Rebuttal Letter for Passive Assessment of Geophysical Instruments Performance using Electrical Network Frequency Analysis

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1 Introduction

We thank the editor and reviewers for their recommendations. The suggestions greatly helped improve the clarity of the description of the method and presentation of the results, particularly figures 4, 5, and 6. We think the manuscript has becomes a lot more convincing at demonstrating the capabilities of the technique. Below we address the comments made by the reviewers point by point:

2 Response to Reviewer B

Reviewer Question: *Using varying electrical network frequency is a clever approach. In most cases, especially within arrays of sensors, timing and orientation oddities are revealed in the geophysical data themselves. In some cases this may not be feasible and an independent method such as that described here can produce fruitful results. Could the misalignment of G680 be clear when analyzing local earthquakes?*

Response: Local earthquakes in the Groningen gas reservoir are at an assumed fixed 3 kilometer depth and are not well expressed on the horizontal components making this challenging. Generally only p-phase arrivals are used for event localization usually. There have been over 750 earthquakes in the past 8 years but this significant orientation anomaly of the surface accelerometer has somehow gone undetected until now. We consider the proposed method to be complimentary to other avaiable tools.

Reviewer Question: *Since the authors state that the "most accurate" way to process the data is with 150 s segments (line 161), a sentence explaining how this conclusion was obtained would be nice (beyond saying it is empirical). Were other segment lengths tested and did they produce less accurate results?*

Response: A longer segment length over-smooths the signal in time, while a shorter segment length essentially averages the signal in terms of frequency (lower number of samples used in the DFT means a lower number of output frequencies). There is always a trade-off in the spectrogram and these settings provided the most information in both domains to resolve the ENF and be able to accurately cross correlate it with measured ENF data. We have extended the sentence that explains this trade-off in isolating the ENF: *"This segment length provided the best trade-off in resolution between time and frequency to resolve the ENF from the spectrogram."*

Reviewer Question: *I do not understand figure 5. Normally we expect the cross correlation value to approach 1 for signals that are well correlated and zero for uncorrelated signals. Values approaching negative 1 indicate two signals are well correlated but have opposite signs. The text leading up to figure 5 does not explain how the analysis was done. I assume that the instruments analyzed did not have free-running oscillators for time, rather they were tied to GPS or another good reference. The cross correlation values are very low, especially compared to what's shown in figure 4. What did they stack? Why is there an asymmetry? Why would timestamps rarely run ahead of true time? If the time differences are caused by imperfections in oscillators keeping time in the instruments, why would their frequencies preferentially be off in one direction? I found Section 5.2.1 odd and unclear.*

Response: We agree that the results in Figure 5 (now Figure 6 after revision) are poorly presented. The goal was to quantify and show the precision and accuracy of the cross-correlation technique, including the variation in the recovered cross correlations between the estimated and measured ENF for multiple instruments. Previously, they were improperly normalised and demeaned, hence the negative and somewhat odd correlation coefficients. We have updated the figure (Fig. 1 in this file) showing the actual ensemble of cross correlations from 71 different stations (211 channels), including all recovered time delays and their respective mean and standard deviations thereof too. The presented y-axis (correlation coefficients) is now factual and correct. The updated figure shows more clearly that timing errors should be able to be recovered at the 1 s level. We have also completely rewritten section 5.2.1 that describes the statistical analysis and figure more clearly.

