Laine, Unto K.

Sound producing mechanism in temperature inversion layer and its sensitivity to geomagnetic activity

Published in:
EUROREGIA BNAM 2022 Conference Proceedings

Published: 01/01/2022

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Laine, U. K. (2022). Sound producing mechanism in temperature inversion layer and its sensitivity to geomagnetic activity. In *EUROREGIA BNAM 2022 Conference Proceedings* (pp. 365-374). (BNAM). Nordic Acoustic Association (NAA). https://bnam2022.org/wp-content/uploads/2022/05/ERBNAM2022_Proceedings.pdf

EUROREGIO
BNAM2022
Joint Acoustics Conference
9th-11th of May, Aalborg, Denmark

Sound producing mechanism in temperature inversion layer and its sensitivity to geomagnetic activity

Unto K. Laine[1,*]

[1]Department of Signal Processing and Acoustics, Aalto University, Espoo, Finland.

* unto.k.laine@aalto.fi

Abstract

Sounds associated with aurora borealis, so called Auroral Sounds (AS), are explained by electrical discharges occurring in Temperature Inversion Layer (TIL) approximately 75 meters above the ground [1]. It is assumed that under favorable weather conditions the number of AS events depends on the activity of the geomagnetic (GM) storm. The historical testimonies of AS indicate that the GM storm should be strong enough to rise the bright and lively auroras to the zenith before these sounds can be observed. The goal of this study is to test the relevancy of this claim by studying the sensitivity of the AS producing mechanism under a moderate GM activity. A four-hour long period of the sound measurements done around the local magnetic midnight Jan 25–26, 2022 at Fiskars village, Finland, is analyzed. Sixty AS event candidates were manually selected and their temporal distribution and period histogram constructed for statistical comparisons with the GM data measured simultaneously by the Finnish Meteorological Institute (FMI) at Nurmijärvi Geophysical Observatory (NGO). The data was also used for regression models to study possible causal relationship between the GM activity and the AS events. A strong causality between the GM activity and the AS events was found. The sounds were predicted by the GM activity with 90% accuracy after a delay of 21 min. The results show that the AS events are much more common than previously thought.

Keywords: aurora borealis, solar wind, magnetosphere, auroral sounds, geomagnetism, temperature inversion layer, regression models, period histogram.

1 Introduction

Based on the present knowledge, Auroral Sounds (AS) have physically existed around auroral zones as long as the Earth has had an atmosphere and magnetosphere similar to the present ones. Thus, the problem of AS is not just *a millennial problem*, as often referred to, but has probably surprised many species before the humans. The question of the first descriptions of aurora borealis and also of the sounds associated, have been discussed a long time. Based on earlier studies [2,3], it is probable that one of the first documented observations was made by prophet Ezekiel around 593 BCE. For some reason the earlier studies of this event are limited entirely to the *visual* part of Ezekiel's observations falling silent in front of his *sound* perceptions. Ezekiel not only described the visual art of auroras, which he called angels, but continued with the sounds. He tells, that he heard "*the roar of rushing waters*".

When the Auroral Acoustics project [1] started and the author made one of his first AS observations, a TV-reporter asked for a description of the sounds. The answer was: "*they sounded like Niagara Falls from a distance of one kilometre*". Afterwards, when the author became familiar with the text of Ezekiel, the similarity of the descriptions surprised. The recent AS observations include descriptions, where a strange sound from the sky woke up the attention and after looking to the direction of the sound source an aurora was observed. The sound focused the mind to search its reason from the direction it was perceived, on the open sky. In Same culture we find opinions that an aurora without a sound is not a real aurora. A 'real aurora' should be bright, colourful, lively with changing structures. Exactly these features are often mentioned as conditions for auroral audibility.

Until around 1930's some authors still believed that under special conditions auroras may come down below the altitude of the clouds and therefore they could be audible [4]. Even after the hundreds of altitude measurements made by Norwegian *Carl Størmer* [5], who first time showed that only in extremely rare cases the lowest edge of the auroral curtain may be a little below 80 kilometres, some authors kept asking, could they still sometimes come much closer to the ground and be therefore audible. Because the *acoustics* is not in the focus of geophysics, the *location of the sound source* was never studied or revealed.

