ensure that the GPS cycle is set to 0 for continuous recording.

6. Make a record of any damage to cables, the solar panel, the battery and if there has been any water penetration.

Figure A4   Servicing a CMG-6TD in the field

CMG-6TD deployment locations:

The initial phase of CMG-6TD deployment consisted of setting out 9 instruments at distances up to 10702m from Dun Law windfarm (centroid GR 347057, 657504). A further CMG-6TD was deployed later in the data collection period at c. 17km from Dun Law wind farm.

Site Name	UTM, Coordinates	Sensor Serial Number	Distance from northwest point of Dun Law (km)
Kelphope 2	NT 48954 58867	T6064 & T6121	1391
Kelphope 1	NT 49927 59007	T6123	2362
Crib Law 2	NT 51950 59469	T6083	4425
Crib Law 1	NT 52764 59735	T6091	5242
Array 1	NT 53210 60479	T6087	5939
Array 3	NT 53349 60246	T6132	5981
Array 2	NT 53455 60477	T6179	6175
Hope Hills 1	NT 55739 61515	T6124	8868

Hope Hills 2	NT 57518 62521	T6047	10702
Johnscleugh	NT 63008 66344	T6155	17287

The instruments were deployed along an approximately straight line from Dun Law, with a triangular array at circa 6km from the windfarm. Seismometers were in the field from 29/07/2004 to the end of November 2004, although the period of recording is less due to intermittent power failures.

Problems encountered:

- Flooding of battery boxes (peat holds a lot of water).
- Power cut out as the days grew shorter – solar panels didn't charge batteries enough.
- Water penetration of CMG-6TD's.
- Sites were a lot noisier than expected.
- Some failure of CMG-6TD's in the field.
- Digitiser noise in results.

References:

BRISBOURNE, A. & HORELSTON, A. **2004**. *SEIS-UK CMG_6TD Instrumentation: Recommended Fieldwork Procedures, Version 2.1*. SEIS-UK, Leicester University.

GÜRALP FACTSHEET. **2004**. *CMG-6TD Digital Output Broadband Seismometer*. Güralp Systems Limited.

GÜRALP OPERATOR'S GUIDE. **2004**. *CMG-6TD Digital Output Broadband Seismometer*. Güralp Systems Limited.
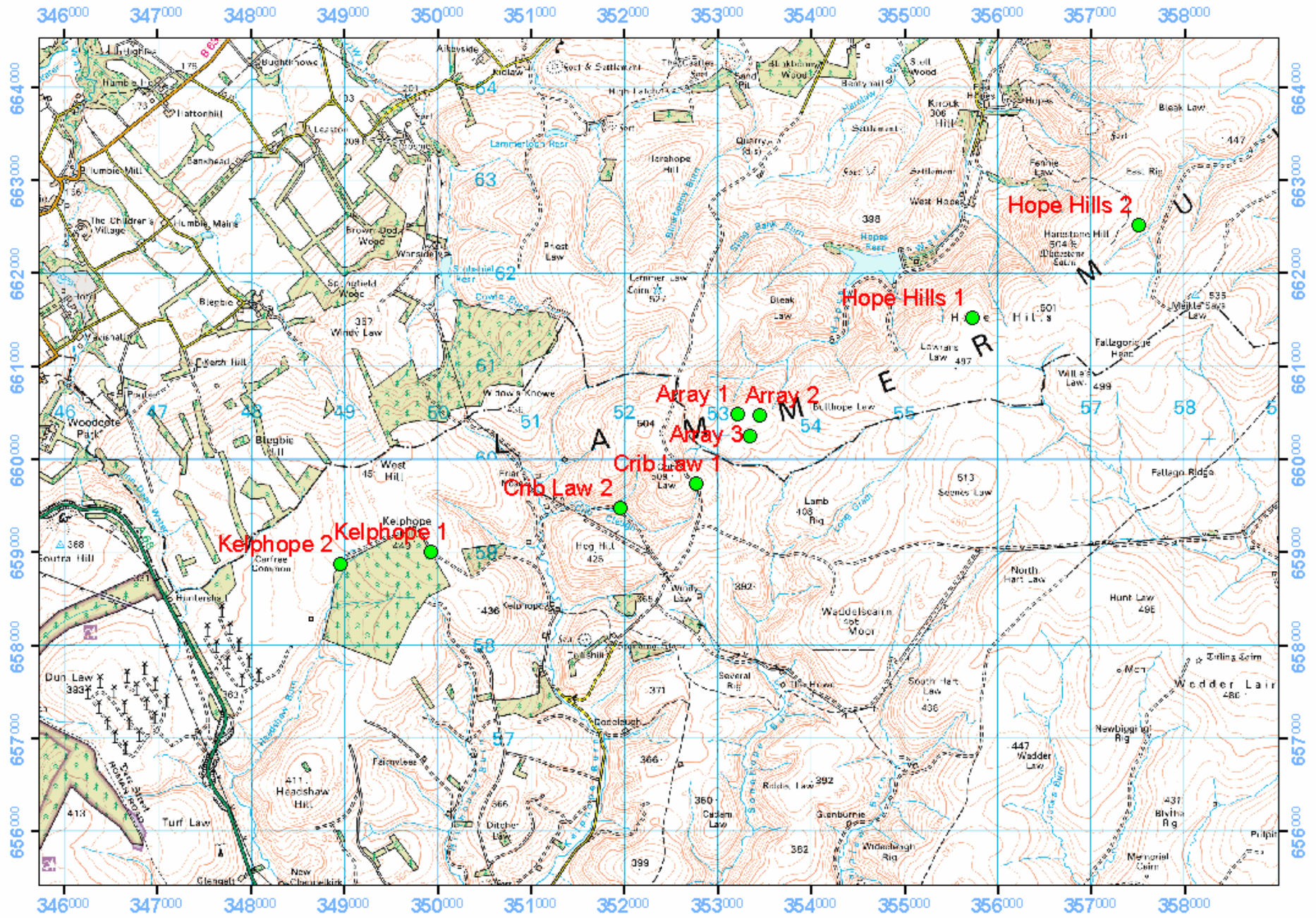
Appendix B

Deployment of Microbarometer Infrasound Equipment

Microseismic and infrasound monitoring of low-frequency noise and vibration from windfarms.