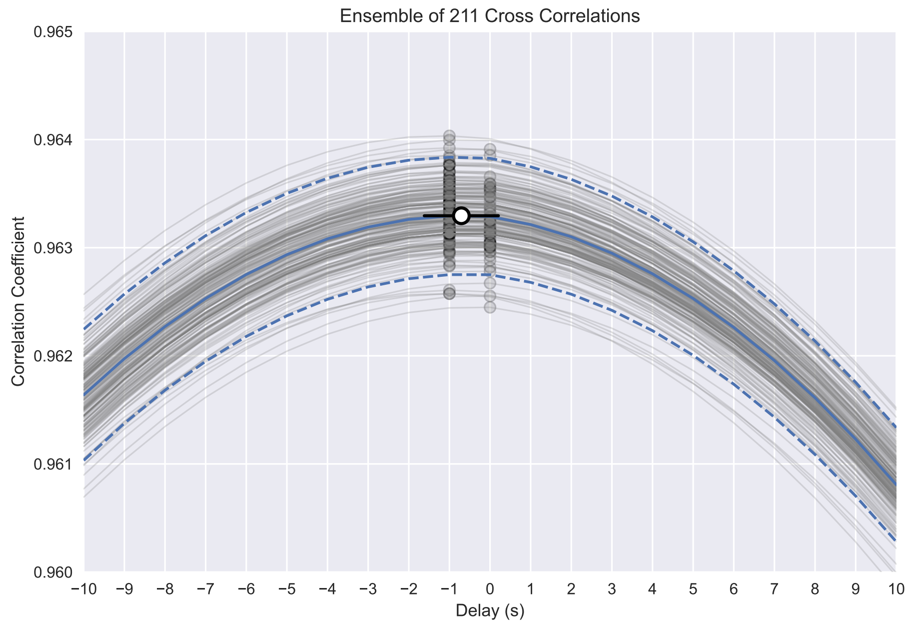


Figure 1: Average and 95 % confidence limits (blue curves) of an ensemble of 211 cross correlations with the measured ENF (grey curves) for all components of all Groningen surface accelerometer in the NSAN G-network on 2020-03-01. The accelerometer data have accurate timestamps and should resolve to a zero-time delay. The grey markers indicate the recovered peaks from the cross correlations and hence the respective delay times with the measured ENF. The black marker represents the mean time lag and 95 % confidence interval, illustrating the resolution of the method approaches 1 s.

Reviewer Question: *Another issue regards the source of the ENF reference data from the power company web site. Have the authors determined how the power company makes the measurement and how reliable it is? One test would be to independently record the mains frequency in the lab referenced to a GPS clock and compare the independent record with the downloaded data from the power company. If that is not practical at least it would behoove the authors to contact the power company and inquire about how the data are collected. Maybe the mysterious 6 s delay described in figure 6 could be illuminated.*

Response: We do not know how accurate the timestamp of the measured ENF data is. We assume it is reliable *enough* to resolve 1 s timing errors (that is verified by Figure 1 of this file). But as demonstrated in our manuscript by the figure with the teleseismic arrivals, this precision varies throughout the year, giving a significant constant 6 s delay which is indeed most likely caused by poor timestamping of the reference data. But we cannot be sure and only hypothesize this is the cause. An experiment to measure and validate the measured ENF data would be helpful, but we consider it outside of the scope of this particular manuscript. And for the experiment to be successful, you need to be lucky that the ENF timestamping is actually inaccurate too (which may not be the case). The license of the measured ENF data states: the data is determined by TransnetBW to the best of its ability and is provided without guarantee. We have sent them an inquiry about the accuracy of the timestamp but got no response yet. We feel like any information on it should be provided by TransnetBW on their own data repository and not in our manuscript. It is unfortunate that we cannot share any additional information on this matter. In any case, relative timing issues between instruments in an array or that are more widespread can still be calibrated from the ENF.

Reviewer Question: *I think some clarifications are needed in section 5.3, starting with figure 7. Exactly how does the probability density color scale relate to the three graphs? Taken at face value, the beige background uniformly in each plot would indicate a very small probability density for all directions except along a red elliptical path (beige, again, inside of it?). Then black outlined white arrows: I doubt the black line is related to the black end of the color scale bar. Perhaps the actual probability density color plots have been edited to accentuate the resolved directions. In any case, what is presented is unclear. In figure 8 a and 8 b, are the red dots the locations of potential sources?*

Response: Figure 7 shows the path of a virtual particle in three-component data bandpassed around the ENF (49.85 to 50.15 Hz). This basically illustrates the instrument E, N, Z data plotted in 3D space and then projected on 2D cross sections. The black/red elliptical path surrounded by beige indeed illustrates that the movement of this virtual particle is only highly probably in this elliptical path, showing extremely high degrees of rectilinearity. The black arrows represent the direction of principal motion (i.e. the major axis of the three-dimensional ellipse) and are unrelated to the color bar. We have modified the figure and caption to emphasize this. The arbitrary values were removed and the colors are just marked with *low* and *high* probability.

The red dots in previous figures 8a and b were medium to low voltage transformers and suspected sources of the ENF. Figure 8a and b have however been removed from the manuscript because they provided no additional information, only that the polarization is not towards these regional electrical infrastructure. The signal is demonstrated to come from much closer (i.e., the instrumental cabinet).