At the end of the 18th century, the question of whether electricity could explain the auroras garnered increasing attention. The earliest texts proposing that the AS events are caused by electric discharges are probably from the years 1831 and 1834 [6,7]. Sometimes AS were even used as a proof for the electric nature of the aurora. In the 1920's *C. A. Chant*, editor of *The Journal* (JRASC) interested about this problem and asked the readers to send their sound observations to the editorial [8,9]. Professor *William C. Baker*, from Queen's University, Kingston, sent a letter to Chant where he described an AS event which occurred in mid-winter in 1884 or 1885. Baker's story was exact and rich in ideas. He described the sounds as *"the crumpling of stiff paper"*. He assumed that the sounds are produced by *the same electro-magnetic* (EM) source that also controls the visible aurora and describes the sound; "*It reminds of the noise heard when discharging the glass jar*", referring to a capacitor known as *Layden jar*. Baker summarizes that because the delay between the auroral movements and the sounds was small (1–2 s), the sound source must be closer to the observer than the light source. It is obvious that Chant learned much of these accurate observations and embraced Baker's brilliant ideas. However, the problem of *where such capacitor is and how it is charged*, remained unresolved almost one hundred years during which, with a few exceptions [10], more speculation was produced than genuine research to solve this problem.

However, the electric fields caused by the GM activity are never large enough to produce *directly* discharges and sounds in the lower atmosphere. Tree tops are quiet. The present Inversion Layer Hypothesis (ILH) provides a physical explanation for the sound production [1]. It assumes that after a calm and sunny day the warm air at the ground rises carrying negative ions up forming a Temperature Inversion Layer (TIL) about 70-100 metres from the ground. Above this layer positive ions are 'raining' down from the upper atmosphere accumulating in the layer above the warm air. Because vertical movement of the air is minimal at the inversion, these two layers continue to accumulate charges forming finally a structure like a large plate capacitor. The activation of a GM storm generates the needed additional potential between the layers and triggers the discharges. It should be noted that *the energy for the sounds* is loaded to the capacitor during the evening and night, meanwhile the GM activity works just as an *activator* for the discharges.

The main goal of this paper is to study the sensitivity of the sound production mechanism of the inversion layer under *moderate* GM activity. The statistical connections between the magnetic field measurements made by the FMI and the recorded AS events are studied. Four different methods to reveal these connections are introduced. They all provide similar results showing *a causal relationship* between the magnetic field fluctuations and the sounds. Surprisingly many periodic events known in the field of geomagnetism have left their fingerprints to the sound sequence. The new findings support the presented ILH.

Next chapter starts with a description of the measuring system, the weather, and the GM conditions during the night of measurements. Then the selection of sixty AS events is described with examples of their temporal and spectral properties. Chapter 3 describes the four approaches to show the causal and statistical connections between the magnetic field measurements made by FMI and the recorded AS events. The paper ends with a conclusion that summarises not only the new results, but the whole Auroral Acoustics project.

2 Sounds and magnetic field measurements Jan 25–26, 2022

The same measuring system as described in [1] was used in this recording, too. Its 'soul' is the high–quality measuring microphone of Brüel & Kjær (4179 with preamp 2660) that was mounted at the focus of a parabolic dish antenna directed vertically to the sky. The internal noise of this microphone is around -3 dBA and it is carefully shielded against all EM-interferences. Additionally, two other microphones and a VLF loop antenna were connected to a four–channel digital recorder thus allowing the sound source localization.

2.1 The weather and geomagnetic conditions

A moderate GM activation occurred on Jan 25–26, 2022. The Kyoto Dst index [11], shown in Figure 1, stayed at -35 during the hours 19–20 LT. The intensity of the GM activation degreased during the period of data collection. The local magnetic field activity, measured at NGO (60° 30.5' N, 24° 39.3' E), was moderate, too. The FMI has estimated that the GM activity meter should rise over 0.3 nT/s before the probability of auroras in the southern Finland is high. The highest measured activity was only 0.14 (see Figure 5 chart in blue) indicating that during the night in question aurora was probably not visible in the southmost Finland.