Phase 2 – Deployment of MB2000 Microbarometers.

Figure B1   **MB2000 Microbarometer**

The equipment consists of sensitive microbarometers which are deployed at the ground surface. They have a four-port manifold which is connected to 4 leaky hoses which act as filters to smooth out high-frequency fluctuations in air pressure. This enables the microbarometers to sense low-frequency variations in acoustic pressure which are known as Infrasound when they are beneath 20 Hz. The equipment is capable of recording much lower frequencies down to periods of many minutes.

Phase 2 – DASE MB2000 Microbarometer deployment:

To deploy microbarometers co-located with Phase 1 seismometers to quantify infrasound from windfarms. Co-location of infrasound and seismic sensors will allow us to determine whether infrasound couples with the ground to generate the seismic signal.

Equipment:

4 Département analyse, surveillance, environnement (DASE) MB2000 microbarometers with 4 ORION portable data loggers on loan from the CTBTO.

MB2000:
- Measures small variations of atmospheric pressure and also those generated at large distances.
- Sensitivity of output is 1MV/Pa.
- Frequency response is 0.0001 to 40Hz (filtered output is 100s to 27Hz).
- Electronic noise is less than 2mPa rms (0.02~4Hz).
- Can be deployed with weather/environmental monitoring equipment.

ORION:
- Field portable seismic data logger.
- Data recorded to removable disk cartridge.
- Can operate in continuous recording mode.
- Timing referenced to UTC by an internal GPS receiver.

Deployment procedure:

1. Locate the site position and remove a sod.
2. Place the metal MB2000 box in the depression and connect permeable hoses.
3. "Thread" hoses underneath heather cover in a loop.
4. Use cables provided to connect MB2000 to Orion data logger (and weather monitoring system if using).
5. Power the system with 4*85AH 12V batteries.
6. Seal batteries and data logger in a tank.
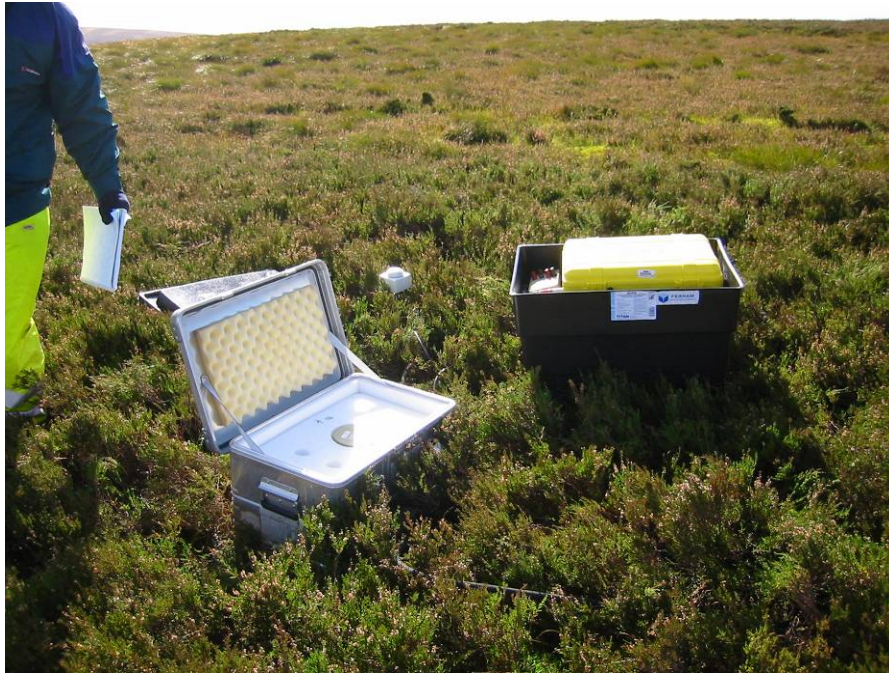
Figure B2   **MB2000 (in metal box), ORION datalogger (yellow box) and battery deployment at an infrasound site.**
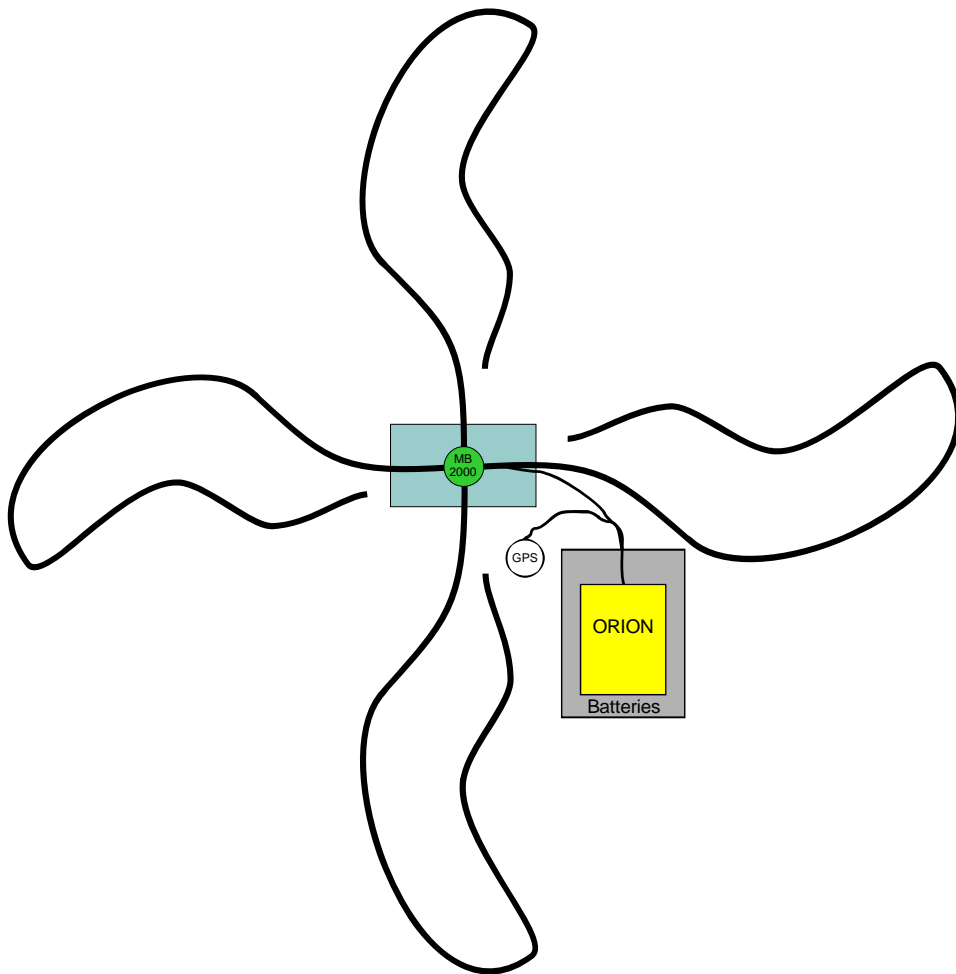
Figure B3   **Plan view of Infrasound deployment showing arrangement of leaky hoses**