Reviewer Question: *The authors state that the likely source of the signal is electronics inside the cabinet; one might assume, given the sentence, "The cabinet that hosts the accelerometers and electronics.....," that the cabinet houses both the electronics and the accelerometers themselves. Is that the case? If not that should be clarified, otherwise the arguments about cabinet orientation* *can be confusing, especially the resolution of the G680 anomaly. Do the terms "instrument" and "accelerometer" in lines 284 and 286 refer to the cabinet, too? Could the authors speculate whether it is the interaction between the power supply in the cabinet and the amplifiers or recorders inside the cabinet, actual vibration of the ground caused by, say, a transformer inside the cabinet, or an EM signal transmitted between the cabinet and the accelerometers?*

Response: We have clarified that the electronics and accelerometer are maintained within the same rectangular cabinet. We have also clarified that we think it is a physical vibration of this cabinet that is causing the signal to appear in the seismometer data. The cabinet likely vibrates because electrical components are mounted on its wall and these *hum* in response of the alternating current of the ENF. This may not be true for the geophones inside the seismic boreholes which likely pick up some electromagnetic radiation.

Reviewer Question: *The authors might consider reversing the color bar for figures 8c and 8 d. The eye is drawn to the sites in 8 c marked with red circles – these are the ones to actually be ignored because of their low degree of rectilinearity.*

Response: We have indeed reversed the colorbar and scaled the markers as a function of angular misfit too (see Figure 2 in this file). This draws more attention to G680 in both the map and graph. Subfigures A and B were removed because they provided redundant information that was not used about regional electrical infrastructure.

Reviewer Question: *In the supplementary note, I'm a bit skeptical that the hum would be detectable 2 km away. Could the 7 second delay be similar to the 6 s mystery noted in figure 6?*

Response: We were a bit sceptical at first too. However, during the same timespan seismometers show zero delay with the measured ENF data and the timestamp of the infrasound station is guaranteed to be correct too. So the lag as a result of a physical travel time remains our leading hypothesis. We have spoken to colleagues with a background in infrasound and low-frequency audible sound (100 Hz) propagation, and a low-frequency hum can travel quite far under the right atmospheric conditions (wind speed and direction). This has been added to the acknowledgements. This little piece of information was shared in the supplementary material because we found it quite remarkable but not part of the manuscript.

Reviewer Question: *Line 165 should say sigma, not sigma^2 since it is preceded by "standard deviation" and given in units of Hz (not Hz^2).*

Response: This has been fixed.

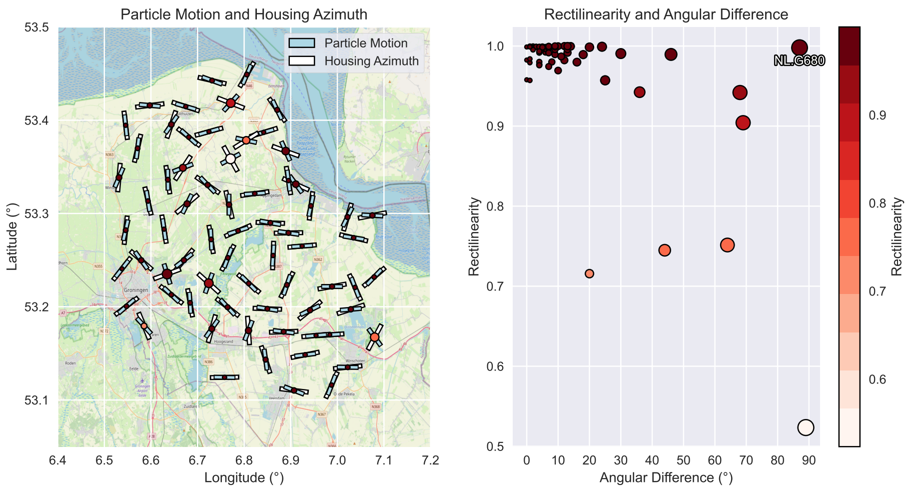


Figure 2: Left) comparison between azimuths of the principal direction of particle motion (lightblue) and the orientation of the installation cabinet (white). Right) Angular misfit between the cabinet orientation and dominant particle motion against the degree of rectilinearity. Map data are provided by OpenStreetMap contributors, 2017.

Reviewer Question: *Line 199 should be analysis*

Response: Fixed.

Reviewer Question: *Line 250: 24 what?*

Response: Accidentally dropped the units but it is hours. Fixed.

Reviewer Question: *Line 405 (and elsewhere), maybe there is a better word than "amplitude." Electrical Network Frequency amplitude seems awkward*

Response: We have replaced the word with a better description "the signal amplitude at the ENF".