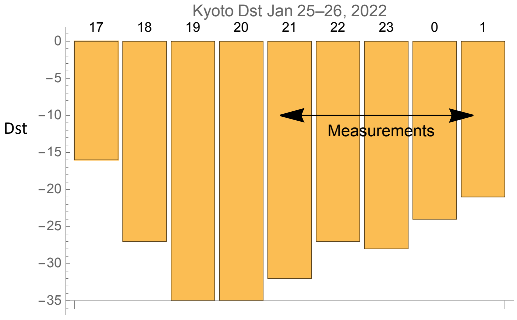

Figure 1. Kyoto Dst in the night Jan 25–26 2022. The arrow shows the time window of The data collection for this work (21:20–01:20 LT).

The quasi-K-index calculated for the three last hours before the local midnight gives K=4 and for the next three hours after the midnight K=3 (in decimals: 4.6 and 3.7). The probabilities of these occurrences at Nurmijärvi are correspondingly: 8.1% and 19.3% [12]. However, still the developed automatic analysis of the recorded audio material was able to find around two hundred AS candidates and a careful manual selection (carried out before the automatic analysis) sixty cases in the 4 h time window. This means that *the sound production in the TIL is much more common than ever imagined*. Under favourable weather conditions, TIL is sensitive to even relatively small geomagnetic disturbances as will be seen. The probability for similar geomagnetic activities is over 25% in south Finland, however, the build–up of a strong TIL is not equally common and both of them are needed for the sound production.

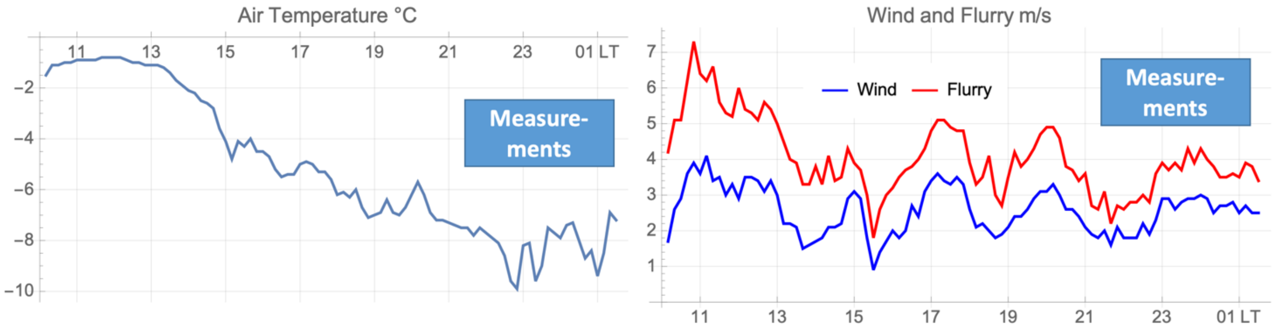

Figure 2. Wind and temperature conditions at Jokioinen Jan 25–26, 2022. Blue boxes indicate the time window of the measurements used in this study. Data from the FMI.

The closest fully armed FMI weather station to the Fiskars village locates at Jokioinen, about 90 km to the North. According to the data of that station, the air pressure degreased from 1020 to 1017.6 hPa during the measurements, and the sky was clear. The clear night produced about 9 °C temperature drop at the ground from the highest midday reedings indicating that an inversion layer was formed. The wind speed was around 2 m/s at the beginning of the data collection and increased later close to 3 m/s (see Figure 2).

2.2 Sixty AS event

Sixty AS event were manually collected from the 4 h long recording of the B&K microphone signal based on their auditive, temporal and spectral properties. Twenty examples of them are shown in the Figure 3. The AS events have large temporal variability. Some of them are like impulses, very compact in time, meanwhile some others are like clap or pop sounds with noisy echoes. In the left frame a sequency of cracks is shown (the fourth signal from the top). Due to the amplitude (peak) normalization, it looks like the background noise is varying. In reality it varied quite little. The night was calm and quiet.

