

PEER REVIEW OF REPORTS PRODUCED BY HMSC INC, DR FABIAN LIMBERGER AND PROF. GEORG RUMPKER

Vienna Austria, November 28, 2025

The review is prepared by Dr. Yury Starovoyt (Shererstrasse 38-42/5, 1210 Vienna, Austria) based on the letter of instruction from CWP Energy Limited (Godscroft Lane, Frodsham Cheshire, WA6 6XU Tel:01928 734544 Co. Registration no. SC803977), dated 12 November 2025, to prepare a peer review of the above noted Reports.

I was tasked to provide a short note upon the technical review of three documents enclosed:

1. Report by Dr Fabian Limberger dated September 2025.
2. Final Technical Report by HMSC Inc dated May 2025.
3. Correspondence from HMSC Inc dated 13 August 2025.

It is my understanding that the future development of Wind Turbines (WT) near auxiliary seismic array-station AS104 in Eskdalemuir (Scotland) has faced approval difficulties and objection from the MoD because they consider WTs may degrade seismic signals detection capability, by introducing an undesirable elevation of the seismic background noise in the frequency band 2-8Hz. Therefore, a strategic plan to retain the historically known, high quality operation of AS104 by proceeding with borehole installation has been proposed and is the subject of consultation between stakeholders.

My note is divided into several sub-sections titled in bold in the text below. These sub-sections are aimed not only to express my technical opinion about utilization of the borehole technology for AS104. Also, I was trying to provide relevant comments about implementation of this plan within the context of CTBTO technical rules and regulations.

1. Report by Drs. Fabian Limberger and Georg Rumpker

The report by Drs. Limberger and Rumpker shows that even without WTs, the noise at the array element (EKB1 p.8) already has variations between day and night of about 8dB, almost equally spread in the passband from 2-8Hz. The conclusion in the 2005 report (p.90) recommended a 10km buffer zone (Fig.67) around the array centre.

In a recent (Limberger et al, 2023) and in the submitted report, a study was conducted on the attenuation of the seismic noise induced by wind turbines as a function of distance to an operating wind farm, taking also into consideration the wind speed in the area. To this end, they deployed ten seismic sensors on a line, with sensor spacing of approximately one kilometre. The results in their report show that seismic energy induced by the vibration of the wind farm, shows a drastic reduction as a function of distance. At approximately 4 km from the wind farm the reduction in noise is almost two orders of magnitude smaller than that observed in the instrument located near the wind farm. The results of this study show that at distances of over 5 km, the effect of the noise induced by the wind farm is no longer observed.

Thus, any wind farm operating at a distance over 5 km will not affect the operation nor the detection capacity of EKA.

2. Seismic noise reduction with depth in boreholes.

Two technical reports from HMSC provide sufficient evidence on the reduction of seismic noise as a function of depth. The measurement of seismic noise in the borehole demonstrated an additional attenuation factor up to 10-12dB (Fig. 1 in HMSC report) even during calm days. The reason is that the main contributor to seismic noise is the vertical component of seismic surface waves, which rapidly attenuate with depth, vertical components of seismic surface waves are the main contributor to the noise field.

The HMSC report also shows that, besides WT, the seismic noise pattern at AS104 is currently contaminated by daily forestry activities and surrounding vegetation containing harmonic and random components.

In 2005, a similar report [Styles et al, 2005] was presented with the purpose to only investigate attenuation of WT signals. The current measurements were carried out in different conditions, as the overall pattern of the seismic background has changed with the additional contribution of the man-made activities (forestry logging etc) and grown vegetation. Such situation reflects the known and often inevitable data quality (signal detection) degradation tendency for seismic facilities located in densely populated areas, with growing infrastructure sustained by green technology challenges.

The new studies supplement the WT noise attenuation estimates with measurements in depth up to 195 m providing a solid conclusion that borehole installation will assure considerable suppression of

the surface sources in the frequency range 2-8Hz. Ultimately, the minimum background noise displacement 0.336 nm *rms* (root mean square) threshold, estimated in 2005, must be reconsidered nowadays accounting the last 20 years of infrastructure and vegetation growth around AS104. It should be noted that in the official technical specifications, a minimum value of background noise displacement is not required.