3 Response to Reviewer C

Reviewer Question: *This is an interesting paper that analyzes the little-explored phenomenon of ENF noise on geophysical measurements, largely from the perspective of using that noise to diagnose data issues. For a topic I have not thought about in detail, I found it a fascinating read. I suspect that the application of the method may have limited utility in practice, especially given the* *limitations in time resolution possible and questions about the timing accuracy of ENF signal alluded to in the discussion (e.g., lines 312-314). However, the paper will motivate station and network operators to explore using the information in ENF noise to complement existing data QC tools. It may also motivate interested scientists to improve our understanding of how this noise couples into instruments. It motivated me to read about how this signal is used in audio forensics!*

Response: We agree that currently the method may have limited applicability but it is another tool in the toolbox. Furthermore, as far as we know, this is the first paper that investigates the utility (and does not consider it noise!) of the ENF in geophysical data. There are many more avenues for exploration and we may discover some other useful properties (e.g., the amplitude of the ENF signal) that may be leveraged too.

Reviewer Question: *The key information for the interested reader on how to extract the ENF signal from data is contained in Lines 156-171. I wish there was a companion figure that complemented the discussion and illustrated the effect of each processing step. For instance, it could show the spectrogram before and after application of the Gaussian filter. I also would prefer to see a spectrogram after filtering without the blue line through the middle tracing out the peak. In the current figures it is not possible to discern the dB delta of the peak.*

Response: We agree and have modified the figure to clearly show the reference measured ENF (A), raw spectrogram (B), the filtered spectrogram (C), and the spectrogram with the resolved ENF projected on top (D). See Figure 3 in this file. The cross correlation image has been removed from this figure and now belongs to a separate figure (Figure 4 in this file).

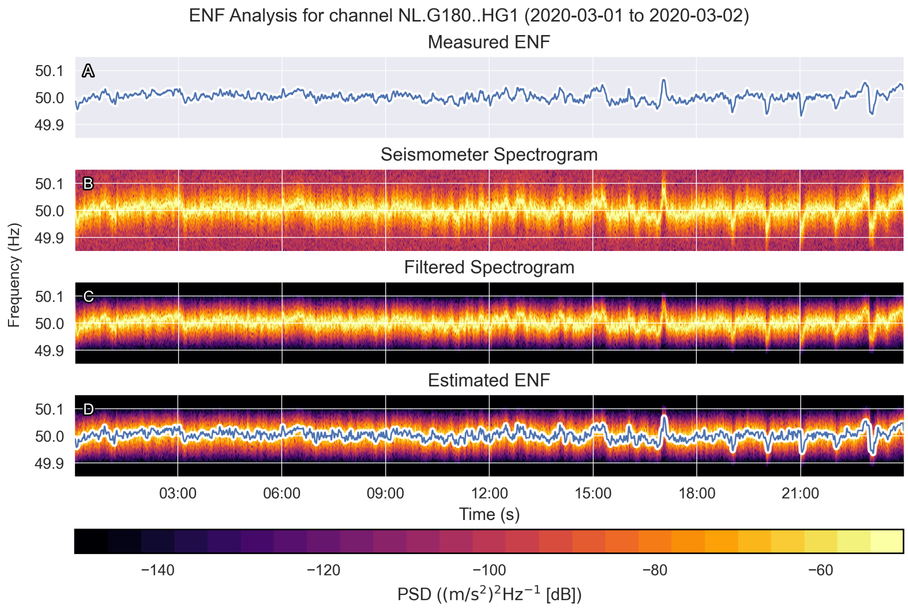


Figure 3: A) The reference ENF provided by TransnetBW GmbH. B) Accelertion spectrogram of EpiSensor NL.G180..HG1 (Groningen, the Netherlands) on 2020-03-01. C) Filtered spectrogram using the Gaussian filter. D) The estimated ENF from the filtered spectrogram.

Reviewer Question: *In Figure 4, the value cross-correlation is almost 1 (I thus assume this is normalized). However, in Figure 5 it appears that most values of the normalized cross-correlation are much lower, yet still provide reasonable estimates of time delay. This made me wish there were a few more representative examples that illustrate graphically the estimated and measured ENF at more typical cross-correlation values.*

Response: Figure 5 was poorly made and clearly led to confusion and we have improved it showing the ensemble of 211 cross correlations from all components of the surface accelerometer network on a given day (with the proper correlation coefficients). See response to reviewer B and figure 1 of this file. Most of them resolve very similarly, while only a handful have poor data quality from which the ENF cannot be resolved. We think this is a more satisfying and clear way of presenting the results.

