Final Technical Report

CWP Eskdalemuir Seismic Station

May 2025

HMSC
HASTING MICRO-SEISMIC CONSULTING, INC.

CWP Energy

IMS Primary Seismic Station PS5 (Mawson, Antarctica)

Executive Summary

The Comprehensive Nuclear-Test Ban Treaty Organization (CTBTO) maintains a global monitoring system to detect any nuclear explosions. CTBTO report that ALL nuclear countries, save North Korea, completed their underground nuclear testing by December 1999. North Korea has carried out 6 underground tests, of which the last one took place in September 2017.

In a recent 2024 CTBTO paper on 25 Years Progress of the CTBT Verification System (CTBT 2024 Report), they report that the IMS seismic network comprises the largest number of seismic array stations in the world, which provide the weak signal detection capability ***with the highest number of seismometers emplaced into boreholes up to 100 m depth.*** This report states that: "*The majority of the IMS stations reporting to CTBTO use the borehole method of sensor installation. CTBT report that it is known in seismological practice that sensor installation below the ground surface has diminished seismic noise levels especially in the high frequency domain. It is site dependent but in general the deployment in the borehole is one of the methods used to reach better detection capability of the weak ground motion at higher frequencies f>3-5Hz*".

Many of the CTBTO auxiliary arrays, of which Eskdalemuir seismic array (EKA) is one, are shared among other scientific projects rather than being exclusively used for the Comprehensive Nuclear-Test Ban Treaty (CTBT). Such cooperation enables the IMS to follow modern trends in equipment upgrades keeping abreast of market innovations and ready to adapt them to the specific IMS requirements, such as machine learning to denoise and filter out known background noise which is becoming the norm across seismic stations across the Globe.

Notwithstanding natural noise from the North Sea (which the author notes dominates the frequency passband below ~2Hz), and ignoring transport noise created by the M74 motorway and West Coast Train Line, the principal anthropogenic noise is caused by commercial forestry and harvesting operations.

The borehole's performance improves significantly at higher wind velocity as the surface sensors are impacted by noise from the surrounding Eskdalemuir commercial forestry as higher winds blow through the forests creating ground vibrations. The borehole sensors are naturally attenuated by the ground above the sensor so consequently, over the period we see average increases in noise reduction from 15-25dB at higher wind velocities and as noted about 10dB even on calm days. At high wind velocities this is the period when wind turbines will be operating, noting modern turbines reach maximum power at approximately 12 m/s(~43km/h). This data correlates well with findings at the British Geological Society (BGS) borehole in Glasgow.

The design requirements for IMS Stations are set out in *The Operational Manual For Seismological Monitoring And The International Exchange Of Seismological Data* (IMS Manual). This sets out how both Primary and Auxiliary Stations are designed, operated and maintained, and there is a well-defined process for implementing the configuration change proposed in this Final Report.

Based on the requirements set out by the CTBTO in the CTBT 2024 paper, we have proceeded to design an upgrade to EKA which both complies with all technical requirements of the CTBTO and is designed to provide the maximum performance benefit to the Ministry of

Defence (MoD) and Atomic Weapons Establishment (AWE). This comprises a minimum of 10 additional borehole installations of between 30m and 100m, each containing a new 3-component or 1-component borehole seismometer (noting that the minimum requirement for CTBTO purposes is one 3-component sensor). Subject to dialogue with the MoD, it would be possible to expand the upgrade to the remaining 10 sensor locations, which are proposed to be drilled to 30m to 80m and contain a vertical-component sensor in line with the CTBTO requirements. To ensure the best possible array performance, the boreholes sensors are to be cemented in place.

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Design compliant proposals have been secured from a well regarded Scottish drilling contractor, and two British seismometer manufacturers. The practical procedure for completion has been specified, and a high level programme for completion identified.

There is no doubt that the 25-year restriction on the construction of wind turbines within 100km of Eskdalemuir, the only development control placed by the MoD in this region, can be resolved by upgrading the existing seismic array with new state of the art British sensors installed into deep boreholes. This in turn will bring EKA up to date with CTBT standards, provide much needed attenuation from existing anthropogenic noise including forestry, agricultural and traffic noise, and afford long-term future proofing, whilst allowing turbines to be built within close proximity to EKA. Wind turbines near certified CTBTO stations are not uncommon, currently there are wind turbines generating electricity within 100m to 1km at 3 Seismic Stations in Antarctica, Mawson Station, McMurdo Station and Princess Elizabeth Station.

When considering the implementation of the upgrade to the array and future development of wind farms in the vicinity of the array, it is my opinion that given the average reduction in surface noise that will be gained from the upgrade is 15dB, this would indicate that on most days the borehole sensors will be capable of detecting and analyzing signals of approximately ~18.25% the amplitude of the surface sensors. If we apply this performance improvement to the MoD’s wind farm noise budget it would mean that by using the borehole sensors, the noise floor could be raised from 0.336nm of ground displacement at the surface to 1.792nm, as the borehole sensors would still be below the 0.336nm limit. This is well above the budget forecast calculated by the MOD’s current windfarm assessment tool of 0.502472nm for Scoop Hill, which can therefore be accommodated through this mitigation method. It is also the authors opinion that the allocation of noise budget, if that is still considered necessary by the MoD following the upgrade, could start from 0 given the reduction in surface noise is a reduction against the surface noise as it currently stands today, which includes all installed and operational wind farms within a 50km radius of EKA which have already been accommodated and do not need to be mitigated. It is the authors opinion that the increase in noise budget provides so much headroom for further development of renewable energy that this is an enduring solution and no noise budget will be needed in the future once the array has been upgraded as per the proposal set out herein.

Introduction

Hasting Micro-Seismic Consulting, Inc. (HMSC) was contracted by CWP Energy (CWP) to investigate ways to mitigate induced surface seismic noise generated by wind turbines near Eskdalemuir Seismic Array (EKA). Since it was constructed by the BGS in 1962, EKA has recorded seismic data comprising earthquakes and presumed nuclear test events. As of July 22, 1974 EKA has been managed by the Atomic Weapons Establishment (AWE) on behalf of the UK Ministry of Defence (MoD). Under the IMS, part of the CTBT, EKA is designated as one of 120 Auxiliary Seismic Stations which supplement a further 50 Primary Seismic Stations with the IMS station reference of AS104. Auxiliary seismic stations are mandated to provide data to the International Data Centre (IDC) in Vienna upon request only and as such do not send continues data to the IDC in real-time. The AS104 site must comply with the Technical Requirements of the IMS operational manual, (IMS Manual)[1]. In 1980, the station converted from an analog to a digital recording which allowed it to more efficiently transmit data on request. Beginning in 2007, renovation work to the stations infrastructure and equipment began and over the years there have been several modifications to elements in the EKA array to include the addition of several 3 component surface sensors.

In addition to technical modifications to seismic arrays, recent innovations in mathematical modelling, machine learning and AI are being recognised as valuable new techniques to enhance detection using existing data to deliver 99% accuracy[2]. Machine learning denoising autoencoders are in development by CTBTO and Industry to provide crucial tools to filter and clean data which tremendously enhances detection of seismic activity and distinguishes nuclear explosions from other seismic activities[3].

Of concern to the MoD is noise generated by wind turbines during windy days when the towers vibrate and produce seismic noise in the 2Hz to 8Hz passband, the frequency bands that are used for detecting seismic energy from nuclear tests. CWP is aware of the perceived problem and has contracted with HMSC to design a solution that complies with the IMS Manual whilst meeting the needs of Scottish and UK Governments to deliver their 2030 Net Zero Targets and mitigating the impact of noise produced by wind turbines.

Following the methodology set out in the Technical Proposal which is supported by the AWE Paper, IMS Manual and CTBT 2024 report a test 200m borehole was installed to see how much improvement in signal to noise could be gained in the 2Hz to 8Hz band, the primary area of interest to AWE who manage EKA on behalf of the MoD. The construction and installation of this borehole is fully described in the Interim Report dated 10 March 2025. The Global Seismic Network Review Briefing Book (2015) points out that using boreholes for seismic sensors is the best practice for acquiring high quality data. Hutt et al, 2017, also concluded in their study that for permanent observatories 100–200m depth in hard rock is desirable to achieve lowest noise, although 30–60m may be acceptable. For new seismic arrays, and some single 3-component (3C) stations, constructed by the IMS as part of the CTBTO global seismic monitoring network, borehole elements/stations are used whenever possible.

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[1] https://www.geo.uib.no/nnsn-technical/uploads/Main/IMS_Operational_Manual_for_Seismological_Monitoring_.pdf

[2] Seismic moment tensor classification using elliptical distribution functions on the hypersphere | Geophysical Journal International | Oxford Academic

[3] CTBT Science and Technology Conference 2021 (SnT2021) (June 28, 2021 - July 2, 2021): Deep learning denoising applied to regional distance seismic data in Utah · CTBTO Conferences and Workshops (Indico)

The experiment proposed taking measurements at 50m, 100m, 150m and 200m in order to measure the different levels of noise attenuation, as illustrated by the BGS sensor in Glasgow referenced in the Technical Proposal, and as a result the sensor wasn't sanded or concreted in place and used a mechanical borehole hole-lock to couple the sensor to the casing. Consequently, water seeped in into the borehole and created periodic harmonics and noise in the data over a broad spectrum of the bandwidth. Several mitigation methods were imposed to try and reduce the noise. In hindsight, the sensor should have been concreted in at 200m which would have produced far superior attenuation, which is in alignment with methods proposed by Güralp System Limited and others. That said, the data since installation in December shows far superior noise levels due to the attenuation of the ground and regularly falls below the Peterson 1993 New Low Noise Model (NLNM) in low wind speeds.

On average the data shows a ~10dB reduction in noise on the borehole sensor against surface sensors during no and low wind periods in the 2Hz to 10Hz passband, and at higher frequencies, which is remarkable.

This Final Paper briefly expands upon the results described in the Interim Report, then goes on to describe in detail how EKA should be upgraded to improve operational performance, and mitigate anthropogenic noise.

Summary Findings

The primary goal of this project is to mitigate the effects of induced surface noise from wind turbines by using borehole seismometers. As we have noted previously, installation of borehole sensors is a tried and tested method of reducing surface noise. This is acknowledged throughout the seismological community and by the CTBTO. In the CTBTO 2024 Report, they stated that "*in general the deployment in the borehole is one of the methods used to reach better detection capability of the weak ground motion at higher frequencies f>3-5 Hz*". For the depth of the borehole, they targeted 30m for the vertical elements and 60m for 3 component elements for any new array constructed by the IMS. Furthermore, the IMS operational requirements in relation to noise changes at seismic stations allow for relocating or altering the configuration of the array in response to such changes.

The best way to show improvements in data quality and noise reduction is to look at background noise levels. As such we looked at various wind velocities to see how much noise is being produced and the reduction in noise between the surface and borehole sensors. All sensors used during the experiment were calibrated at the BKN seismic vault at AWE Blacknest and compared against the permanent station in the vault. Additionally, a "huddle test" was conducted prior to deployment of the borehole sensors to ensure all three sensors were providing the same data and working within the Manufacturers specifications. HMSC, and the MoD, pulls continuous real-time data from a SeedLink server located at the test site, as well as all publicly available data from EKA via the DMC. HMSC also manually pulled data from the second sensor that AWE installed at the EKR4 pit that has higher sampling rates than the standard sensor used by EKA. All data are backed-up locally on the data loggers in case of communications outages and data are then backfilled once communications is reestablished.

The borehole's performance improves significantly at higher wind velocity as the surface sensors are impacted by noise from the surrounding Eskdalemuir commercial forestry as higher winds blow through the forests creating ground vibrations. The borehole sensors are disconnected from ground movements and this background noise is naturally attenuated by the ground above the sensor. Consequently, over the period we see average increases in noise reduction from 15-25dB at higher wind velocities and as noted about 10dB even on calm days. At high wind velocities this is the period when wind turbines will be operating, noting modern turbines reach maximum power at approximately 12 metres per second (~43km/h). This data correlates well with findings at the BGS borehole in Glasgow where multiple sensors are installed between 40 to 198 metres, as reported in our White Paper dated 15 September 2023.

The frequencies that arrive at the site for teleseismic events are typically lower frequency energy whereas local (Regional) seismic events will have higher frequency energy, but are random and so we have only been able to find a few smaller events in the recorded data to date. Additionally in the borehole, given the proximity to the North Sea, we see the natural earth tidal noise known as the microseisms, which are caused by ocean waves and storm swells impacting the coast. These microseisms can be further categorized into primary and secondary microseisms. Primary microseisms occur at periods of 10-20 seconds, while secondary microseisms have periods between 1-10 seconds. While seen at the test borehole these are below the primary bandwidth of interest for this report.

New Low Noise Model (NLNM)

One key observation from the test borehole sensor is that the sensor is approaching and even below the NLNM on a significant number of occasions. The NLNM was developed through many global recordings and in seismic circles refers to a reference model that represents the minimum expected level of background seismic noise across a range of frequencies. It essentially defines the lowest level of ambient earth noise that can be recorded at a given location, based on data from numerous globally distributed seismic stations, and is widely used to assess the quality of seismic data and identify potential noise sources at a specific site. It is achieved when a PSD plot drops below the white line bounding the bottom of the X axis in Figures 1 and 2. Figures 1 and 2 show two examples of the new borehole sensor touching and below the NLNM.