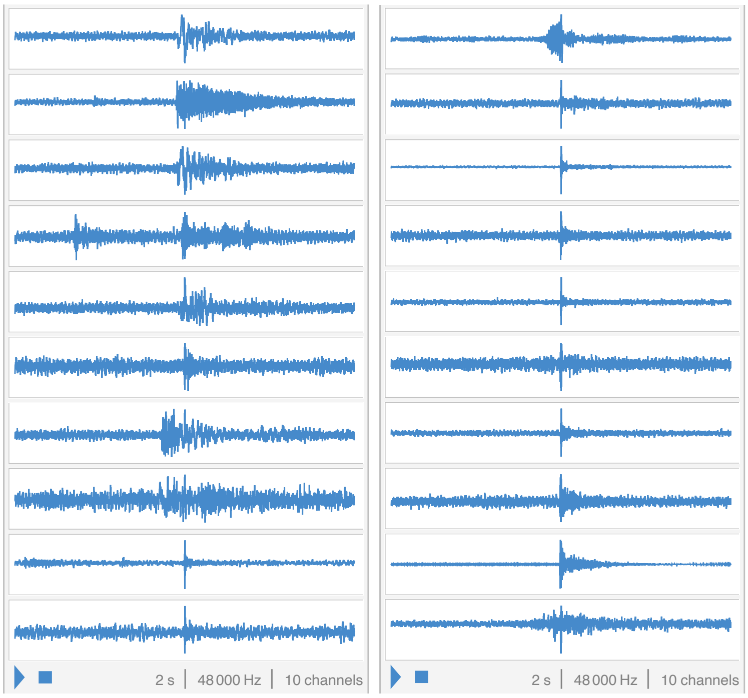

Figure 3. Twenty randomly selected AS events from the set of sixty cases.

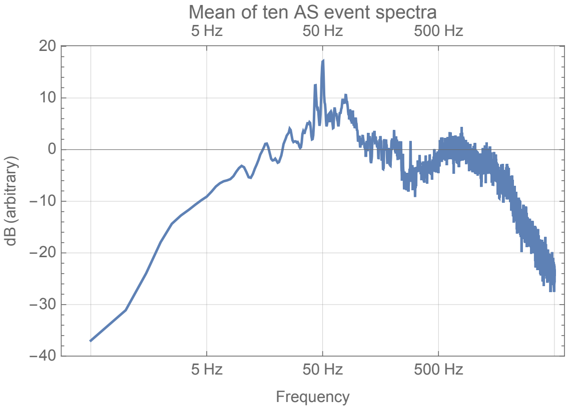

Figure 4. Mean of ten randomly selected AS event spectrum.

Figure 4 shows the mean of spectra of ten AS events that occurred in a row. The signal of the B&K measuring microphone is high-pass filtered before the recording. The filter with -6 dB/oct roll–off and 500 Hz cut–off is used to hinder strong infra sounds to clip the signal by driving it out of its dynamic range.

The spectral peaks below the 300 Hz occur often at the Schumann resonances. They are sometimes clearly intensified around the AS events. These components from a constant background hum on which the AS events are superimposed. A strong 50 Hz component is seen. It cannot be caused by any direct electric or magnetic field leakage from the mains to the microphone which is carefully shielded and has a low output impedance. The present supposition is that also this acoustic hum is created at the inversion layer. The observation that this peak often varies between 47–52 Hz supports this idea. The electric network in Finland is based on 50 Hz AC and this frequency can't vary so much out of its standard. However, these details in the low-frequency range need still more work. The main spectral peak of the AS events is located around 700–2500 Hz. Sometimes spectral peaks may appear even around 7–9 kHz.

In the following the time instances of the AS events are studied in comparison to the GM activity and in more detail to the magnetic field measurements made by FMI at NGO.

3 Causality between GM activity and AS events

During the first phase of the Auroral Acoustics project one attempt was made to build a bridge between AS events and geomagnetic measurements made by the FMI. This was published in the Master's Thesis of *Janne Hautsalo* [13]. Without extracting the individual AS events from the audio signals the whole material was analysed by a 1/3–octave filter bank and the RMS values of the outputs correlated with those of the GM field at different delays. Statistically significant correlations were found at many frequency bands and at many delays. Since that analysis it was clear that the variations in the geomagnetic fields are the cause for the sounds, even though that time the localizations of the sound sources were not solved, neither the physical mechanism of the sound production. The experience of the past years provides methods to extract the AS events from the noisy background both manually and algorithmically. An automatic method is under development, but it is not yet working sufficiently well to serve the research like this.

After the extraction of the individual AS events their *temporal histogram* in 10 min windows is constructed (the right histogram in red in Figure 5). The data starts at 21:20 and continues to 01:10 local time. The data for the histogram in blue is taken from the web–page of the FMI [14]. Both histograms have a clear peak of maximal activity. The GM activity seems to precede and predict the AS events.