Deployment locations:

DATE:	20.09.2004
LOCATION:	Infrasound 1
GRID REFERENCE:	NT 53333 60478 (bisects CMG-6TD sites Array 1 & Array 2
SENSOR:	WB1103
DATALOGGER:	Orion number 0190

DATE:	20.09.2004
LOCATION:	Infrasound 2
GRID REFERENCE:	NT 53280 60363
SENSOR:	WB1107
DATALOGGER:	Orion number 0190

DATE:	20.09.2004
LOCATION:	Infrasound 3
GRID REFERENCE:	NT 53415 60368
SENSOR:	WB1146
DATALOGGER:	Orion number 0139

DATE:	21.09.2004
LOCATION:	Kelphope 1 Infrasound
GRID REFERENCE:	NT 49931 59031
SENSOR:	WB1144
DATALOGGER:	Orion number 0192
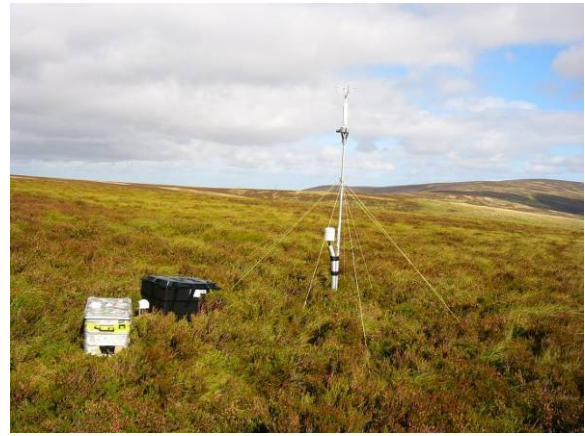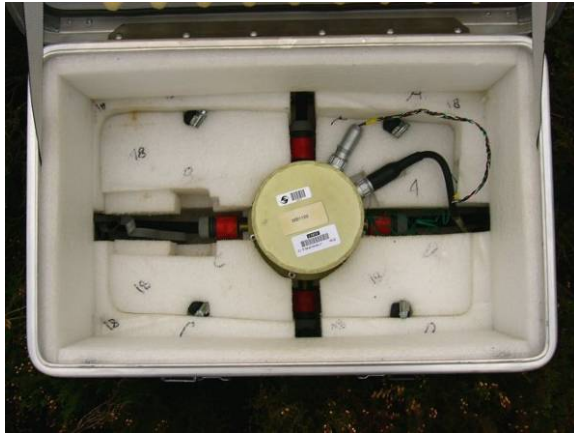
Figure B4   Microbarometer and associated equipment

Appendix C

ON-Turbine Deployment

Equipment:

CMG-DM24S12AMS:
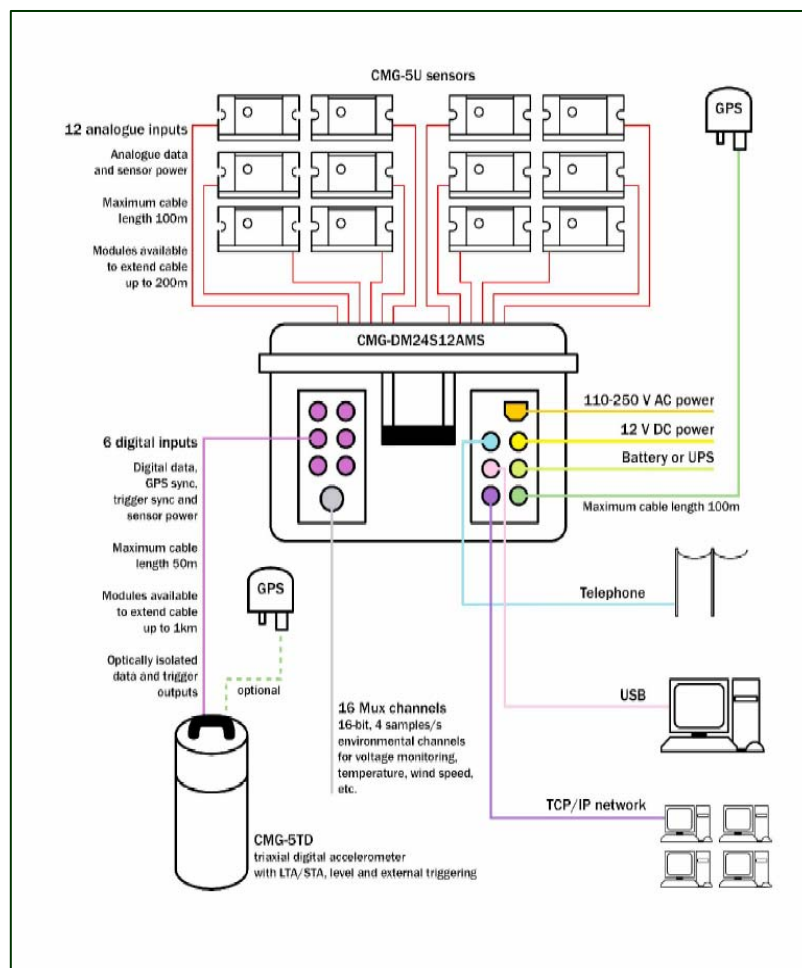
Figure C1   Schematic of the Accelerometer acquisition system