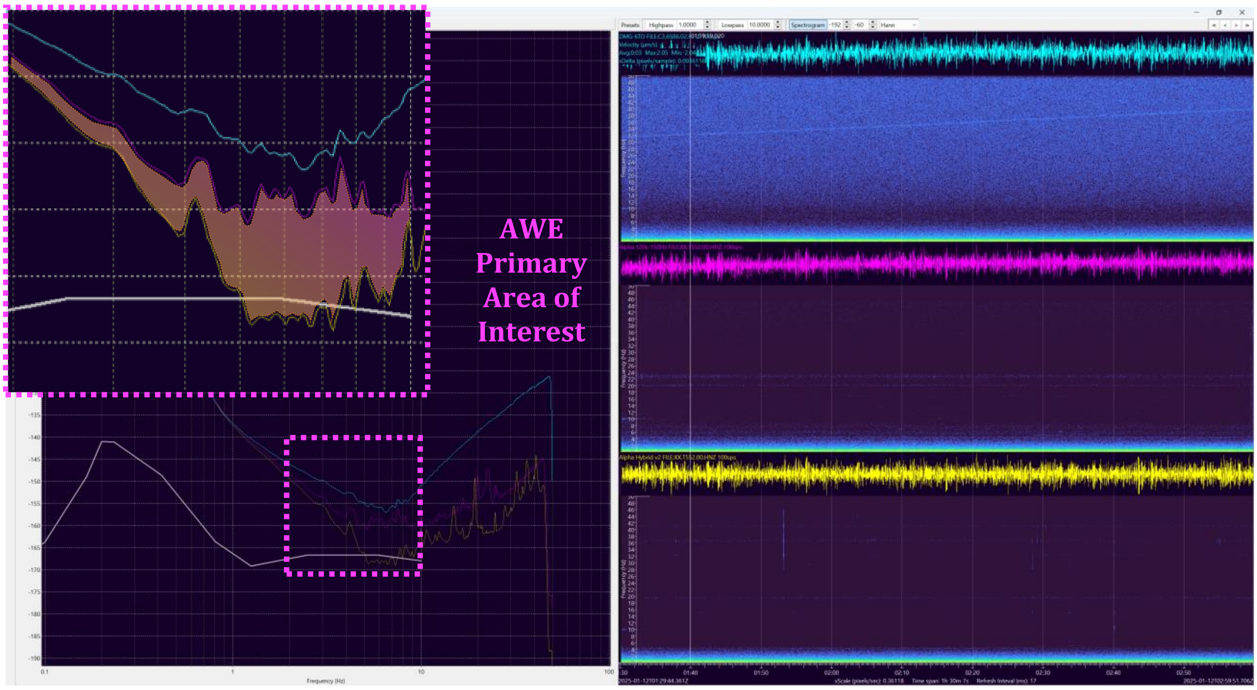

Figure 1, Reproduction of Figure 4 in the Short Report dated 11 March 2025. Data from deployment depth of 195m on a calm wind day. Shaded area in upper left figures represents the area of improvement in noise reduction between surface and 195m.

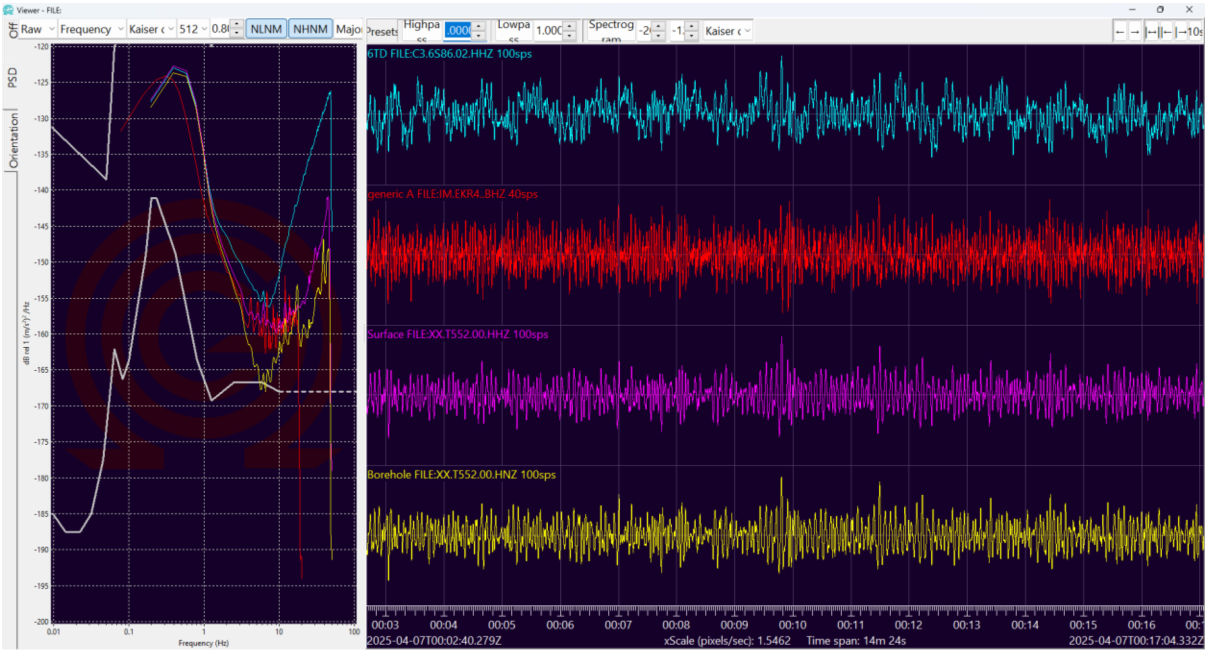

Figure 2, New data from 7 April 2025, deployment depth of 183m, recorded on a calm wind day. Borehole ALPHA Yellow, Surface ALPHA Magenta, CMG-6TD Cyan, EKR4-40Hz Red.

There are only a few examples around the world where this level of performance has been achieved, or is even achievable, with the only immediately obvious one being the IMS Primary Seismic Array PS26, in Niger, Africa, defined in the CTBT 2024 Report as having "*a superior detection capability*". As such this achievement at the test borehole is incredibly significant and shows how the use of modern sensor technology coupled with a borehole deployment can significantly improve the detection capabilities of the Array, especially on windy days.

Note, for reference in spectrograms the stronger the signal at a given frequency the richer the colour. So stronger signals are plotted in red and weaker lower values in lighter blue colours. As you can see in the data when the winds are higher you see more red colours and less blue. The spectrogram plots show the lower frequency at the bottom and the highest frequency at the top. The maximum/highest frequency we can measure is what is known as the Nyquist frequency, which is ~40% of the sampling rate. So at 100sps we can resolve the signals up to a maximum of ~40Hz, which is more than suitable for the purpose of the array with the Technical Requirements only requiring data up to 16Hz. Most of all the pit elements of the array only sample at 40Hz so can only resolve frequencies below ~18Hz. We can also see in the Spectrograms some horizontal banding at discrete frequencies. This is caused by specific local noise sources.

Anthropogenic Diurnal Noise

Over the course of analyzing the data we see various interesting noises of an anthropogenic nature. Most noise occurs during normal daylight/working hours and appears at discrete frequencies. Figure 3 shows an example of one such noise source over an approximately 2.5 day window of data from the borehole and surface ALPHA sensors. There are several other periods that we see the same type of noise, but this is just one example for reference. The strong blue line in the spectrogram is at about 4.8Hz and was only present during daylight hours. It abruptly turned on and off.

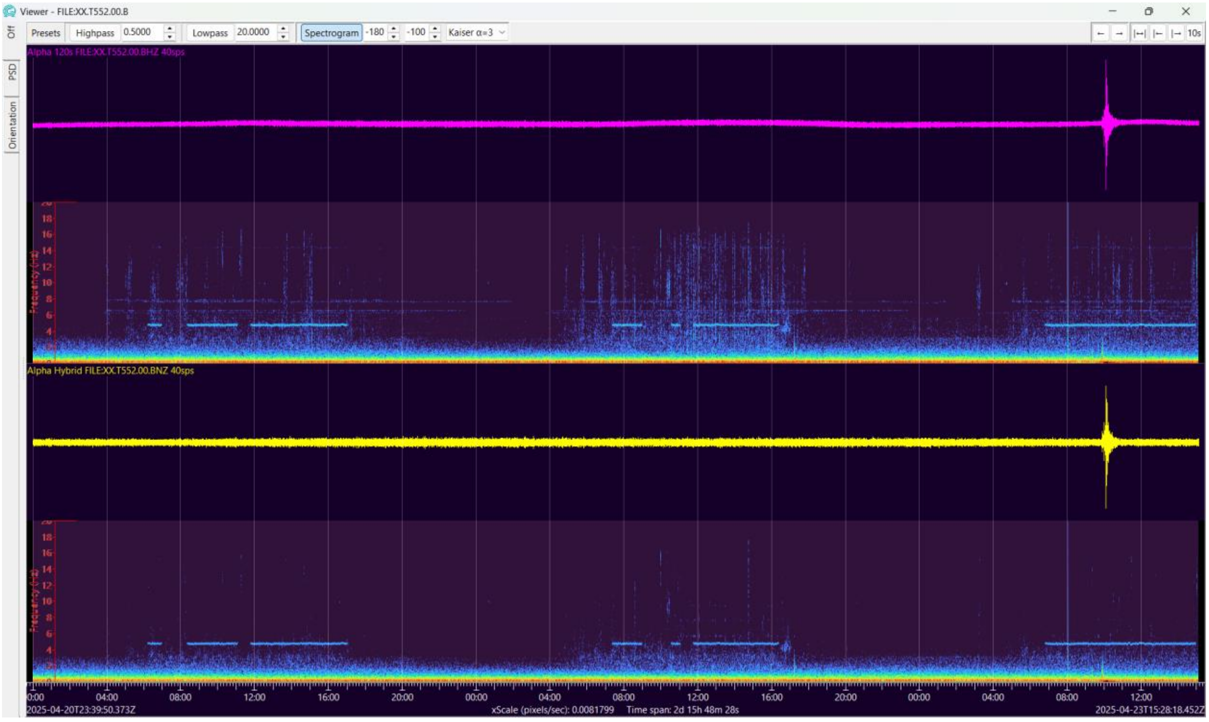

Figure 3, Surface and Borehole ALPHA Sensor, noise shown by strong blue line in spectrogram at 4.8Hz. Note, the large spike at about 10:00GMT was from the M 6.2 - 21 km SE of Marmara Ereğlisi, Turkey.

Figure 4 shows a plot with data from both the test site and selected elements of the EKB and EKR arms of the array. As can be seen the 4.8Hz noise is present throughout the entire array, however, is most prominent on EKR9 and diminishes in power moving west through the EKR sensors. This indicates to the Author that the noise source is at the far eastern end of the EKR arm of EKA. Local forestry managers have confirmed that forestry operations are ongoing at the forestry property known as Ramseygrain West, within which EKR9 is sited. Also note that the amplitude of this noise is over 25dB when compared to the baseline of the data.

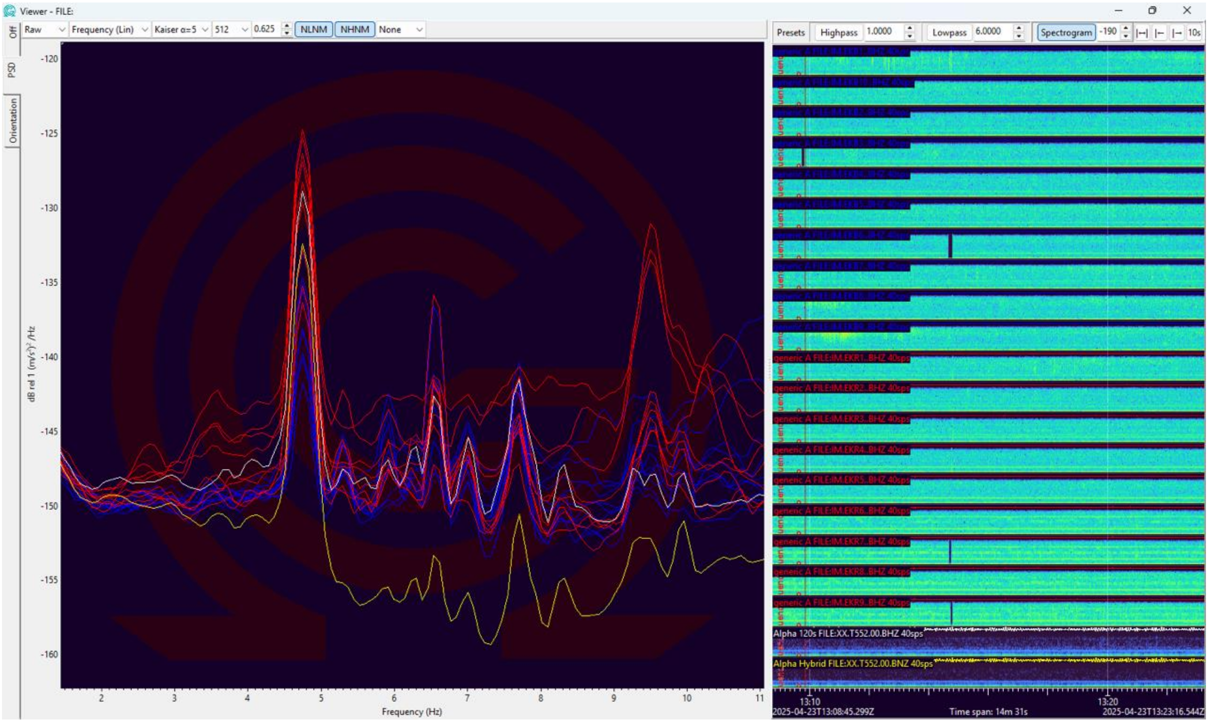

Figure 4, Blue Lines = EKB1 to EKB10 (Blue Arm), Red Lines = EKR1 to EKR9 (Red Arm), White = Surface ALPHA, Yellow = Borehole ALPHA

Other anthropogenic noise sources can be seen throughout the data at various frequencies but this is one of the largest noise sources and is in the peak area of AWE interest. We also see noise at 5.3Hz, 5.9Hz, 6.6Hz, 7.0Hz, 7.7Hz, 9.6Hz, 14.2Hz and 19.9Hz, though the last one is only seen on the test sensors as it is above the Nyquist frequency of the EKB and EKR elements. This noise, like the 4.8Hz noise shown above, is also random and typically during day time hours.