It should be noted, however, that as shown in HMSC report, the noise decrease factor is not uniform having maximum suppression around 3-6Hz and often less prominent at higher frequencies especially in calm days. Such fact could reflect the known difficulties of the temporary (not settled) borehole installation, related to the coupling of the borehole casing with surrounding rock, possible water leakage and the influence of the digitizer quantizing noise floor. Such things evidence that the noise decrease factors could have been even underestimated at high frequencies and could be improved in permanent installation.

3. How to account for the free surface effect (FSE)?

The results observed of seismic noise decreasing with distance and depth of the borehole may sound as sufficient justification for enhancement of AS104 operational quality, provided that the nearest turbine should not be closer than 5 km to the array nearest element. However, the discussion reflected in Letter2RodWood exhibits the concern of AWE, that signal distortion (in the terminology used by AWE) of the borehole relative to the surface sensor caused by the FSE. This effect is well known in seismology as body wave decrease amplitude with depth. This has been observed at several stations with simultaneous borehole and surface observations [Bowers and Selby, 2024; Shearer and Orcutt, 1987]. Such phenomenon therefore creates the danger of the potential decrease of the signal-to-noise ratio (SNR), if the signal amplitude decrease factor is balanced by an adequate decrease of seismic noise in the borehole. The extra complexity comes from the fact that the degree of deterioration is not constant but frequency dependent value.

The term distortion applied in the documentation is misleading. Distortion usually reflects the influence of non-linearity that is not a subject of this evaluation. Amplitude decrease reflects a scaling change of signal amplitude components as a spectral ratio between surface and at depth observations taken at the same moment of time. In my opinion a borehole depth in the range of 50-80m, may deliver more favourable results in the passband of interest.

4. Teleseismic versus regional array

IMS array-stations are divided in two main categories: regional and teleseismic. The main difference between them is the array aperture or the distance between the most remote elements. For AS104 the aperture is about 10-11 km. which brings it to the category of teleseismic array. Regional arrays in IMS have smaller apertures of about 3km. From a data processing standpoint, teleseismic arrays are tuned to locate remote events located at epicentral distances greater than 3,000 km. Regional arrays, which account for the larger fraction in the IMS, are utilized for the characterization of closer events. Several specific methods like f-k (frequency-wavenumber) and beamforming are utilized for data processing from both array types. It allows optimizing signal detection and location quality by simultaneous processing of signals recorded at all array elements. The type of array defines appropriate frequency range of seismic signals used for processing.

The reviewed materials reflect some debates about the frequency range from 2-8Hz, which AWE mentions as the band of interest. However, this frequency range is more relevant for regional arrays rather than for teleseismic. The beamforming technique utilizes both, the correlation of seismic signals between array elements and the decorrelation of seismic noise to achieve the known \sqrt{N} noise decrease factor, where N is the number of elements. Based on the vast amount of IMS observations, the band from 4-8Hz of the signal is barely correlated between array elements at inter-sensor distances of ~1km, along the aperture of ~10 km relevant for AS104. The other point is that the inter-sensor distance of ~1km at AS104 is too big to be consistent with the minimum wavelength of seismic waves expected for high frequencies around 8Hz. The lower frequencies of interest to this type of array would be less sensitive to the FSE.

5. EKA in the context of CTBTO

AS104 in Eskdalemuir is an auxiliary (AS) array-station of the International Monitoring System (IMS). In total, the IMS operates over 30 arrays located worldwide and combined in primary and auxiliary networks, making the IMS verification system a unique worldwide monitoring tool. It should be noted that verification monitoring work is an integral triple task aimed to detect, locate and screen out explosion-type events from the natural seismicity. In accordance with the Treaty mandate auxiliary stations are contributing only to location and screening tasks based on the segmented data, whereas primary stations deliver 24/7 continuous data stream to the main CTBTO office in Vienna.