Out of interest in this rebuttal letter we have attached the cross correlation from a very poorly resolved ENF (due to elevated background noise) in Figure 5 of this file at the bottom, that still managed to find a more-or-less appropriate time lag but with a much lower correlation. Most accelerometers show strong correction coefficients above 0.96.

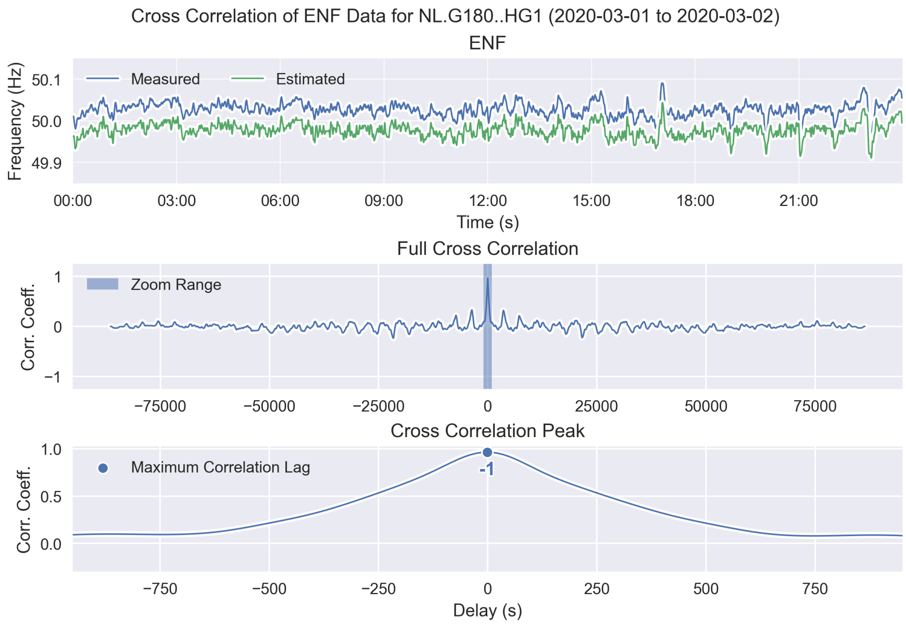
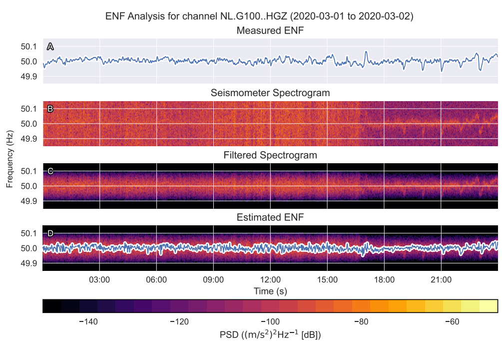


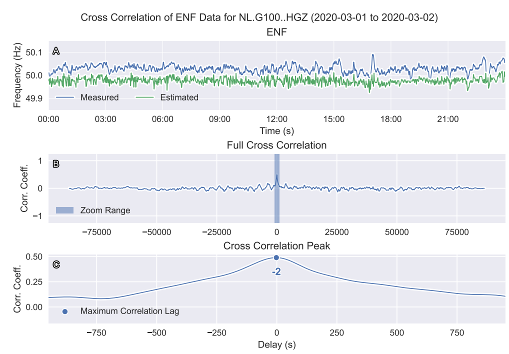
Figure 4: A) Comparison between the reference ENF (blue) provided by TransnetBW GmbH and the estimated ENF (green). The data have been offset from the mean of 50 Hz for illustrative purposes to show their similarity. B) The full cross correlation between the estimated and reference ENF. C) Zoom in on the blue span around the correlation maximum (0.96) with the recovered peak and hence time delay indicated (-1 s).

Reviewer Question: *In Figure 8 there are red dots in the map. What do these dots represent?*

Response: We forgot to add labels and the red dots were high-to-medium and medium-to-low voltage transformers. We assumed they were a likely candidate for the source of the ENF, and hence the polarization analysis could point towards them. The source however, turned out to be more local (on-site), and these maps have been removed because they were only used to show that regional sources do not introduce the ENF which is redundant information. The figure has now become Figure 2 in this file (see response to reviewer B).



(a) Spectrogram



(b) Cross Correlation

Figure 5: Poorly resolved ENF from spectrogram and cross correlation.