Figure 5 shows just the Red arm elements for the same noise source shown in Figure 4, but slightly later in time and duration, and shows several of the other noise spikes in the data. Figure 6 shows data from just EKR7, EKR8 and the EKR9 elements, which better illustrates the various noise seen on the sensors as well as the higher frequency noise at 9.6Hz and 14.2Hz.

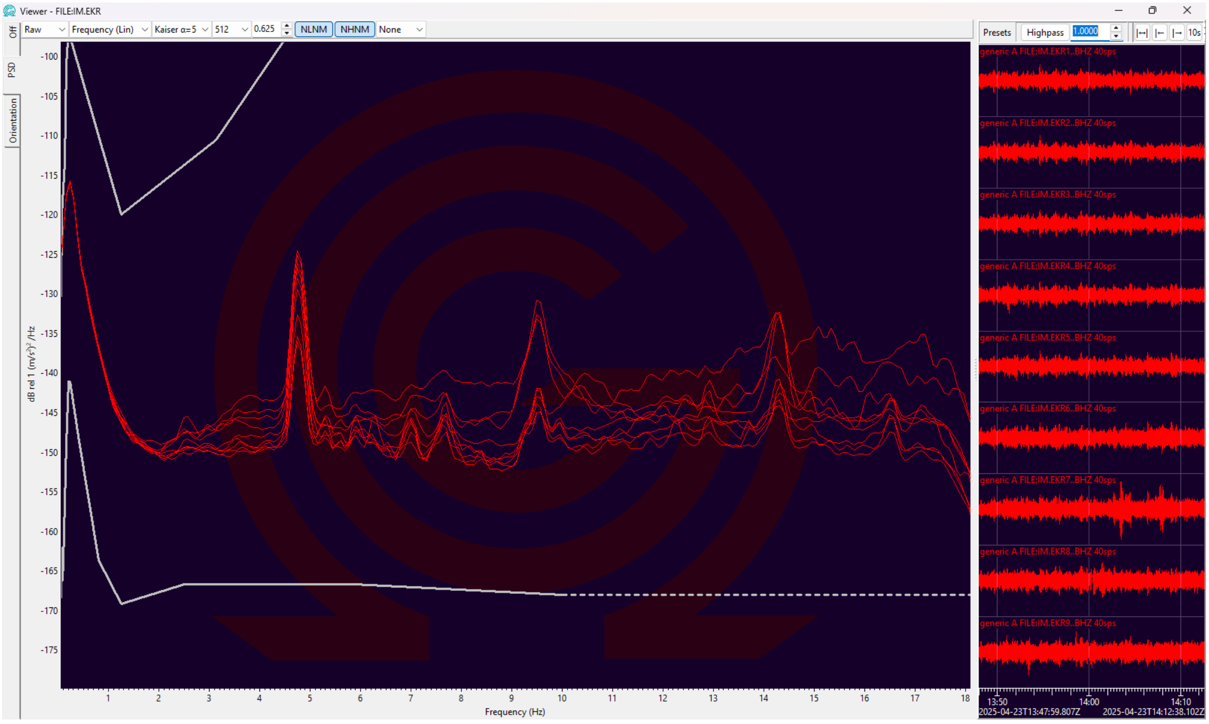

Figure 5, Red Arm EKR1-9 data for locally induced noise, note the various frequencies.

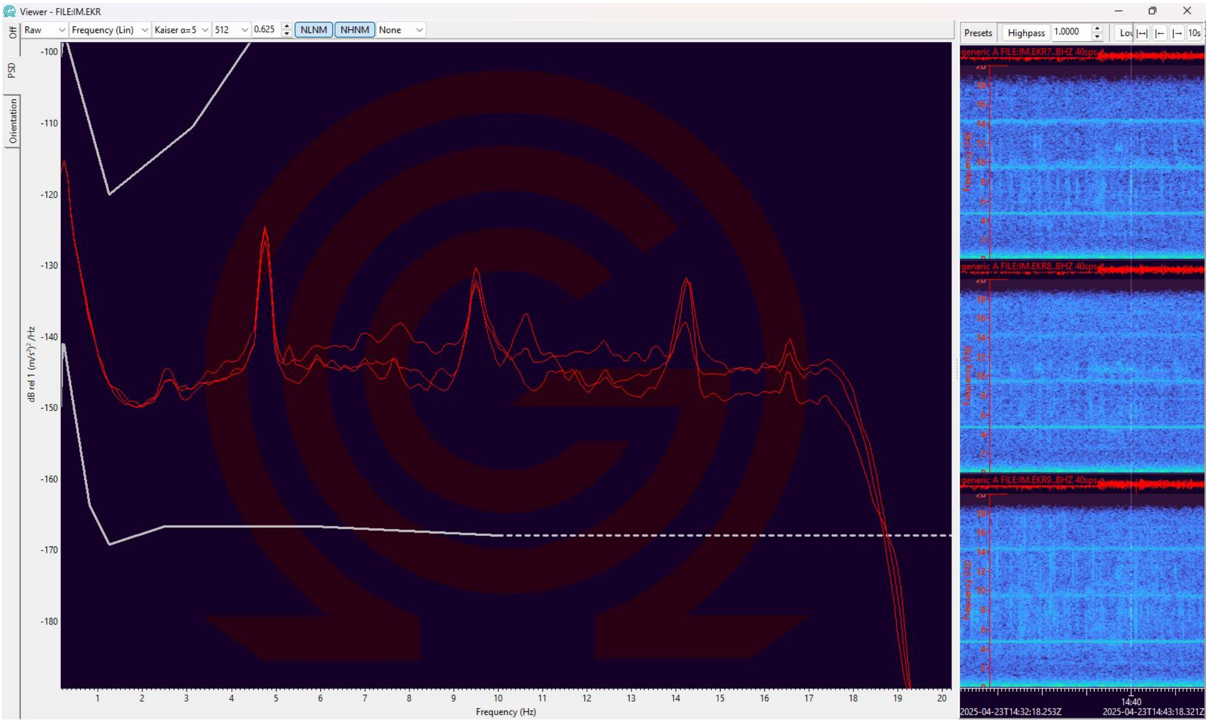

Figure 6, EKR7, EKR8, EKR9 Only with spectrogram that shows the horizontal noise.

Plotting of each element of the arm clearly shows that the noise source is closer to the east end of the Red arm. Figure 7 is a plot of the noise amplitude in dB measured at each station and shows that from east to west there is an approximate 10dB drop in the noise. Overall there is a linear decay in this data. Additionally, while not shown, we can see large localised surface noise at the EKR7, EKR8 and EKR9 elements at this time that the Author attributes to local vehicular traffic near the elements given the wind speed in the area at the time was relatively calm, the induced noise could not be attributed to wind turbines. Communications with TilHill Forestry indicates that there was logging operations taking place in that area of EKR10 at the time we see noise.

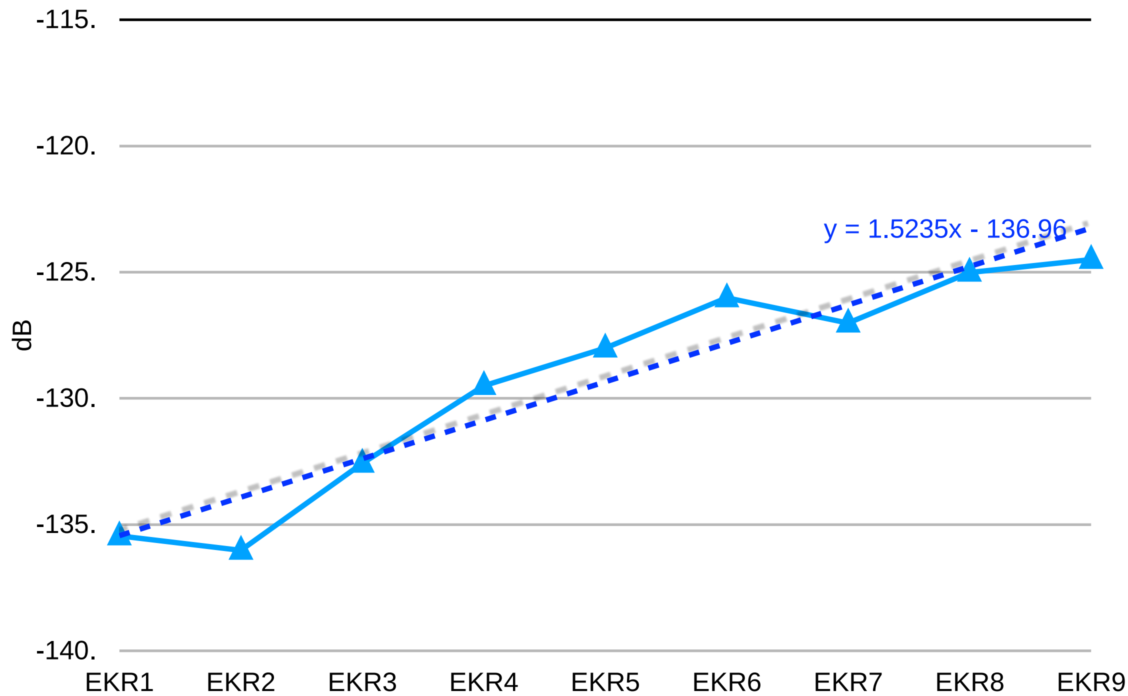

Figure 7, Peak noise measurements for elements of the Red Arm

The 4.8Hz noise is seen only during normal working hours on weekdays and starts abruptly and ends the same way but with a decay in the frequency over about 10 seconds. In Figure 8 when the signal stops we can clearly see the decay in frequency indicating to the Author that this noise is from a motor that is turned off, or turned to idle, and the frequency lowers as the motor slows down. This decay is seen each time this noise ends.

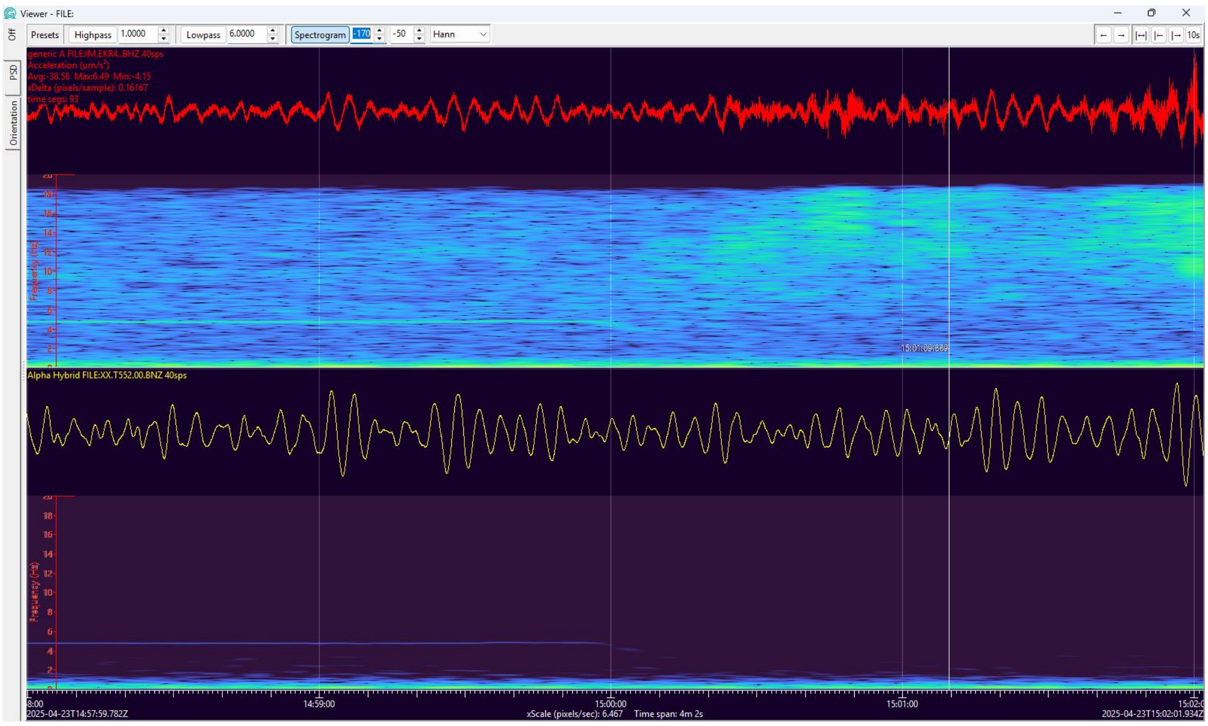

Figure 8, Note the end of the signal at 4.8Hz how the frequency drops off over about 10 seconds. EKR4 Top, Borehole ALPHA bottom.