- 12-channel self-contained seismic data collection station.
- Operates 12 single-component CMG-5U strong motion accelerometers. The unit's 12 analogue input connectors match the output connectors for the CMG-5U, and also serve as the sensors' 12V power supply.
- Integrated laptop PC with Güralp Systems Scream! software for viewing and transmitting recorded data.
- Up to 6 digital output seismometers or accelerometers (e.g. CMG-5TD) can be connected and the data stored and processed on the CMG-DM24S12AMS system.
- Can be powered by either 110-250V AC mains power, or from a 12V DC power course.

- Digitizer (DM24S) features :

  o A built-in Digital Signal Processor (Motorola 56002) provides simultaneous multiple sample rate data streams at user selectable rates. Up to 4 streams of data for each component are available at sample rates from 1 to 200 samples/s.
  o A precision microprocessor-controlled time base synchronizes Analogue to Digital Converters, and DSP and time-stamps data blocks.
  o Time synchronization to external GPS or serial time code.
  o A control microprocessor (Hitachi H8) formats and buffers data in an on-board 512k RAM ring buffer.
  o Efficient data storage and transmission using the Güralp Compressed Format.
  o Serial data output (RS232) at user selectable baud rates—options of RS422, DPSK or fibre-optic.
  o Built-in microprocessor system configuration and sensor control, including locking and unlocking, centring and calibration.
  o Low system power consumption, less than 3W (excluding the integrated PC)
  o Flash EEPROM for program code and filter coefficients.

CMG-5U:

- Vertical or Horizontal single axis strong motion accelerometer.
- Over 140 db of dynamic range
- Operates from 12 volts
- Dual output; high gain and low gain differential outputs
- Does not require mechanical adjustment to convert the sensor from horizontal responsive to vertical responsive accelerometer
- Output offsets can be set to be less than 1 millivolt.

Figure C2

CMG-5TD:

Figure C3

- Combines the CMG-5TD 3-axis strong motion accelerometer with the CMG-DM24S/3 (3 channel) 24-bit Digitiser Module in a single sealed case.
- Internal dc-dc converter ensures an isolated sensor system with operation from 10 to 36V.
- Timing from an external GPS receiver.
- Extremely large dynamic range, combining the 140dB sensor with a 132dB noise-free resolution digitizer.
- Up to four simultaneous sample rates can be selected from 1 to 200 samples per second.
- Detailed system calibration information provided.
- Has an internal flash memory with capacity up to 256Mb.

Deployment procedure:

CMG-5U:
1. Locate north, south, east and west on the interior wall of the wind turbine to be used.
2. Secure pre-made glass plates to the interior wall of the turbine at north, south, east and west with araldite.
3. Secure glass plates to the concrete floor inside the turbine at north and south with plaster of Paris.
4. Using heavy duty double sided tape, secure the six CMG-5U's to the set glass plates, with positive acceleration as in the table below.

CMG-5U position	Positive acceleration direction
North wall	Horizontal towards south
North floor	Vertical
East wall	Horizontal towards west
South wall	Horizontal towards north
South floor	Vertical
West wall	Horizontal towards east

5. Connect all CMG-5U outputs to CMG-DM24S12AMS analogue inputs.
6. On the CMG-DM24S12AMS acquisition system check the sensors are working and offsets are reasonable.