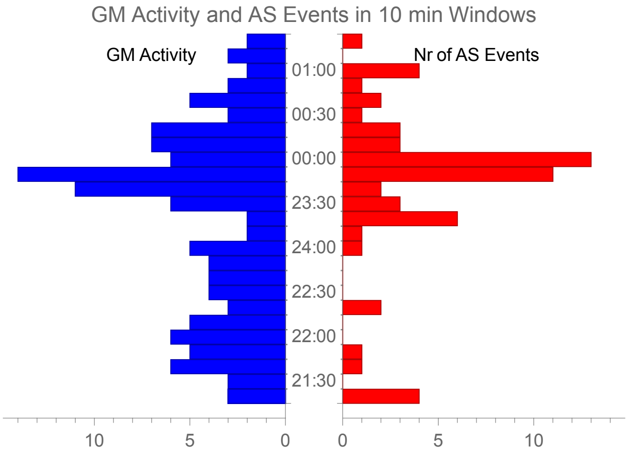

Figure 5. Comparison of the number of AS events and the GM activity at NGO in 10 min windows. The unit of the GM data is 10 pT/s. The time scale in the middle is the local time.

The direct correlation between the GM activity and the number of AS events gives $r = 0.44$ with a large $p = 0.38$. When the GM activity is delayed by 10 and 20 minutes, these numbers are: $r = 0.69$, $p = 0.4$ and $r = 0.47$, $p = 0.09$. This indicates that a statistically significant fit should occur at a delay around 20 minutes. A closer picture of the connections between the magnetic field fluctuations and the AS events can be created by applying the regression analysis.

3.1 Regression Model

A standard method to reveal possible *causality* between a set of independent variables and a dependent variable, or a response of a system to variations in the independent variables, is the *regression analysis*. Now, the GM data provided by the FMI containing three magnetic field components (Bx, By, Bz) and sampled with ten second periods is used for a regression model to predict the number of the AS events counted in overlapping 12–34 minute windows moved in one–minute steps. The mean of the magnetic field components are removed and the sequences partitioned to ten–minute segments consisting of 60 samples each. The RMS values of each segment of each component is computed. The obtained RMS sequences form the independent variables for the regression model.

First, eleven time-sifted variants of the AS event sequence are produced moving the window's centre starting from 1 to 12 min after the first AS event in steps of one minute. Additionally, there was a constant delay of 10 min between the magnetic field data and the first AS event. Now, each time–sifted variant represents the AS event sequence with a delay varying from 11 to 22 minutes providing the solving of the optimal lag for the regression model. The optimal regression model was found with a lag of 21 minutes. It predicts the AS events with 90% accuracy (R2 = 0.895). The correlation between the best regression model and the optimal AS event shift–variant is $r = 0.95$ with $p < 0.0001$ when the 32 min window size is used.

The regression coefficients for the {Bx, By, Bz} sequences are {0.91, 0.22, -0.12}. When the mean RMS values of these sequences are multiplied with their coefficients, we get: {6.58, 3.15, -2.49}. This indicates that the Bx has more active role in the sound production than the By and the effect of Bz is negative. This leads to a conclusion that *the variation in the horizontal magnetic field component H={Bx, By} has an important role in the sound generation in the temperature inversion layer*. This outcome provides a deeper insight to the Inversion Layer Hypothesis: Variations in the H–component induces vertical potentials (electromotive forges) which may increase the ionization in and between the charged layers thus increasing the probability of a discharge between the layers in the form of an avalanche of electrons [15].