Note, the anthropogenic noise associated with logging activity is one of the largest sources of localised noise the area. In the Author's opinion this activity severely impacts the array's performance in the AWE area of interest, yet there are no restrictions placed on the logging activity, as has been placed on power production from wind turbines. The deployment of borehole sensors should, and will, help mitigate this noise source and improve EKA's capabilities during logging operations.

Average Noise Performance

In the context of increased anthropogenic and cultural noise, and with the target being quantification of noise gains in that context, we feel the best way to demonstrate proof of concept here is to view and analyze the data based on wind.

Notwithstanding natural noise from the North Sea (which the author notes dominates the frequency passband below ~2Hz), and ignoring transport noise created by the M74 motorway and West Coast Train Line, the principal anthropogenic noise is caused by wind blowing through the commercial forestry, and agricultural operations.

On a calm wind day (3m/s, 10.8km/h) wind turbines are not generating as modern turbines start operating at around 3-4 m/s (10.8-14.4km/h). Likewise seismic noise produced by local commercial forestry cover is less. Whilst the results show an average 10dB noise gain during those periods, it is of little consequence given the mitigation targets are effectively irrelevant. However, there is an immediate benefit in terms of the overall enhanced detection capabilities of the array, and will help mitigate anthropogenic noise from other manmade sources in the area.

Of much more importance for these purposes are moderate and high wind days, and in particular periods when average windspeeds exceed 12m/s (43.2km/h). These are the times when the wider commercial forestry cover and turbine towers will produce seismic noise.

Low to Moderate Wind Day, 10 to 30km/hr (2 to 8 m/s)

In Figure 9 we plot data for a 28 minute period of time on 11 January 2025 when the average winds over this time period measured at ~21km/hr (6m/s), which is low wind. You can see that even at winds speeds of 21km/hr (6m/s) the borehole sensor is still touching the NLNM line at about 5Hz to 6Hz, which is an incredible achievement. At this time the sensor was deployed at a depth of 175m and submerged in water. This is just one example of the noise reduction seen in the data over the course of the initial monitoring efforts. Over the project we have seen, as reported in the Interim Report, higher levels of noise reduction of 17dB to 26dB being measured at various times. The variation in noise performance/reduction measurements were due to sensor deployment depth, whether or not the sensor was in water, air or sand, water dripping noise, if the top of the borehole was sealed due to wellbore mitigation efforts, and length of time noise is average over, to name a few.

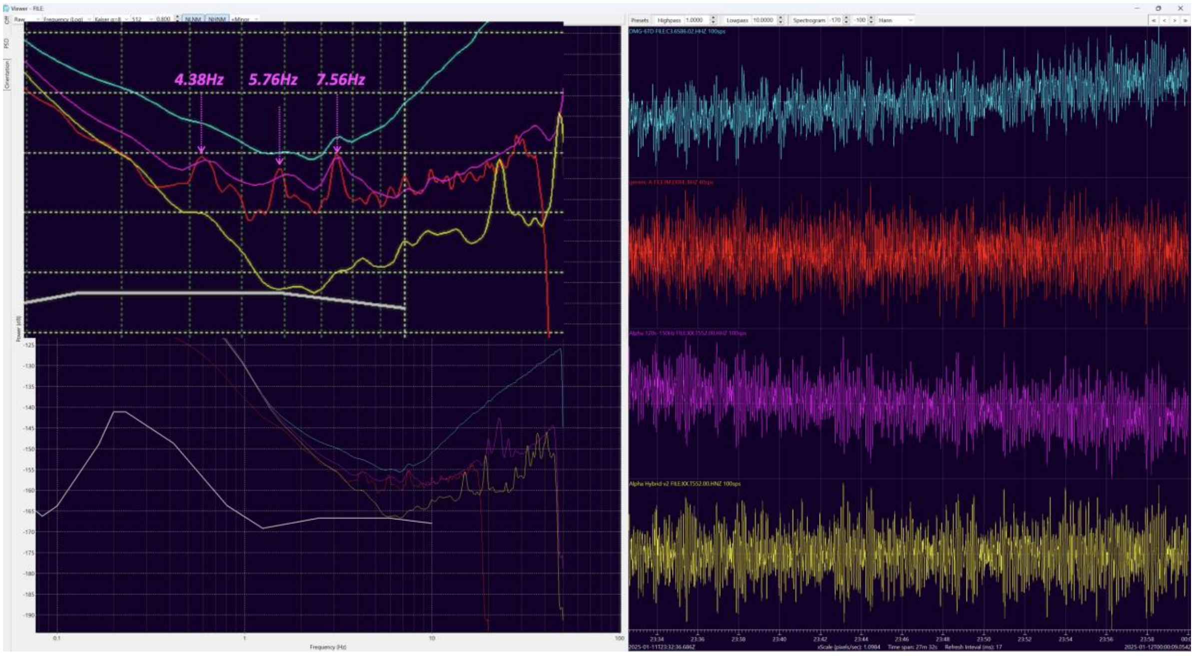

Figure 9, 11 Jan 2025, 28min data set, Cyan = Surface CMG-6TD, Red = EKR4, Magenta = Surface ALPHA and Yellow = Borehole ALPHA

Figure 10 is another example of noise reduction at the site for the 10th of February 2025 with the sensor deployed at 195m depth, but the top of the borehole was not properly sealed, which allowed for some noise to be transmitted through the slit in the flange at the top of the casing to the sensor. The average winds on this day during this timeframe were measured at 26km/hr (7.2m/s). The average noise reduction was measured at about 10dB over the 2hr time period.

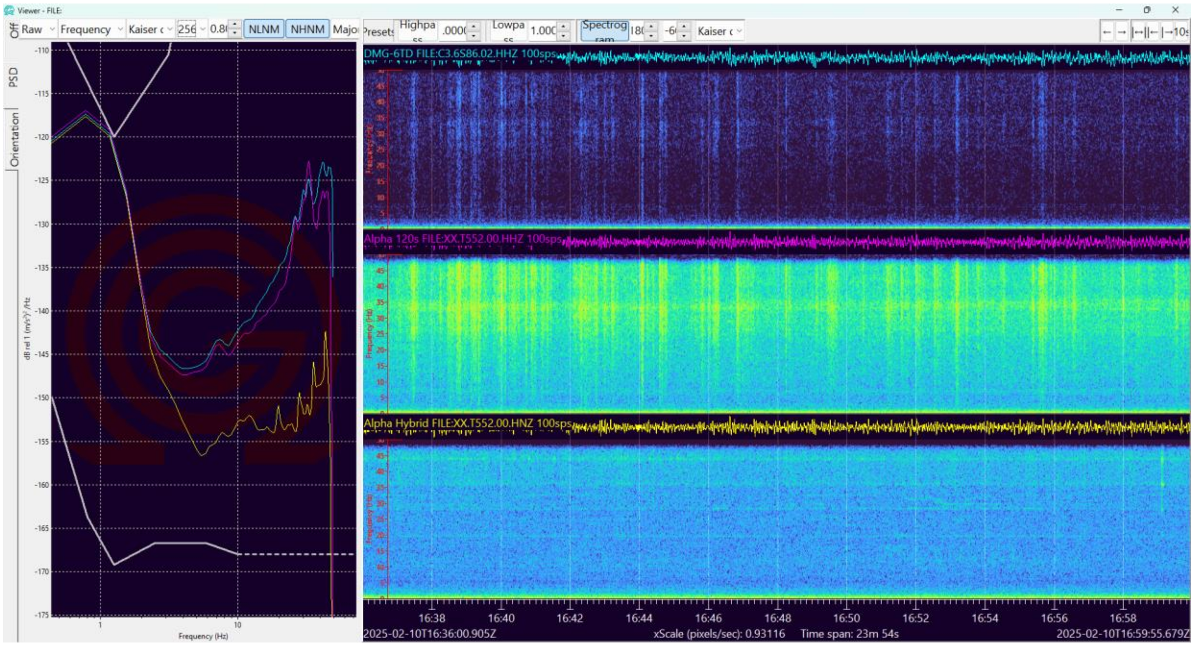

Figure 10, 10 February 2025, ~16:37gmt to 17:00gmt. Average noise reduction measured at ~10dB. Average Winds Recorded at 26km/hr (7.2m/s).

As mentioned previously there have been several mitigation efforts to provide higher quality data. After a recent mitigation effort about 20m of sand was placed in the borehole around and above the sensor on the 23 April 2025, which after settling improved the data quality and reduced much of the noise associated with the leaking casing. Shortly after this work was completed there were local winds recorded by the Eskdalemuir weather station with average hourly winds speeds of 28km/hr (7.8m/s) and gusts of 46km/hr (12.8m/s). In Figure 11 we show a 34-minute timeframe of data recorded on 27 April 2025 during this moderately higher wind event. As can be seen in the figure there were large noise spikes in surface stations, Top (Cyan-CMG-6TD) and Middle (Magenta-Surface-ALPHA) waveforms on left, but not on the borehole sensor (Yellow). As can be seen in the PSD plot on the left we measured ~17dB noise reduction between the two surface sensors and the borehole sensor at ~5.9Hz.

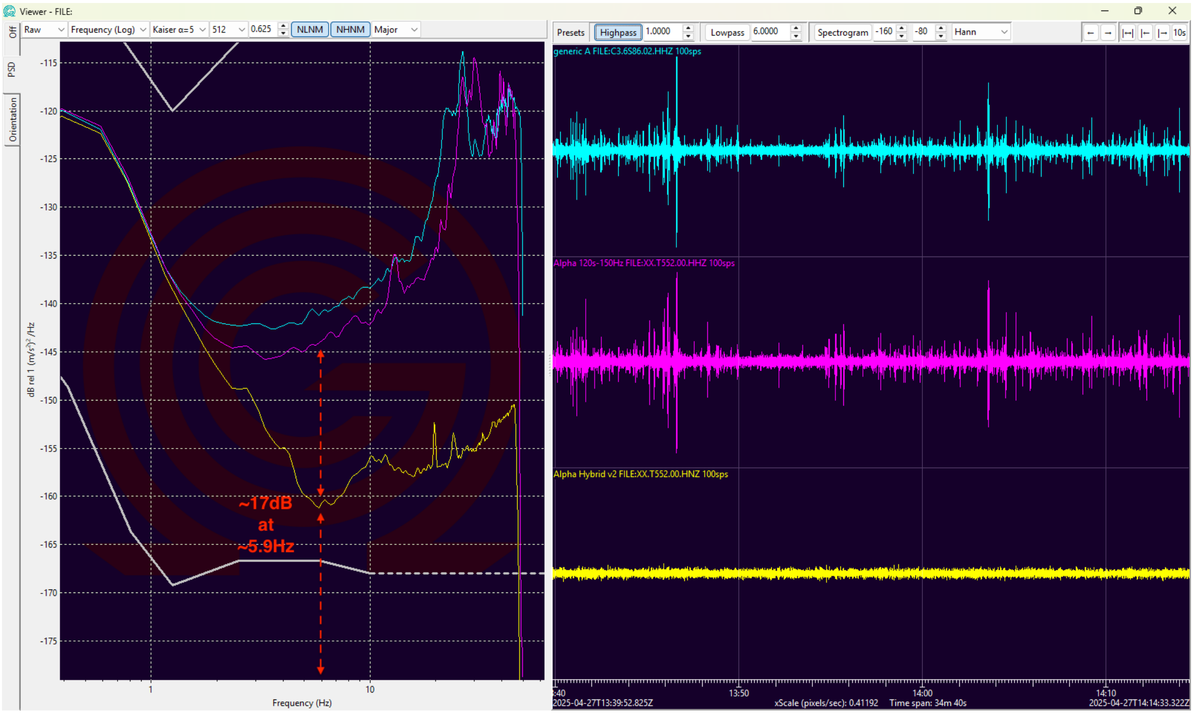

Figure 11, 34min 27 April 2025, 13:40GMT to 14:14GMT. CMG-6TD Top Trace (Cyan), Surface ALPHA Middle Trace (Magenta), Borehole ALPHA Bottom Trace (Yellow). ~17dB noise reduction between the Surface and Borehole ALPHA sensors measured at ~5.9Hz.