Figure C4   CMG-5U sensor showing positive acceleration direction

Figure C5   CMG-5U sensors deployed at north on the interior wall of a wind turbine.
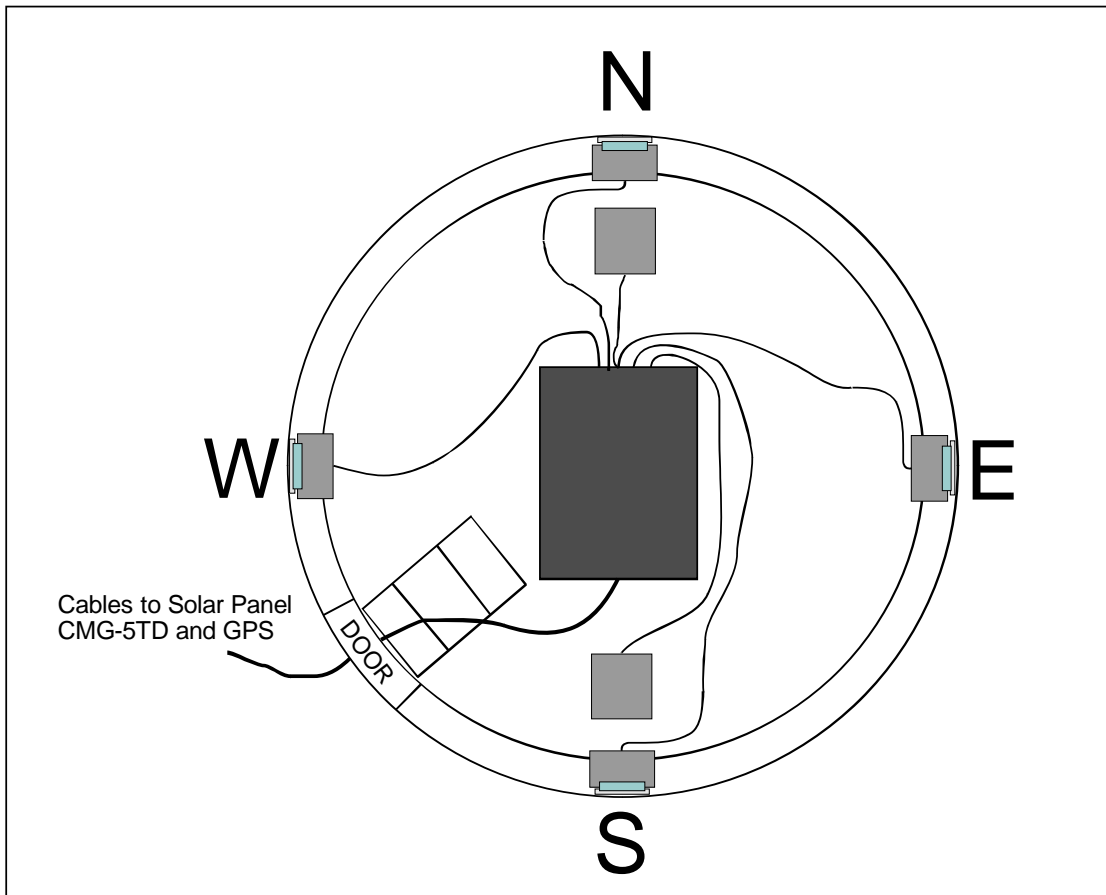
Figure C6   Deployment inside the wind turbine.

CMG-5TD:

1. Select location between 50 and 100m from turbine on which CMG-5U sensors are deployed, ensuring there is enough slack on the cable to prevent mechanical strain on the connectors.
2. Dig a hole wide enough to lower the CMG-5TD into, to about 80cm depth.
3. Line the base of the hole with sand and level it.
4. Secure the CMG-5TD in a bag once all cables are attached.
5. Place the sensor in the hole, pack in with sand and cover.
6. Connect sensor to the CMG-DM24S12AMS acquisition system.

Figure C7   A CMG-5TD installed in the ground at Dun Law Windfarm.

CMG-DM24S12AMS:

1. Place the system in the centre of the wind turbine on which the CMG-5U accelerometers are deployed.
2. Connect the GPS receiver to the digitizers GPS socket for time synchronization. Place the GPS receiver outside the turbine with a clear sky view.
3. Power up the system (using a 3 phase converter and the mains in the turbine, or a 12V DC battery).
4. Power up the laptop PC, Scream!'s main window will automatically open.
5. The two internal 6-channel digitizer modules should appear under "Local" in the left hand pane.
6. Connect the 6 Güralp CMG-5U sensors to channels 1-6 on the side of the unit, after having deployed them as described above.
7. Open the streams in *WaveView* to view the data and ensure correct operation.
8. Connect the CMG-5TD cable to one of the Digital (A-F) connectors. This should result in a third digitizer appearing in the left hand pane.
9. Again, ensure correct operation of the CMG-5TD by opening the streams (Z, N and E) in *WaveView*.
10. Data is stored on the systems laptop and can be transferred back in the lab.

Figure C8   CMG-DM24S12AMS acquisition and monitoring system
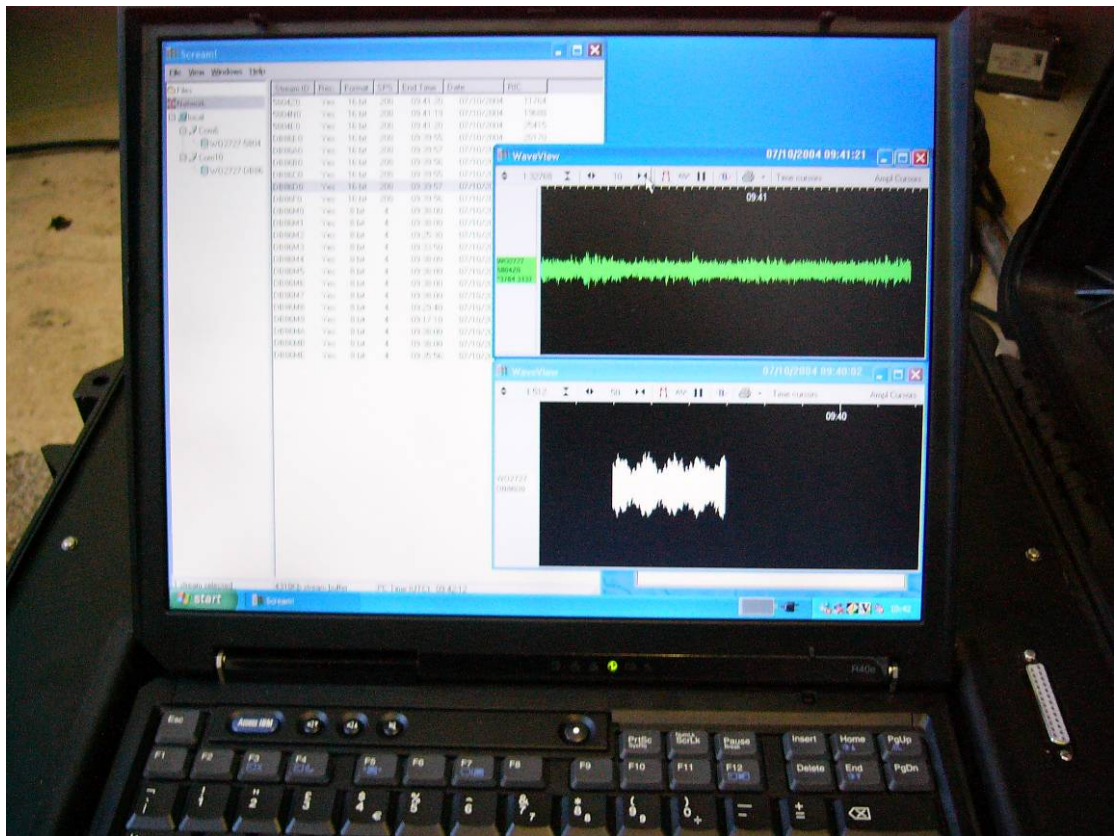
**Figure C9   CMG-DM24S12AMS acquisition and monitoring system
showing Scream! WaveView**