The screening of explosions and natural seismic events is technically challenging and based on several approved algorithms including the ratio of body wave magnitude (m_b) to the surface wave magnitude (M_s). An additional benefit of potential borehole installations is that it will also reduce the low frequency seismic noise generated by air pressure fluctuations, especially during windy days [Hutt et al, 2017; Sorrells, 1971]. This supports the argument for improving AS104 with borehole instrumentation and, therefore, contributing to a better estimate of M_s , as one of the main contributors to event screening criteria in CTBTO. The installation of broadband (BB) seismometers in boreholes is a well-established technique utilized in the GSN (Global Seismic Network) stations to improve the signal to noise ratio.

The IMS is responsible to monitor and coordinate any equipment or configuration change at any IMS stations, proposed by the station operator (SO). The configuration change process is well explained in HMSC report. In case of the need for station modification, the SO will submit the technical justification for the change (deterioration of the detection capability, for example) and technical description of the new equipment components including proof of the continued compliance with the IMS minimum requirements specified in the IMS Operational Manual (OM) as presented in the HMSC report in p.19.

6. Conclusions

1. The addition of borehole instrumentation to EKA is the most feasible and technically robust path for the array to protect itself against undesirable seismic ground noise caused by man-made and endogenic sources like forestry logging, growing vegetation and wind turbulence.

2. The report by Limberger and Rümker shows that beyond a distance of ~5 km from the nearest WT, the ground seismic noise induced by the WF is not observable. Thus, wind farms should not be installed closer than 5km to the nearest array element. Such conclusion is based on the investigation of the attenuation and depth decrease property of seismic background noise carried out by deployment of the surface profile and borehole seismic sensors.

3. The impact of the free surface effect affecting the SNR improvement for seismic signals should be minimized by selecting borehole depths that maximise the noise reduction but minimise free surface effects on the body waves in the appropriate passband of interest. Borehole depths of between 50 to 80m will achieve this balance.

4. Borehole installations will be potentially beneficial not only for body waves but for the enhancement of the surface waves detection and characterization capability in the low

frequency part of the required IMS passband. This may positively contribute to event screening capabilities of EKA array in context of CTBTO needs.

The proposed upgrade plan for EKA would be mostly compliant with CTBTO hardware and operational requirements.

7. References

1. Bowers, D., and N. Selby. 2024. Some thoughts on borehole seismometers in the IMS. ECS WGB-63 WEG-9, 2 Sep. CTBTO Vienna.
2. Shearer, P.M., and Orcutt, J.A. 1987. Surface and near-surface effects on seismic waves –theory and borehole seismometer results. Bull. Seismol. Soc. Amer., 77, 1168-1196. <https://doi.org/10.1785/BSSA0770041168>
3. Styles, P., I. Stimpson, S. Toon, R. England and M. Wright. 2005. Microseismic and infrasound monitoring of low frequency noise and vibrations from windfarms. Recommendation on the siting of windfarms in the vicinity of Eskdalemuir, Scotland. Keele University Staffs ST5 5BG, 18 July.
4. Hutt, C. et al. 2017. Broadband seismic noise attenuation versus depth at the Albuquerque seismological laboratory, Bull. Seismol. Soc. Amer., 107, 1402-1412. doi: 10.1785/0120160187
5. Sorrells, G. G. 1971. A preliminary investigation into the relationship between long-period seismic noise and local fluctuations in the atmospheric pressure field, Geophys. J. Roy. Astron. Soc. 26, 71–82.
6. Limberger et al. 2023. The impact of seismic noise produced by wind turbines on seismic borehole measurements, Solid Earth, 14, 859-869. <https://doi.org/10.5194/se-14-859-2023>.

Dr. Yury Starovoyt



Vienna, 28 November 2025

CV

The reviewer has background in physics with a university degree and PhD in Geophysics (Seismology) since 1987. I have more than 35 years working experience in experimental seismology both in research and applied activities related to design, installation, and quality control of seismic instrumentation and data in the framework of different seismological projects. In 1998 I was employed by the Comprehensive Nuclear Test-ban Treaty Organization in Vienna as seismic officer and then promoted to the position of seismic manager. Within my duties and responsibilities, I was involved in the technical and administrative tasks related to establishment of the worldwide verification regime by commissioning of the primary and auxiliary stations designated in the Treaty. With my participation as the team leader or member more than 70 IMS seismic stations have been completed, certified and/or upgraded.