High Wind Days, wind greater than 30km/hr (8m/s)

On high wind days, which are the periods of most interest, given that is when turbines will be making noise, is when we see the most improvement in the data and shows how the borehole sensor will out perform any surface sensor. Figure 12 shows the Spectrograms and PSD for a 3 day period of time when the winds were high in the area with average hourly wind speeds ranging from ~10km/hr (2m/s), which is on the calm side, with average wind speeds of ~28km/hr (8m/s), with higher wind gusts of ~47km/hr (13m/s) recorded during those hours. For comparison to wind we have overlayed the hourly average wind speed on to the plot. Again at this time the top of the casing was not properly sealed with the gaskets which allowed for some wind noise to be transmitted through the top of the casing to the borehole sensor. Recent sanding mitigation efforts helped reduce this effect, but unfortunately we have not had winds at these velocities as of the writing of this report to compare with this data. Based on initial results seen after sanding there is an additional 1.5-2dB improvement on calm days and 2-4dB on moderate days.

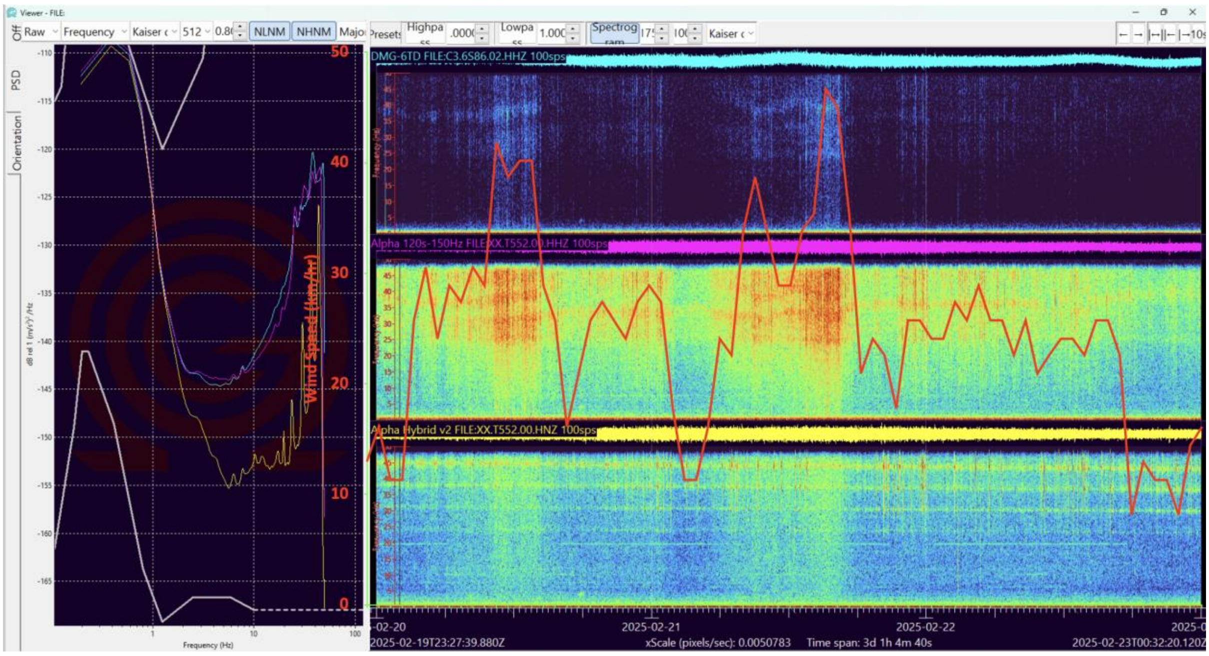

Figure 12, High wind days, 23:27GMT on 19 February to 00:32GMT 23 February 2025. Magenta = Surface ALPHA, Yellow = Borehole ALPHA, Cyan = CMG-6TD. The Red Line = Hourly Average Wind Velocity is ~28km/hr (8m/s).

In the PSD plot on the left of Figure 12 we can see an improvement in noise reduction between the two surface sensors and the borehole by ~10-11dB for the entire 3 days of data at approximately 28km/hr (8m/s).

In Figure 13 we measure approximately 12dB and 18dB noise improvement between 2Hz and 8Hz with winds recorded at approximately 46km/h (12.7m/s) during this timeframe. On 4 February 2025 between 03:30GMT and 04:30GMT, Figure 14, there were reported winds of 47km/h (13m/s). During this 1hr period HMSC measured noise reduction of ~12dB between 5Hz and 8Hz, again the area of primary interest to AWE.

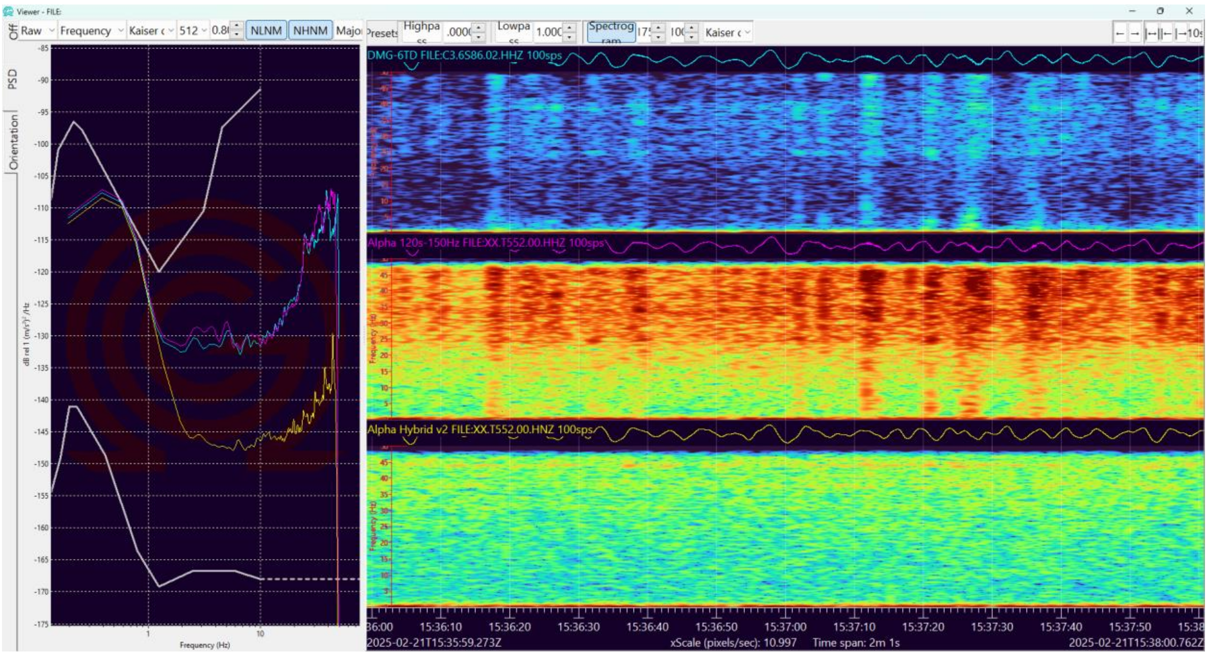

Figure 13, 2min data at the highest average hourly wind speeds of 72km/h (20m/s). For shorter time scales, as would be used for processing of seismic data, we measure ~15-18dB

2Hz to 10Hz and over 20dB improvement above 10Hz in this 2min segment of data between the surface sensors and the borehole. Note, Surface Winds were recorded at over 46km/h.

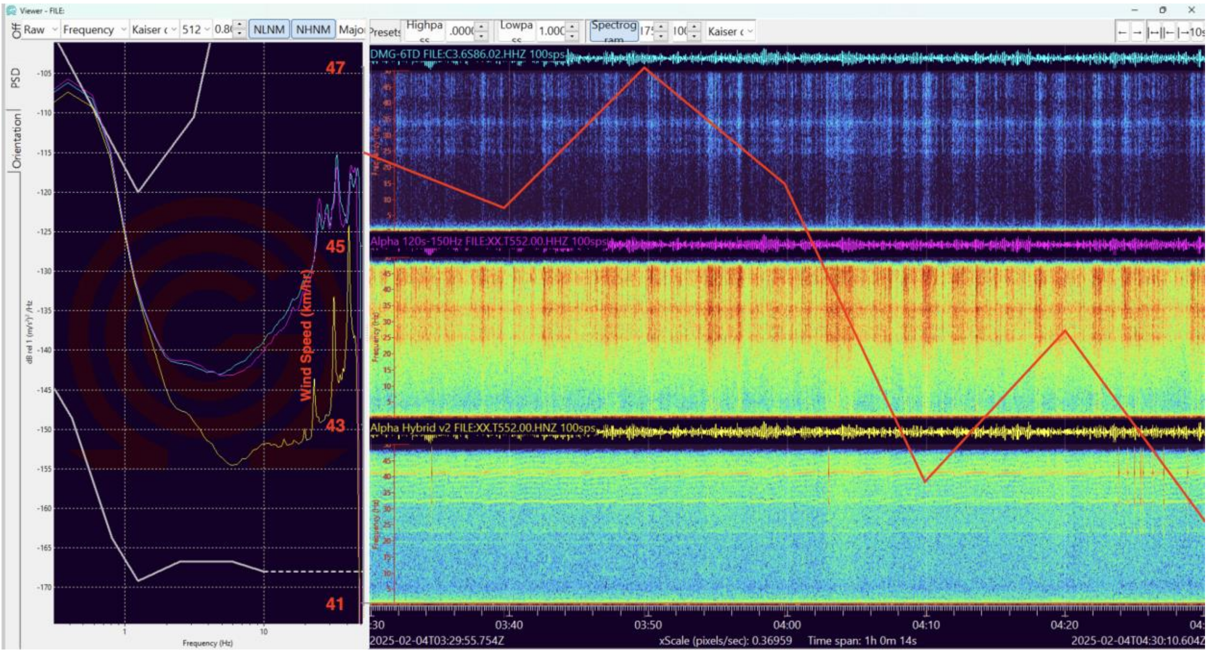

Figure 14, 1 Hour Window of data from 4 February 2025 between 03:30GMT to 04:30GMT. Wind speeds were measured on nearby anemometers at over 47km/h (13 m/s). Again we measure ~12dB improvement in the borehole over the two surface sensors between 5Hz and 8Hz.

The most striking results were recorded on 24 January 2025, Figure 15, when 10min winds speeds peaked at over 87km/hr at about 11am local time. During this 24hr window we measured average wind speed at ~60km/hr (17m/s) with noise reduction between the surface and borehole sensors at over 26dB for the entire timeframe. As noted above the measured noise reduction will vary depending on the timeframe used, such that at shorter windows we can see improvements from 20dB to 28dB.

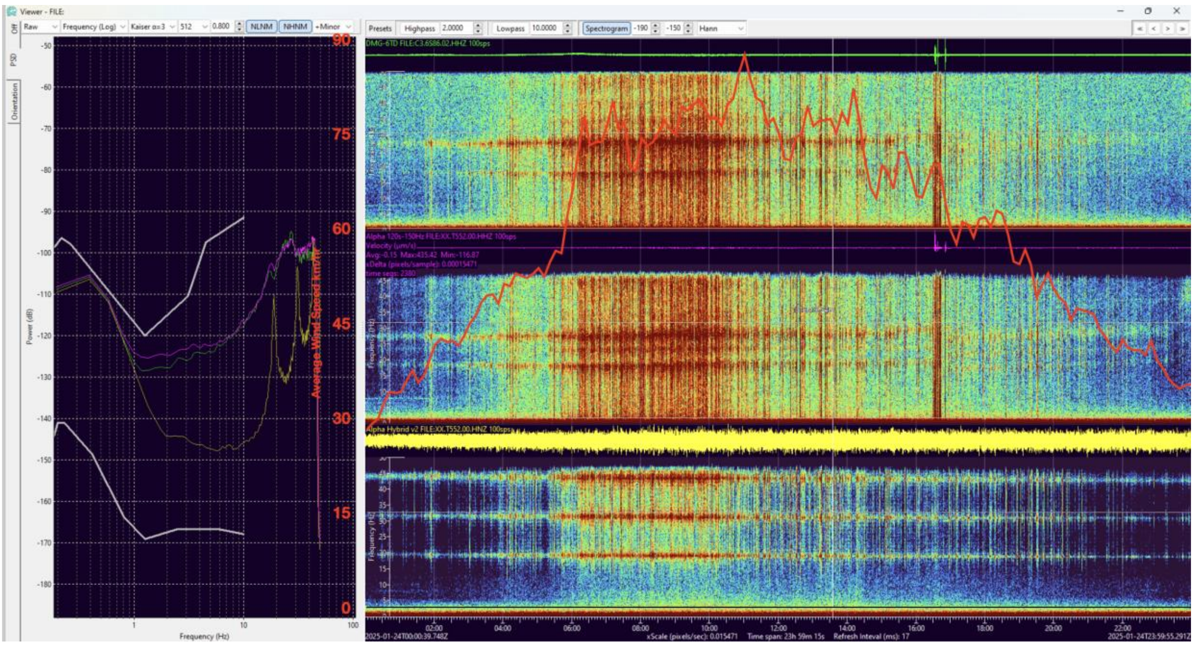

Figure 15, 24 Hour Window of data on 24 January 2025 where winds peaked at almost 90km/h. As much as 26dB of improvement is seen between 2Hz and 10Hz in this time period.