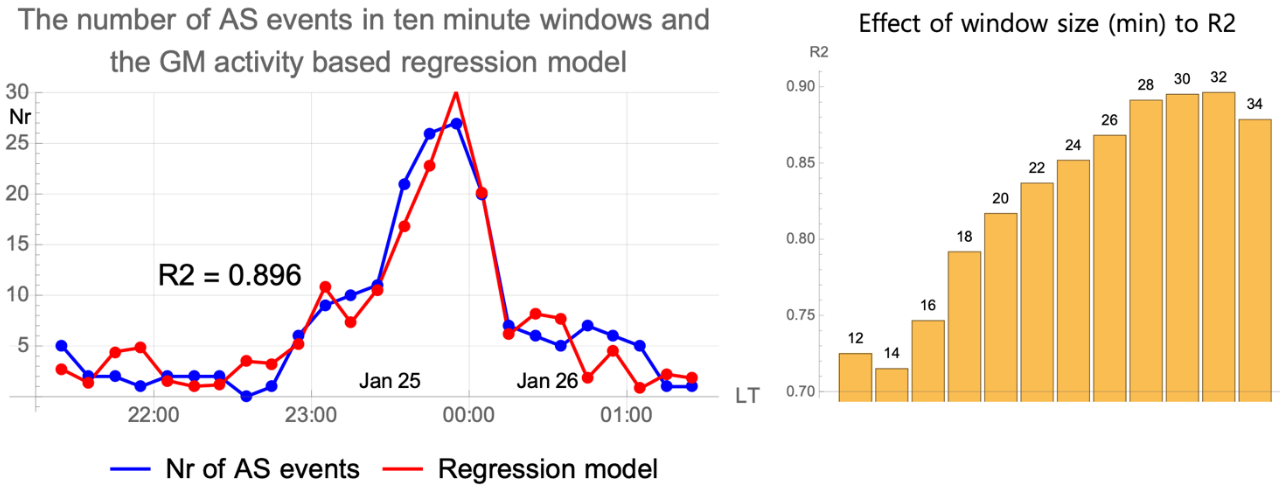

Figure 7. Smoothed temporal distribution of the sixty AS events (in blue, delayed 21 min) predicted by a magnetic–field–based regression model (in red). R2 values as a function of the window size (on the right).

3.2 Period histogram of the AS event sequence

A novel, not earlier discussed aspect related to AS is their *period histogram*. Knowing the time instances of the sixty AS events, a histogram of all time periods between the events is easily constructed by subtracting every time instant from all the later ones. The number of periods in a gliding four–minute window is calculated at one–minute intervals to construct the histogram shown in Figure 8 in blue. Also, period histograms of one hundred randomized cases with the same number of events were constructed. Their mean and deviations from the mean by one standard deviation are correspondingly illustrated in gray, red, and green. The AS events are clearly not located randomly in the four–hour window, but certain periods are occurring more often than the others. Especially periods of 10, 17, 26, 37, and 53 minutes arise strongly above the random statistics. These peaks deviate from the random mean 15.2, 9.4, 10.8, and 12.0 times the random STD. Their largest p–value is smaller than 0.007 indicating the statistical significancy of these peaks. The histogram shows also how the number of the shortest periods is high. These cases include clap–pairs, known as "klip–klap"–events. These cases together with the crackling sounds have been analysed earlier and their statistical connections to Schumann resonances shown [16].

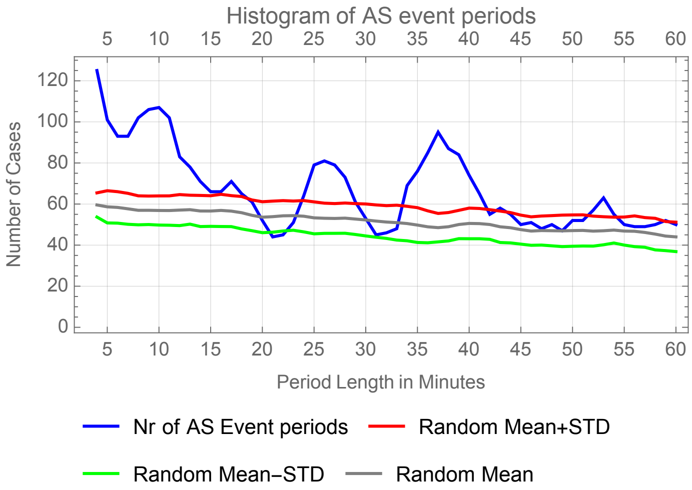

Figure 8. Period histogram of the AS events shows peaks at durations of 10, 17, 26, 37, and 53 minutes. Statistics of one hundred random cases are presented as a reference (see text).