Windfarm shutdowns:

Measurements were made on the following turbines at Dun Law and Ardrossan windfarms:

Dun Law turnoff 1

DATE: 07.10.2004
LOCATION: Dun Law windfarm, Turbine 22
                              (Grid Reference: NT47680, 58284)

CMG-5U DEPLOYMENT:

Location	Sensor Serial No.	Positive acceleration	Channel
North wall	U5207	South	1(d)
North Floor	U5205	Up	5(b)
East wall	U5202	West	2(e)
South wall	U5206	North	3(f)
South Floor	U5203	Up	6(c)
West wall	U5204	East	4(a)

CMG-5TD: Grid reference: NT 47704 58301

SWITCH OFF ORDER AND TIMING (BST):

Time	Description
09:40:00	All turbines switched off
09:45:00	All turbines stopped
09:55:00	Turbine 22 on
09:57:00	Turbine 23 on
09:59:00	Turbine 18 on
10:01:00	Turbines 19 & 24 on
10:03:00	Turbines 20 & 25 on
10:05:00	Turbines 21 & 26 on
10:07:00	Turbines 15,16 &17 on
10:09:00	Turbines 11,12,13,14 on
10:11:00	Turbines 6,7,8,9,10 on
10:13:00	Turbines 1, 2, 3, 4 & 5 on
10:15:00	All on by

Ardrossan turnoff 1.

DATE: 02.11.2004
LOCATION: Ardrossan windfarm, Turbine 1
                                   (Grid Reference: NNS 23365 47548)

CMG-5U DEPLOYMENT:

Location	Sensor Serial No.	Positive acceleration	Channel
North wall	U5206	South	1(d)
North Floor	U5205	Up	5(b)
East wall	U5204	West	2(e)
South wall	U5202	North	3(f)
South Floor	U5203	Up	6(c)
West wall	U5207	East	4(a)

CMG-5TD: Grid reference: NS 23414 47546

SWITCH OFF ORDER AND TIMING:

Time	Description
15:15:00	All turbines off
15:17:00	Turbines stopped moving
15:25:00	Turbine 1 on
15:27:30	Turbine 1 full speed
15:30:00	Turbine 7 on
15:32:00	Turbine 7 full power
15:34:00	Turbine 2 on
15:36:00	Turbine 2 full power
15:38:00	Turbines 8, 11 & 3 on
15:40:30	Turbines 8, 11 & 3 full power
15:42:00	Turbines 5 & 9 on (4 in service)
15:44:00	Turbines 5 & 9 full power
15:46:00	Turbines 10, 6 &12 on
15:48:00	Turbines 10, 6 &12 full power

NOTE: Turbine 4 being serviced

Dun Law turnoff 2.

DATE: 03.11.2004
LOCATION: Dun Law windfarm, Turbine 22
                              (Grid Reference: NT 47680, 658313)

CMG-5U DEPLOYMENT:

Location	Sensor Serial No.	Positive acceleration	Channel
North wall	U5206	South	1(d)
North Floor	U5203	Up	5(b)
East wall	U5204	West	2(e)
South wall	U5202	North	3(f)
South Floor	U5205	Up	6(c)
West wall	U5207	East	4(a)

CMG-5TD: Grid reference: NT 47670 58284

SWITCH OFF ORDER AND TIMING:

Time	Description
11:30:00	All turbines switched off
11:31:15	All turbines stopped
11:38:00	Turbine 22 on
11:39:20	Turbine 22 full power
11:41:00	Turbine 23 on
11:42:22	Turbine 23 full power
11:44:00	Turbine 18 on
11:45:40	Turbine 18 full power
11:46:00	Turbines 19 & 24 on
11:49:25	Turbines 19 & 24 full power
11:51:00	Turbines 20 & 25 on
11:52:50	Turbines 20 & 25 full power
11:54:00	Turbines 21 & 26 on
11:56:00	Turbines 21 & 26 full power
11:57:00	Turbines 11, 12 & 15 on
11:59:10	Turbines 11, 12 & 15 full power
12:01:00	Turbines 6, 7, 13 & 17 on
12:03:07	Turbines 6, 7, 13 & 17 full power
12:05:00	Turbines 8, 9, 10 & 14 on
12:07:35	Turbines 8, 9, 10 & 14 full power
12:10:00	Turbines 1, 2, 3, 4 & 5 on
12:12:30	Turbines 1, 2, 3, 4 & 5 full power

NOTE: Turbine 16 being serviced
                              RAF overflights at 11:50:00 and 11:51:30

Ardrossan turnoff 2.