As can be seen in Figure 15, on high wind days locally induced noise from multiple sources can overwhelm the surface sensors over a broad spectrum of bandwidth such that it will be almost impossible to detect any weak incoming signals in the data, even with advance filtering techniques. This would especially be true if there were logging activities underway during a high wind event where you have not only the noise from logging equipment, but trees vibrating and induced broad spectrum noise. The Author feels, as the data shows, that using borehole sensors throughout the array will greatly improve the overall data quality, especially on high wind days and high anthropogenic noise levels. The use of borehole sensors will lower the detection threshold and improve the overall capabilities of EKA for not only recording high quality data for seismic events, but also for detection of covert nuclear tests.

CTBT Policy

The design requirements for IMS Stations are set out in *The Operational Manual For Seismological Monitoring And The International Exchange Of Seismological Data* (IMS Manual). The IMS Manual sets out how both Primary and Auxiliary Stations are designed, operated and maintained.

At a high level, Chapter 2 narrates what an IMS Station is, the basis under which it is required, who should operate it, and broadly how it is to be certified.

Chapter 3 describes in detail the geographic design of an IMS Station, what its characteristics should be, what apparatus should comprise the IMS Station, how data should be gathered and communicated, and how it should be secured.

In Chapter 4 the operational aspects of an IMS Station are set out. This is principally designed to ensure a high level of availability and data provision, as well as how assets are calibrated and performance is to be reported. There are, however, several paragraphs of particular relevance for our purposes:

"99 Regular monitoring of noise level is carried out by the Technical Secretariat and the station operator as part of quality control. Long term changes in noise level may require station relocation in accordance with relevant Treaty provisions. For array stations, it may be appropriate to relocate particular elements without relocating the station or altering the configuration of the array in response to changes in noise conditions.

104 The station operator makes surveys of changes in site characteristics that may potentially alter station operational characteristics from those noted during station certification. The area surrounding the station is examined for encroachment of cultural features that could act as possible noise sources, for example new roads. Also, the area around the station is examined for degradation of infrastructure, involving power, communication circuits and access to sites. Such features are noted and added to the station site specific documentation, and the Technical Secretariat is notified in the Monthly Report or a Problem Report if appropriate."

These essentially describe how noise performance is to be monitored, and the process that should occur if a degradation is measured. If a configuration change is deemed necessary, then 135(d) specifies that this is to be promoted under Section 4.7 (Configuration Management):

"4.7. Configuration Management

126. Configuration management provides the capability at any time to know and control the configuration of an International Monitoring System station by:

(a) Ensuring that the station continues to meet specifications,

(b) Controlling the interfaces between the station and other parts of the verification system,

(c) Providing inputs to the logistical support system.

127. Initial baseline station configuration information is provided to the Technical Secretariat during the certification process, and can include information on hardware, software, firmware, procedures, databases and preset values in files and database tables. A station specific list of configuration items is included as part of the station specific documentation defined in Appendix III. The Technical Secretariat must be informed of, and give approval for, any configuration change by the station operator.

128. Configuration is managed between the station operator and the Technical Secretariat using two types of reports, the Configuration Change Request and the Configuration Change Notification. Templates for these reports are given in Appendix II. Configuration Change Requests are submitted by the station operator for changes in any equipment in the list of configuration items in Appendix III, at least 20 days in advance of the planned configuration change. Configuration Change Notifications are submitted for all changes that are made to equipment in the list of configuration items, after the change has been made."

Accordingly, there is a well-defined process for implementing the configuration change proposed in this Final Report.

Chapter 5 describes the practical maintenance activities required to operate an IMS Station which are of lesser relevance to our purposes.

In the context of this Final Report to upgrade aspects of EKA, we are principally focused on the design specification set out in the IMS Manual. In particular, we are cognizant of the relevant parameters in Appendix I.2:

Characteristics	**Minimum Requirements**
Sensor type	Seismometer
Station type	Three component or array
Position (with respect to ground level)	Borehole or vault
Three component station passband[a]	Short period: 0.5 to 16 Hz plus long period: 0.02 to 1 Hz or broadband: 0.02 to 16 Hz
Sensor response	Flat to velocity or acceleration over the passband
Array station passband	(Short period: 0.5 to 16 Hz Long period: 0.02 to 1 Hz)[b]
Number of sensors for new arrays[c]	9 short period (one component) plus (1 short period (three component) plus 1 long period (three component))[d]

Seismometer noise	≤10 dB below minimum earth noise at the site over the passband
Calibration	Within 5% in amplitude and 5° in phase over the passband
Sampling rate[a]	≥40 samples per second[e] Long period: ≥4 samples per second
System noise	≤10 dB below the noise of the seismometer over the passband
Resolution	18 dB below the minimum local seismic noise
Dynamic range	≥120 dB
Absolute timing accuracy	≤10 ms
Relative timing accuracy	≤1 ms between array elements
Operation temperature	–10oC to +45oC[f]
State of health	Status to be transmitted to the International Data Centre: clock, calibration, vault and/or borehole status, telemetry
Delay in transmission to the International Data Centre	≤5 min
Data frame length	Short period: ≤10 s; long period: ≤30 s
Buffer at the station or National Data Centre[g]	≥7 days
Data availability	≥98%
Timely data availability	≥97%
Mission capable arrays	≥80% of the elements should be operational
Precision on station location	≤100 m absolute for stations (World Geodetic System 84) ≤1 m relative for arrays Elevation above sea level: ≤20 m
Seismometer orientation	≤3°
Data format	Group of Scientific Experts format
Data transmission	Primary station: continuous Auxiliary station: segmented

[a] *For existing Global Telemetered Seismic Network stations, upgrading needs further consideration.*
[b] *For a one component element of teleseismic arrays, the upper limit is 8 Hz.*
[c] *In the case of noisy sites or when increased capability is required, the number of sensors could be increased.*
[d] *This can be achieved by a single broadband instrument.*
[e] *This applies to three component and regional arrays. For existing teleseismic arrays, 40 samples per second are necessary for three component sensors but 20 samples per second are suitable for other sensors.*
[f] *Temperature range to be adapted for some specific sites.*

[g] *Procedure for buffering to ensure minimum loss of data and single point failure should be addressed in the International Monitoring System Operational Manual.*

Design

The CTBTO have recently set out their specification for borehole design in their CTBT 2024 Report.

Section 4 of the CTBT 2024 Report describes how an IMS Station should be constructed. In particular, it notes "*The majority of IMS arrays use the borehole method of sensor installation. It is known in seismological practice that sensor installation below the ground surface has diminished seismic noise level especially in the high frequency domain (Carter et al. 1991)*". Whilst noting it is site dependent, the CTBT 2024 Report notes that *"in general the deployment in the borehole is one of the methods used to reach better detection capability of the weak ground motion at higher frequencies f>3-5Hz".* That conclusion accords with our experience in the field and the results we found, as described in HMSC's Interim Report.

Turning to the particular requirements the IMS has for borehole installations, the CTBT 2024 Report details 3 acceptance tests as a minimum IMS requirement:

1. Each finished borehole must be tested for its final verticality to be less than 2.5 degrees;
2. Each finished borehole should be tested against obstruction inside the casing using a cylindrical test dummy the length and outer diameter of the largest piece of borehole instrumentation to be installed; and
3. Each finished borehole should be tested inside the casing against leaks, by filling and monitoring the pressurized water level for at least 24 hours.

The CTBT 2024 Report goes on to specify a number of further desirable characteristics for borehole installations, which are listed below:

a) To diminish the influence of air pressure fluctuations on low frequency seismic noise the installation in sand at the bottom of the borehole should be utilized (Holcomb et al. 1998)
b) Ten boreholes (nine for vertical-component sensors and one for a 3-C broadband sensor) should be drilled and cemented to provide the best coupling to house seismometers with surrounding rocks.
c) The target depths should be a minimum of 30m for the vertical element boreholes, and 60 m for the 3-C element borehole.
d) Deviation from target depths is possible if appropriate geological justifications are discovered during drilling.

This same set of requirements was implemented by the Author when he upgraded the Primary IMS Station, PS40. It was originally installed more than 40 years ago as part of the United States nuclear test monitoring programme and has been upgraded several times since then. In November 2001 a final upgrade of the station was made by the Provisional Technical Secretariat in cooperation with the Instituto Geografico Nacional, the current station operator, due to increased anthropogenic noise caused by the growth of the nearby city of Sonseca.

Taking this into account, HMSC Inc. feels that a Change Proposal (as set out in the IMS Manual) should be to upgrade EKA with new 3-component borehole sensors to mitigate the impact of induced noise over a broad spectrum of bandwidth. We do not recommend changing any of the existing array elements but enhancing them with the addition of the borehole sensors.

It is important to note that EKA currently comprises principally vertical-component seismometers, with 3-component seismometers found at elements EKB, EKB3, and EKR3, and possibly at the end of each arm though HMSC has not been able to verify if these stations are operational as at this time data is not available from either the IRIS DMC or via the AWE portal at Blacknest. As such, there is an inherent benefit arising by supplementing these legacy vertical-component seismometers with new 3-component seismometers, which will provide the MoD with enhanced array performance through an increased ability to record and define Shear waves that is currently more difficult using a vertical-component seismometer alone. Aside from providing improved performance in its capacity as an Auxiliary IMS Station, this upgrade will allow EKA to offer additional defence capability for close regional seismic events and monitoring activities, where the analysis of S wave arrivals is currently much more difficult.

In line with the CTBT 2024 Report, HMSC recommends that 10 elements of the array be modified as follows:

i. the addition of a new deep borehole sensors at each location;
ii. each borehole housing a 3 component sensor shall be at least 60m deep;
iii. each borehole should be within the 2.5^{o} tolerance set out in the 2024 Report;
iv. each borehole shall house a 3 component borehole type sensor;
v. each seismometer shall be cemented into place with a Portland cement mix to surface;
vi. power, data and communication assets should be utilized where possible.

Note the 2.5^{o} tolerance set out in the report was due to the tolerance of the sensors being deployed with them needing to be vertical. With the new ALPHA borehole sensors this tolerance can be relaxed to over 5^{o} tolerance based on the manufacturer's specifications. However, when drilling the borehole we always strive to keep them as vertical as possible.

Table 1 below details the proposed upgrade specifications:

LOCATION	BOREHOLE DEPTH	SENSOR TYPE
EKR1	100m	3-C
EKR3	30m	Vertical 1-C
EKR6	30m	Vertical 1-C
EKR8	60m	Vertical 1-C
EKR10	100m	3-C
EKB1	100m	3-C
EKB3	30m	Vertical 1-C
EKB5	30m	Vertical 1-C
EKB7	60m	Vertical 1-C

EKB10	100m	3-C

Table 1, proposed 3-Component and 1-Component element upgrade/enhancements.

Figures 16 shows the locations of EKA and the proposed elements/pits to be upgraded or enhanced with new 3-component and 1-component borehole seismometers.

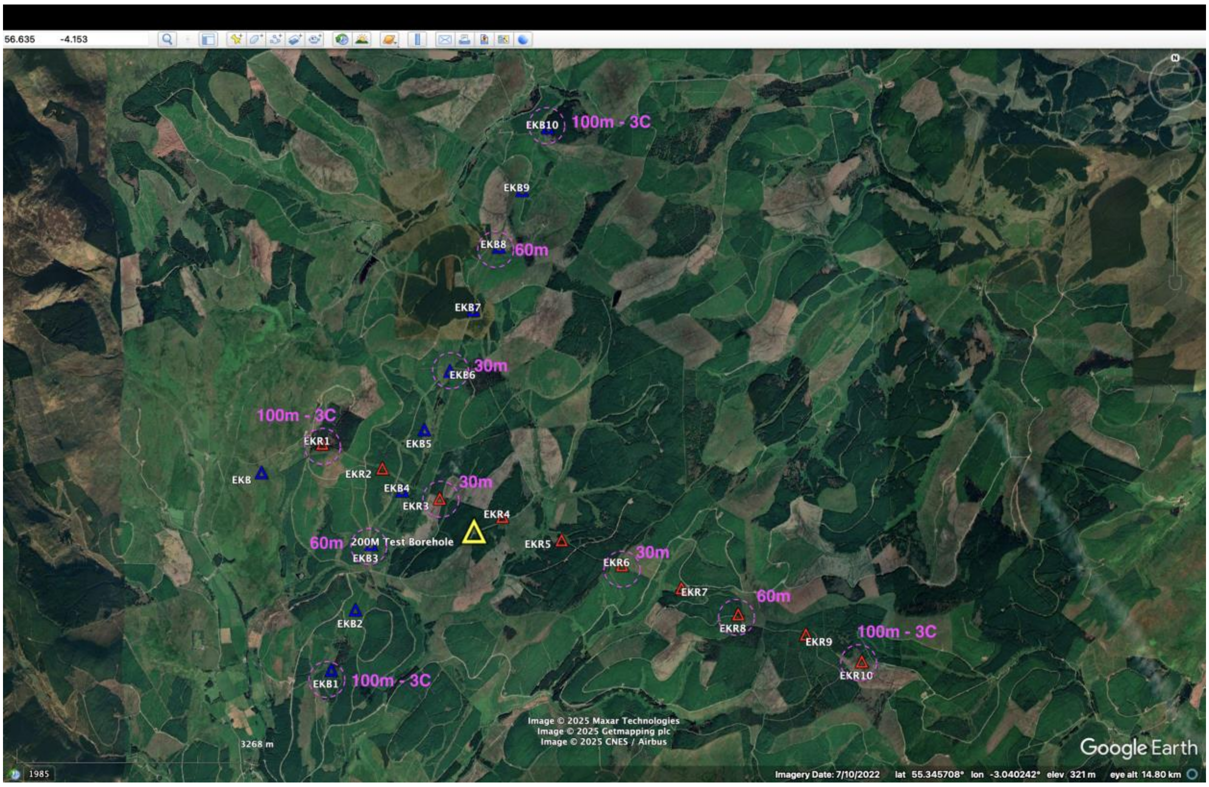

Figure 16, Google Earth Image showing EKA array and elements to be upgraded/enhanced at 30m, 60m and 100m.

This specification is a two-fold increase from the number of boreholes proposed in the White Paper, and the author is keen to a have technical dialogue with AWE seismologists to agree the final design. As noted above, and per the CTBT requirements, HMSC proposed that four (4) of the new 3-component elements be installed at a depth of 100m at the ends of each arm, and the remaining six (6) be installed at 30m to 60m along the arms. This approach should provide better signal to noise performance at the ends of the lines as these sites will be nearer the wind farms and potential noise sources. This also helps to future proof the array in such a way that if there is additional anthropogenic noise near the ends of the arms these sites will be better able to filter that noise out and help alleviate concerns of the MoD/AWE in the Array's ability to record high quality data.

Upgrading the Array will afford the MoD with a significant asset performance improvement, not only in reducing surface noise but also enhancing detection capability. This will ensure that EKA is shielded for the long term from current anthropogenic noise, principally caused by forestry and associated operations included harvesting, forwarding and hauling, alongside additional wind turbines and other regional noise source proliferation. It is very common for

IMS Stations to be upgraded in this fashion and a great number have been supplemented in this way, such as Sonseca PS40 and Brasilia PS7 as examples, to provide long term protection from changes in their local environment. As noted above, the author personally worked on the upgrade to the Sonseca station which was successfully completed and certified into the IMS.

It is known from the findings of the RSK report titled “Background seismic noise at Eskdalemuir array” dated April 2022 (RSK Report) that even though 172 wind turbines have been constructed and commissioned, with a generation capacity of 478 MW since 2015 in the Eskdalemuir area, there has been no measurable increase in background noise since that time. Therefore, whilst not strictly necessary, a belt and braces approach would be to complement the proposal set out above with the remaining 10 locations being upgraded to include vertical-component seismometers set in 30m boreholes, as described in the CTBT 2024 Report, Table 2 and Figure 17.

LOCATION	BOREHOLE DEPTH	SENSOR TYPE
EKR2	80m	Vertical 1-C
EKR4	30m	Vertical 1-C
EKR5	30m	Vertical 1-C
EKR7	30m	Vertical 1-C
EKR9	80m	Vertical 1-C
EKB2	80m	Vertical 1-C
EKB4	30m	Vertical 1-C
EKB5	30m	Vertical 1-C
EKB7	30m	Vertical 1-C
EKB8	80m	Vertical 1-C

Table 2, proposed 1-Component (Vertical Only) element upgrade/enhancements.

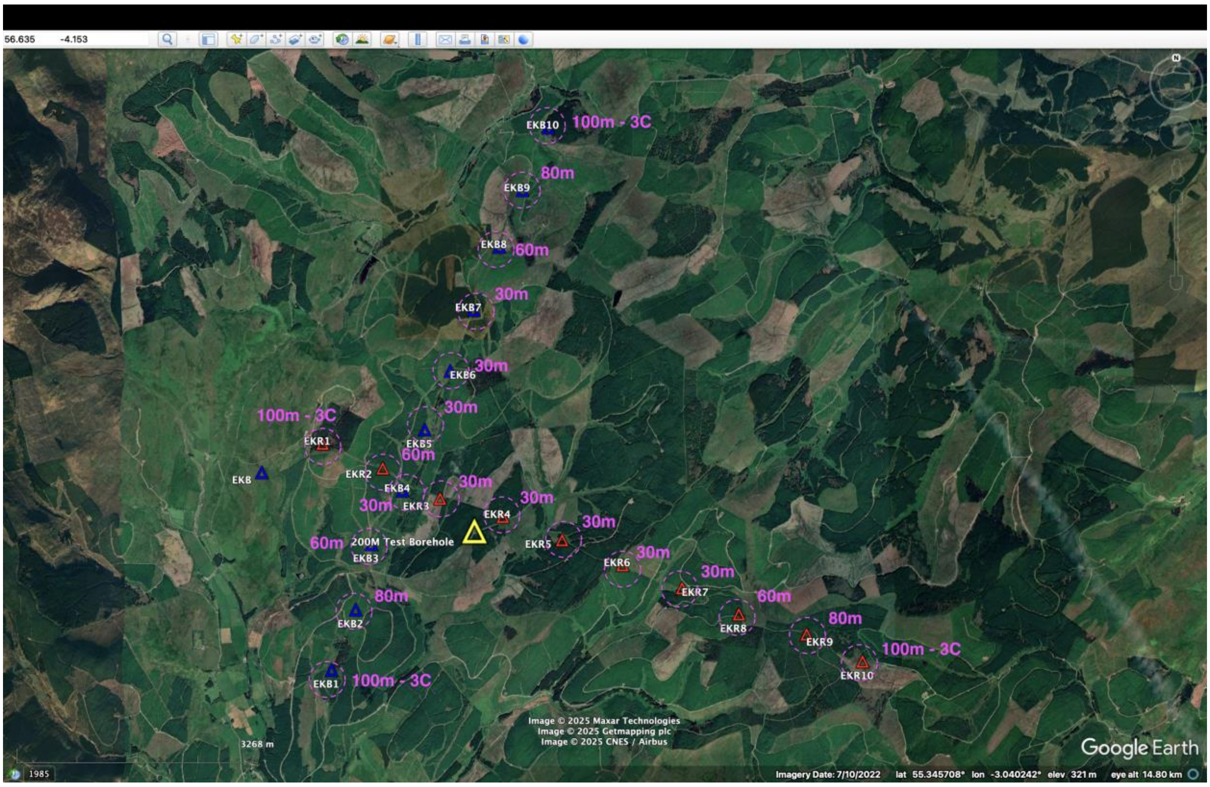

Figure 17, Google Earth Image showing EKA array and elements to be upgraded/enhanced at 30m to 100m.

If the MoD were minded to seize the opportunity to receive a full upgrade of the array at the costs of the renewables industry, it would undoubtedly cement the benefits noted above and future proof the array against all anthropogenic noise now and in the future.

Construction

Boreholes

In the Interim Report, it was noted we have very hard rock and competent geology. As a result, HMSC doesn't consider casing is needed, although that can of course be completed if required by the IMS following a Change Request.

HMSC recommends that boreholes be drilled close to the current EKA pits. This ensures that the functional design of EKA is maintained, and current data and communication assets leveraged.

While site specific plans would need to be developed and agreed with the Stakeholders on the detailed design and method statements. We recommend that a short conductor casing be used in the first few metres to support the opening of the borehole. This is also the basic method that Guralp Systems Limited, one of only two manufacturers referenced in the CTBT 2024 Report, documents as the best overall deployment practice to acquire the highest quality of data[4].

[4] https://www.guralp.com/howtos/creating-low-noise-environments-for-borehole-seismometers/

Typically, while there are several options for the design and installation of the borehole, we would recommend drilling a 6 inch[5] (~152mm) hole. This is in accordance with the specifications of the 2024 Report. An upper conductor casing should be used to keep the hole open at the top where there are typically loosely compacted soil conditions. Given that there will be variations from site to site, the length of this conductor casing can change. Once the conductor casing is installed, we would drill open hole to a total depth of between 30-100m.

Tracked vehicles would be utilized so no major civil works should require to be undertaken. Existing EKA assets would be protected by undertaking a CAT scan of all electronic equipment, including data and communications cables, before mobilizing to site.

All RAMS (Risk Assessment Methods Statement) would be provided to AWE prior to commencing works.

Attached at **Annex A** is a drilling proposal from The Natural Power Consultants Limited, a leading Scottish contractor, meeting the design requirements.

Sensors

The borehole and surface seismic sensors for the test hole were provided by Gaiacode Limited, which is the current seismometer manufacturing business of Dr Cansun Güralp. Dr. Cansun Güralp was the Founder of the current EKA Array sensor manufacturer Güralp Systems Limited, which was one of two manufacturers referenced in the 2024 Report.

Quotations for 10 borehole sensors meeting the specifications set out in the IMS Manual have been received from both Gaiacode Limited, and Güralp Systems Limited. They are attached at **Annex B** and **Annex C** respectively. Both are UK manufactured and comply with the latest IMS Manual specifications. Final seismometer selection will be subject to IMS and AWE approvals.

An indicative borehole seismometer is shown in the photograph below, Figure 18.

[5] Note, in drilling inch is used as a standard of measurement for drilling diameter so we are using those here, and metric for depth.

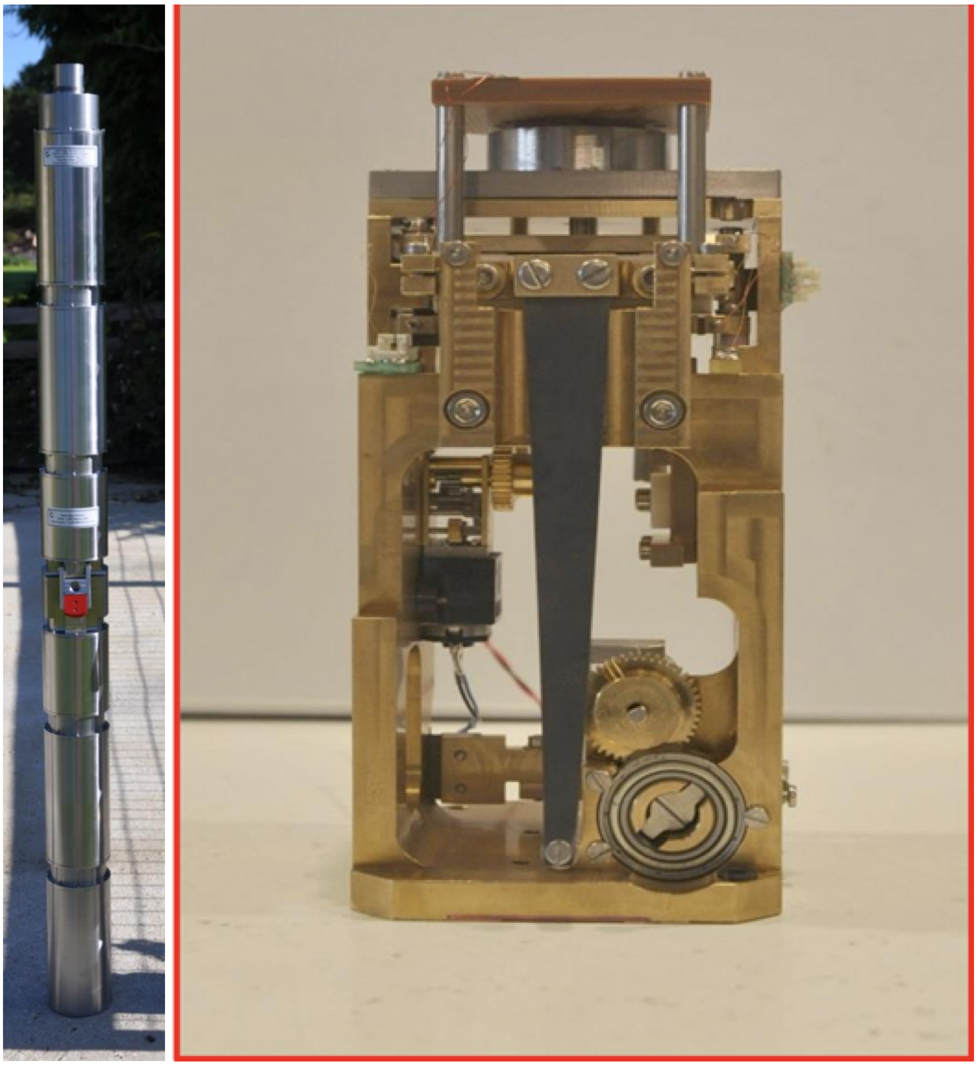

Figure 18, GaiaCode Borehole ALPHA Sensor Left, Internal Vertical Component Design Right, Photos provided by Dr. Güralp of GaiaCode

Additionally, the author notes that the ALPHA sensors used in the test borehole have an inherently better overall performance than the current EKA sensors. These are the latest technology and have much lower internal self-noise, which is a key consideration when reviewing the CTBT 2024 Report, and the IMS Manual. This means that even without installing them in boreholes, simply replacing the current sensors with the new Alpha sensors means that EKA will have much better noise performance, cultural noise avoidance, and a lower detection threshold for both earthquakes and nuclear tests than currently available.

Full details on the sensor specifications can be found on both the Gaiacode Limited[6] and Güralp Systems Limited[7] websites.

Installation

[6] https://www.gaiacode.com/products/broadband-instruments-alpha
[7] https://www.guralp.com/products

Once the borehole has been successfully drilled and tested per the specifications set out in the CTBT 2024 Report, the sensor would then be lowered, tested, then coupled to the surrounding rock.