DATE: 09.12.2004
LOCATION: Ardrossan windfarm, Turbine 7
(Grid Reference NS 23212 47314)

CMG-5U DEPLOYMENT:

Location	Sensor Serial No.	Positive acceleration	Channel
North wall	U5204	South	1(d)
North Floor	U5203	Up	5(b)
East wall	U5207	West	2(e)
South wall	U5206	North	3(f)
South Floor	U5205	Up	6(c)
West wall	U5202	East	4(a)

CMG-5TD: Grid reference: NS 23256 47402

SWITCH OFF ORDER AND TIMING:

Time	Description
11:30:00	All turbines switched off
11:31:45	All turbines stopped
11:35:00	Turbine 7 on
11:37:21	Turbine 7 full power
11:40:00	All off
11:42:00	All stopped
11:45:00	Turbine 6 on
11:46:50	Turbine 6 full power
11:50:00	Turbine 10 on
11:52:30	Turbine 10 full power
11:55:00	Turbine 12
11:57:35	Turbine 12 full power
12:00:00	Turbine 5 on
12:02:10	Turbine 5 full power
12:05:00	Turbine 9 on
12:07:05	Turbine 9 full power
12:10:00	Turbine 11 on
12:13:35	Turbine 11 full power
12:15:00	Turbine 8 on
12:17:20	Turbine 8 full power
12:20:00	Turbine 4 on
12:22:30	Turbine 4 full power
12:25:00	Turbine 3 on
12:27:18	Turbine 3 full power
12:30:00	Turbine 2 on
12:32:10	Turbine 2 full power
12:35:00	Turbine 7 on
12:37:24	Turbine 7 full power

NOTE: Turbine 1 being serviced (hence change to turbine 7 for measurements)

Appendix D

Matlab Software for analyzing wind farm turbine data recorded on GURALP instruments

```matlab
% ("Power Spectral Density Analysis of Dun Law windfarm Data")
%
close all
figure
[data,streamid,sps,ist]=readgcf;
figure
switch streamid.z(1:4)
    case '6123'
        disp('Kelphope 1 - rotangle = 30')
        conv_z = 2.385e-10;
        conv_y = 2.380e-10;
        conv_x = 2.423e-10;
        rotangle = deg2rad(30);
    case '6121'
        disp('Kelphope 2 (New) - rotangle = 45')
        conv_z = 2.439e-10;
        conv_y = 2.552e-10;
        conv_x = 2.004e-10;
        rotangle = deg2rad(45);
    case '6064'
        disp('Kelphope 2 - rotangle = 45')
        conv_z = 2.405e-10;
        conv_y = 2.352e-10;
        conv_x = 2.336e-10;
        rotangle = deg2rad(45);
    case '6124'
        disp('Hope Hills 1 - rotangle = 20')
        conv_z = 2.264e-10;
        conv_y = 2.122e-10;
        conv_x = 2.197e-10;
        rotangle = deg2rad(20);
    case '6062'
        disp('Hope Hills 1 (New) - rotangle = 20')
        conv_z = 2.212e-10;
        conv_y = 2.275e-10;
        conv_x = 2.194e-10;
        rotangle = deg2rad(20);
    case '6091'
        disp('Crib Law 1 - rotangle = 20')
        conv_z = 2.334e-10;
        conv_y = 2.242e-10;
        conv_x = 2.061e-10;
        rotangle = deg2rad(20);
    case '6083'
        disp('Crib Law 2 - rotangle = 20')
        conv_z = 2.212e-10;
```

```matlab
            conv_y = 2.098e-10;
            conv_x = 2.096e-10;
            rotangle = deg2rad(20);
        case '6087'
            disp('Array 1 - rotangle = 20')
            conv_z = 2.101e-10;
            conv_y = 2.183e-10;
            conv_x = 2.006e-10;
            rotangle = deg2rad(20);
        case '6179'
            disp('Array 2 - rotangle = 20')
            conv_z = 2.273e-10;
            conv_y = 2.167e-10;
            conv_x = 2.060e-10;
            rotangle = deg2rad(20);
        case '6132'
            disp('Array 3 - rotangle = 20')
            conv_z = 2.442e-10;
            conv_y = 2.192e-10;
            conv_x = 2.164e-10;
            rotangle = deg2rad(20);
        case '6155'
            disp('Johncleugh - rotangle = 20 - estimated conversion!!!')
            conv_z = 2.4e-10;
            conv_y = 2.4e-10;
            conv_x = 2.4e-10;
            rotangle = deg2rad(20);
end
%rotangle = deg2rad(input('Enter the rotation angle : '));
if isstruct(data),
    x=detrend(data.x)* conv_x;
    y=detrend(data.y)* conv_y;
    z=detrend(data.z)* conv_z;
    dataxy = [x y];
    %rotangle = deg2rad(30);
    rotmatrix = [ cos(rotangle)   sin(rotangle) ; -sin(rotangle)  cos(rotangle)];
    dataxy_rot = dataxy * rotmatrix;
    xr = dataxy_rot(:,1); yr = dataxy_rot(:,2);
    sps = sps.z;
else
    z = detrend(data)* 2.4e-10;
end

%z=y;
%pause
%tot=sqrt(x.^2+y.^2+z.^2);
l=length(z);
dt=1/sps;
```

```
t=[0:l-1]/sps;
% figure
% plot(t,z);
f=wk(z,dt)/(2*pi);
w=wk(z,dt);
% X=fft(z)./l;
% figure;plot(f,abs(X))
[b,a]=butter(5,[0.5/(sps/2),10/(sps/2)]);%plot(t,z,t,filter(b,a,z))
xf=filtfilt(b,a,xr);
yf=filtfilt(b,a,yr);
zf=filtfilt(b,a,z);
%XF=fft(xf);

%Split signal up into nints,  segments and analyse them and then
%plot all spectra next to one another
%Calculate RMS in the time segments

x=z;
%
nints=60

int_points=length(x)/nints
Spectrum_matrix=zeros(int_points,nints);
rms_val=zeros(nints,1);

 for j=1:nints

    xx=x(1+(j-1)*int_points:int_points+(j-1)*int_points);

    l_xx=length(xx);
    t_xx=0:dt:(l_xx*dt)-dt;
    f_xx=WK(xx,dt)/(2*pi);
    XX=fft(xx)./l_xx;

    [b,a]=butter(5,[0.5/50,10/50]);%plot(t_xx,xx,t_xx,filter(b,a,xx))
    xx_f=filtfilt(b,a,xx);

     rms=sqrt(sum(xx_f.^2)./l_xx); % calculate rms value for this interval,
     rms_val(j)=rms;

    XX_F=fft(xx_f);

    Spectrum_matrix(:,j)=Spectrum_matrix(:,j)+abs(XX_F);
 end
 %figure; plot(t,xf,'.',(1:nints).*int_points/sps,rms_val)

psd_len = 2^15;
[XF,f1] = pwelch(xf,[],[],psd_len,sps);
```

```matlab
XF = medfilt1(XF,5);
[XF2,f2] = pwelch(xf,[],[],length(xf),sps);
figure; plot(f2,10*log10(XF2),f1,10*log10(XF),'LineWidth',2);title('X PSD')
ax = axis; ax(2) = 10; axis(ax);
[YF,f1] = pwelch(yf,[],[],psd_len,sps);
[YF2,f2] = pwelch(yf,[],[],length(yf),sps);
YF = medfilt1(YF,5);
figure; plot(f2,10*log10(YF2),f1,10*log10(YF),'LineWidth',2);title('Y PSD')
ax = axis; ax(2) = 10; axis(ax);
[ZF,f1] = pwelch(zf,[],[],psd_len,sps);
[ZF2,f2] = pwelch(zf,[],[],length(zf),sps);
ZF = medfilt1(ZF,5);
figure; plot(f2,10*log10(ZF2),f1,10*log10(ZF),'LineWidth',2);title('Z PSD')
ax = axis; ax(2) = 10; axis(ax);

%Split signal up into 60, 1 minute long segments and analyse them and then
%try to plot all spectra next to one another
Spectrum_matrixX=[];
Spectrum_matrixY=[];
Spectrum_matrixZ=[];

for j=1:60
    xx=xr(1+(j-1)*6000:6000+(j-1)*6000);
    yy=yr(1+(j-1)*6000:6000+(j-1)*6000);
    zz=z(1+(j-1)*6000:6000+(j-1)*6000);
    l_zz=length(zz);
    xx_f=filtfilt(b,a,xx);
    yy_f=filtfilt(b,a,yy);
    zz_f=filtfilt(b,a,zz);
    %XX_F= 2*(fft(xx_f,512).^2)/(l_xx*sps);
    fft_len = 512;
    [XX_F,f] = pwelch(xx_f,[],[],fft_len,sps);
    [YY_F,f] = pwelch(yy_f,[],[],fft_len,sps);
    [ZZ_F,f] = pwelch(zz_f,[],[],fft_len,sps);
    if j == 1,
        Spectrum_matrixX = XX_F(:);
        Spectrum_matrixY = YY_F(:);
        Spectrum_matrixZ = ZZ_F(:);
    else
        Spectrum_matrixX = [Spectrum_matrixX XX_F(:)];
        Spectrum_matrixY = [Spectrum_matrixY YY_F(:)];
        Spectrum_matrixZ = [Spectrum_matrixZ ZZ_F(:)];
    end
end
%figure;surf(1:60,f,Spectrum_matrixZ);title('Z Spectrum');shading interp;
figure;surf(1:60,f(1:52),(10*log10(Spectrum_matrixX(1:52,:))));title('X
                    PSD');shading interp;
ax = axis; ax(4) = 10; axis(ax);
```

```matlab
caxis([-180 -150])
figure;surf(1:60,f(1:52),(10*log10(Spectrum_matrixY(1:52,:))));title('Y
                         PSD');shading interp;
ax = axis; ax(4) = 10; axis(ax);
caxis([-180 -150])
figure;surf(1:60,f(1:52),(10*log10(Spectrum_matrixZ(1:52,:))));title('Z
                         PSD');shading interp;
ax = axis; ax(4) = 10; axis(ax);
caxis([-180 -150])
% figure;surf(1:60,f(1:52),((Spectrum_matrixZ(1:52,:)))));title('Z PSD');shading
                         interp;
% ax = axis; ax(4) = 10; ax(2) = 49; axis(ax);
%caxis([-180 -150])

%INTEGRATE POWER SPECTRUM TO GIVE POWER
%replot z component for integration

 [ZF,f] = pwelch(zf,[],[],4096,sps);
 [ZF2,f2] = pwelch(zf,[],[],length(zf),sps);
 ZF = medfilt1(ZF,5);
 figure; plot(f1,10*log10(ZF),'LineWidth',2);title('Z PSD')
 ax = axis; ax(2) = 10; axis(ax);
 drawnow
 extent=ginput(2)
 st=extent(1,1)
 en=extent(2,1)

 i_s=1
 while f1(i_s)<st
    i_s=i_s+1;
 end
 i_e=1
 while f1(i_e)<en
    i_e=i_e+1;
 end

 ff=f1(i_s:i_e);
 yy=y(i_s:i_e);
 xi=f1(find(f1==floor(st)):find(f1==ceil(en)));
 yi=ZF(find(f1==floor(st)):find(f1==ceil(en)));

 fi=f1(i_s:i_e);
 ZFi=ZF(i_s:i_e);
 Figure;  plot(fi,ZFi)

 Power=trapz(fi,ZFi)

%…………………………………………………………………………………………………………..
```