The best coupling would be to cement the sensor in place with several metres of a Portland cement slurry mix, then backfilled with sand and/ or cutting to the surface, or alternatively the entire borehole can be filled with cement slurry to surface. This will ensure that there is good coupling with the geology, no chance of water noise, and will provide the best reduction in noise associated with local wind. Once the borehole is backfilled the upper conductor casing would be removed to minimize the impact to the site, and a ground level aerodynamic lid fitted to mitigate wind noise further.

Whilst compliant with the CTBTO technical specifications for seismic arrays, this design does mean that the sensor can never be retrieved and repaired. As such, we will remove most of the electronics, that are the typical failure point, from the sensor and move them to the surface as mitigation. This will make the downhole sensor more reliable over its lifespan. As further mitigation, it is possible to have a secondary backup sensor installed such that if the primary fails, the secondary sensor could be connected to the data logger and the station back online within a few hours. However, having a single element in the array fail should not adversely affect the overall operations of the array, and additionally in the author's experience, seismometer failures are incredibly rare if deployed correctly.

Data loggers and/or communications equipment would be powered with AC power from the existing EKA infrastructure and placed in the same pit as the current hardware. Whilst the sensor procurement packages include full replacement of data and communications hardware, it makes sense to leverage the existing EKA assets where possible. If redundant, nearing the end of their functional life, or where operational and/or performance gains will be provided, data and communications assets will be replaced as part of this scope of works.

Figure 19 shows the indicative setup for the borehole sensor/station. Again, there are many options on how best to complete the design and installation of the new element to the array, so a full design plan would be presented to and agreed with the Stakeholders, to move forward with the installation of the new borehole sensors. The final design goal would be to keep things simple and compact, and to have minimal construction impact on the array. The basic design shown in Figure 21 meets the CTBTO/IMS specifications.

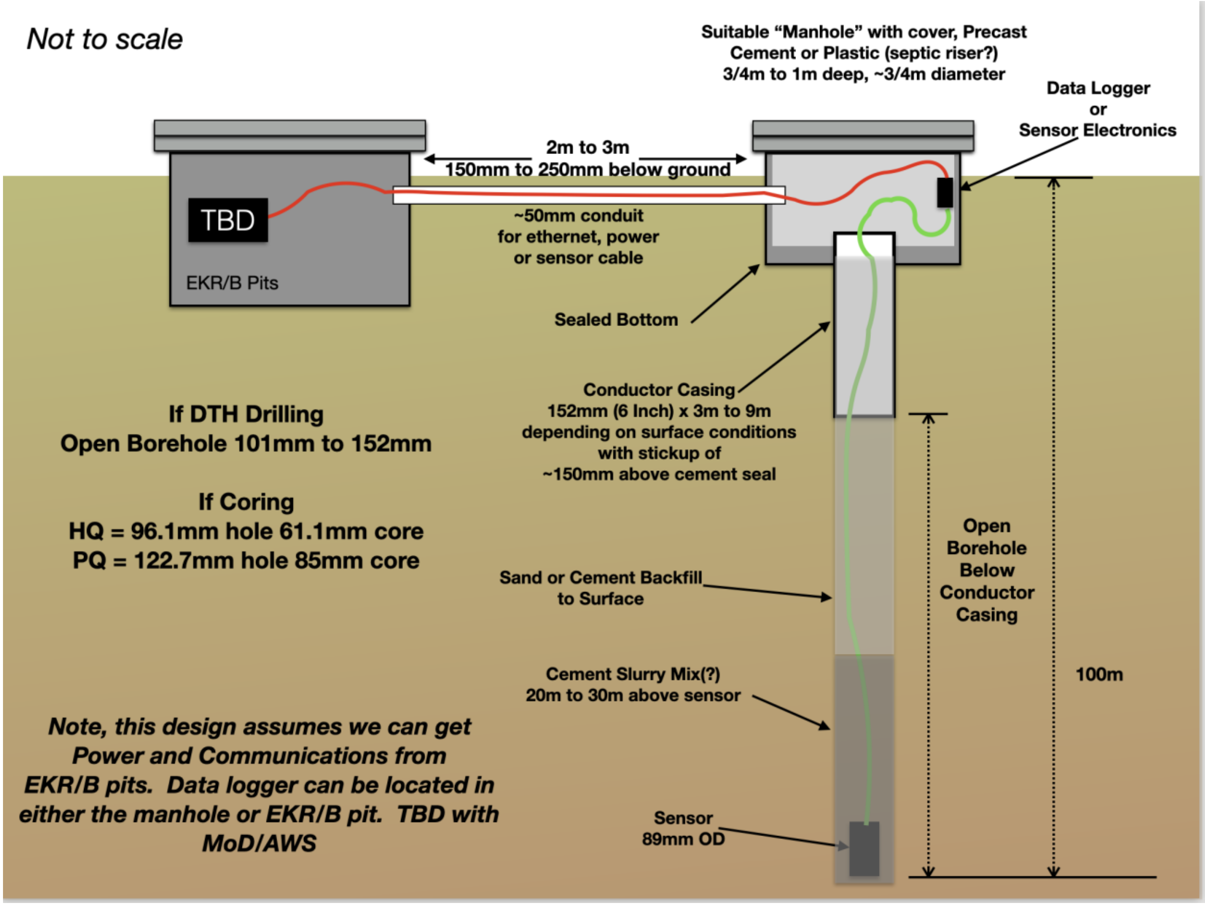

Figure 19, HMSC's proposed borehole design.

Schedule and Timing

Once we have final confirmation from the Stakeholders to proceed, we should be able to move relatively rapidly.

There are short period lead times on the instrumentation and cabling that can take a few months to acquire. Drilling plans would need to be submitted with a final design and access after each site has been visited and access for drilling confirmed. Given the location and conditions at many of the sites, access roads/trails may need to be established. However, there are track mounted drill rigs that can be deployed to reduce the time needed, or negate the need, to construct access tracks.

A basic outline timeline may look something like, Table 3:

Week	Task
1-2	Drilling quotation acquired from various drillers
1-2	Quotation acquired from sensor manufactures (GSL and Gaiacode at a minimum)
1-4	Design plans submitted and agreed upon with Stakeholders
3-4	Review of Drilling Quotation

Week	Task
3-4	Review and Sensor Quotation
End Week 4	Award Drilling and Sensor Contract
5	Site visit with driller
5-7	Driller provide access plan
5-8	Driller acquiring necessary supplies
End Week 8	Driller mobilize several teams to site
Start Week 9	Commencement of drilling operations
9-20	Drilling of borehole and surface site completion, 1 week per location estimated if open hole drilling
10-13	Pits setup for installation of new hardware, power and communications, configured and tested.
10-13	Sensor, Data Loggers and Communications Hardware Arrives
13-21	Install sensor into borehole and connect to power and communications. This is to be done such that we will follow along with the drillers after they have a few boreholes completed.
22-23	Complete installation and commissioning in sensors
22-28	Data review
28	Submit all metadata to MoD/AWE
29-30	Submit installation report to Stakeholders. Report to have section on each station installed with documentation to include drilling reports, sensor and data logger parameters, communications topology, noise study for each site compared to the surface sensor at the pit, other to be determined.

Table 3, basic timeline for construction and upgrading/enhancement of the EKA array elements.

The above timetable is an approximation and will be dependent on approval dates from MoD/AWE and various Stakeholders. However, the quotation by The Natural Power Consultants Limited notes 4 weeks lead time for mobilization to site, and the Guralp Systems Limited seismometer proposal specifies a 120 day delivery date, so this programme is considered reasonably accurate.

For drilling of the borehole, assuming a proper coring rig and open hole, where we will run smaller diameter core bits and have no need to set casing, each location should be complete within 1 week. This is the most time-consuming drilling technique and so the timeline is considered conservative.

Conclusions

In this report we have briefly discussed the construction of the test borehole installation, shown results from sensor deployment and the reduction in noise when compared to the surface stations.

We show in this report examples of anthropogenic noise that affects the entire Array and is not associated with operations at nearby wind farms. We show that the noise associated with local logging efforts causes very high levels of noise, up to 25dB, at several discrete frequencies across the entire EKA array. This noise, while periodical, will continue far into the future as logging efforts continue. It is also my understanding that that there are no restrictions to induced noise levels for logging operations, or other cultural activities, in the area, only wind farms. We have clearly shown that these operations are producing high levels of noise in AWE's area of interest.

We have shown that the test borehole, with the Gaiacode ALPHA sensor, is very capable of recording background noise well below the Peterson NLNM and reducing surface noise to a level that mitigates surface noise from any potential wind turbines such that EKA would not be impacted by such development.

We have thereafter set out the policy background for designing, implementing and verifying such a change. This has included the relevant specifications for upgraded installations as set out in the IMS Manual, and how they should be completed within the framework of the IMS. That has included all necessary data, communications and reporting requirements.

Based on the requirements set out by the CTBTO in the CTBT 2024 Report, we have proceeded to design an upgrade to EKA which both complies with all technical requirements set out in the IMS Manual and is designed to provide the maximum performance benefit to the MoD and AWE. This comprises a minimum of 10 additional borehole installations of between 30m and 100m, each within a 2.5^0 vertical tolerance (though, as noted above, this may be relaxed due to new manufacturers specification), and containing a new 3-component or 1-component borehole seismometer. To ensure the best possible array performance, the boreholes sensors are to be cemented in place, in line with suggestions set out in the CTBT 2024 Report. Subject to dialogue with the MoD and depending on its appetite to seize upon this opportunity of receiving an upgrade to the array which will be funded by Industry, it would be possible to expand the upgrade to the remaining 10 sensor locations, which are proposed to be drilled to 30m to 80m and contain a vertical-component sensor in line with the CTBTO requirement.

Design compliant proposals have been secured from a well regarded Scottish drilling contractor, and two British seismometer manufactures; firstly from the test seismometer manufacturer, and secondly from the current EKA sensor manufacturer. The practical procedure for completion has been specified, and a high level programme for completion identified.

It is clear that sensors installed at depths of between 30-100m will afford long term attenuation from multiple anthropogenic noise sources and will enhance the performance of the EKA array. Forestry operations, not only wind noise but harvesting, logging and transportation are already creating harmful background noise and can clearly be seen in the data. Agricultural, traffic and general anthropogenic noise will only increase over time and, similarly to forestry operations, cannot be curtailed. By augmenting the existing array now with the addition of the new sensors installed in boreholes will future proof the array for the benefit of MoD, CTBTO and BGS.

When considering the implementation of the upgrade to the array and future development of wind farms in the vicinity of the array, it is the Author's opinion that the given the average reduction in surface noise that will be gained from the upgrade being 15dB, this would indicate that the borehole sensors will be capable of detecting and analyzing signals of approximately ~18.25% the amplitude of the surface sensors. If we apply this performance improvement to the MoD's wind farm noise budget it would mean that by using the borehole sensors, the noise floor could be raised from 0.336nm of ground displacement at the surface to 1.792nm as the borehole sensors would still be below the 0.336nm limit. This is well above the budget forecast calculated by the MoD's current wind farm assessment tool of 0.502472nm for Scoop Hill, which can therefore be accommodated through this mitigation method. It is also the Authors opinion that the allocation of noise budget, if that is still considered necessary by the MoD following the upgrade, could start from 0 given the reduction in surface noise is a reduction against the surface noise as it currently stands today, which includes all installed and operational wind farms within a 50km radius of EKA which have already been accommodated and do not need to be mitigated. This is further supported by the findings of the RSK Report which notes that there has been measurable increase in noise at the array since 2014. It is the Authors opinion that the increase in noise budget provides so much headroom for further development of renewable energy that this is an enduring solution and no noise budget will be needed in the future once the array has been upgraded as per the proposal set out herein.

References

Rossi, C., F. Grigoli, P. Gasperini, S. Gandolfi, C. Cocorullo, T. Gukov, and P. Macini (2023). Seismic Noise Reduction as a Function of Depth Recorded by a Vertical Array Installed in a 285-m-Deep Borehole at a Gas Storage Field in Northern Italy, Seismol. Res. Lett. 94, 1925–1935, doi: 10.1785/0220220337.

Charles R. Hutt, Adam T. Ringler, and Lind S. Gee, Broadband Seismic Noise Attenuation versus Depth at the Albuquerque Seismological Laboratory, Bulletin of the Seismological Society of America, Vol. 107, No. 3, pp. 1402–1412, June 2017, doi: 10.1785/0120160187

CTBTO, Twenty-five Years Progress of the Comprehensive Nuclear-Test-Ban Treaty Verification System, https://www.ctbto.org/sites/default/files/2024-07/20240618-CTBTO 25th Anniversary booklet Final LRes.pdf

Jon R. Peterson, Observation and modelling of seismic background noise, USGS Open-File Report 93-322, https://doi.org/10.3133/ofr93322

IRIS GSN Program Management, UCSD Project IDA, USGS Albuquerque Seismological Laboratory, Global Seismographic Network Review, February 2015, https://www.earthscope.org/app/uploads/2024/11/GSN_Review_2015.pdf

ANNEXES

Annex A, Natural Power Consultants Limited Drilling Proposal

Annex B, Gaiacode Limited Hardware Quotation

Annex C, Güralp Systems Limited Hardware Quotation

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