The found peaks at durations of 10, 17, 26, 37, and 53 min happen to be almost identical to those found in a study of the magnetosphere and the solar wind by Huang &al. [17]. They summarize: 'It is known that the solar wind has significant effect on the magnetospheric convection and that magnetospheric electric fields can penetrate into the midlatitude and low-latitude ionosphere. We suggest that the midlatitude ionospheric electron density perturbations were caused by the penetration of magnetospheric electric fields which were controlled or modulated by the oscillations in the IMF (Interplanetary Magnetic Field) or solar wind pressure.' In that study the loss time of the oxygen ions due to recombination at the *F* region altitudes were estimated to be 12, 18, 26, 37, and 52 min at the altitudes of 220, 230, 240, 250, and 260 km. Now a question arises as to whether these processes, occurring at 220–260 km above the ground, could cause the same pattern in geomagnetic field on the ground and further in AS event period histogram or, is this just a coincidence? This cannot be answered in this short study. However, next the period histograms of the magnetic field measurements at NGO are analyzed and compared to the AS event period histogram.

3.3 Period histograms of the magnetic field sequences *B*x, *B*y, and *B*z

Period histograms were constructed for the same magnetic field data that was used for the regression model in section 3.1 by using practically the same algorithm as in the construction of the period histogram for the AS events. In this case the amplitude peaks of the magnetic field components must first be solved. The cross-correlation between the obtained period histograms of the components (*B*x, *B*y, *B*z) and the period histogram of the AS events are: r={0.58, 0.60, 0.58} with the largest p< 0.0001. The period histogram of By and that of AS events are shown in Figure 9. The period histogram of the By component has the three first peaks approximately at the same period length as the AS event histogram, whereas the fourth peak of the AS event histogram doesn't have any clear counterpart in the By histogram. The same is true with the Bx and Bz period histograms.

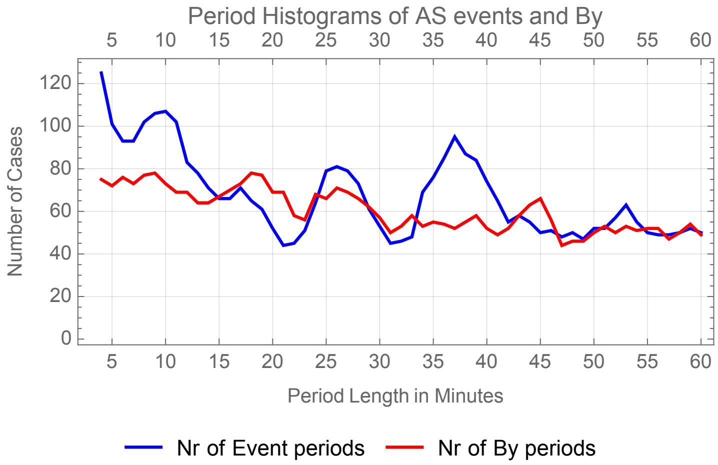

Figure 9. Period histograms of AS events and simultaneous magnetic field By-component at NGO.

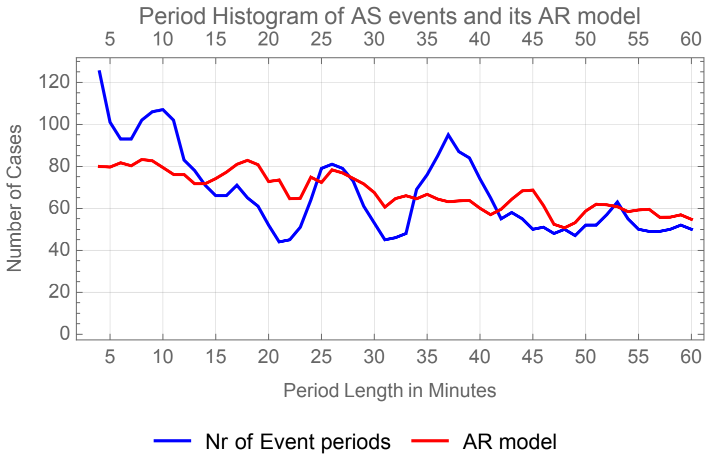

Figure 10. Period histogram of AS events and AR model (see text).

The statistical connections between the period histograms can be illuminated further by constructing a regression model from the magnetic field component histograms to model the AS event histogram. The obtained regression model is depicted in red in Figure 10.

The cross-correlation between the AR model and the period histogram of the AS events is r=0.64 with p<<0.0001. Thus, the magnetic field components explain 41% of the AS events period histogram. However, when the cross-correlation is calculated in a smaller window having period lengths between 5–30 min, the correlation improves to r=0.72 (p<<0.0001) and R2=0.52. The three first peaks of the AS events period histogram are explained by the regression model that is based on the period histograms of the magnetic field components by 52%.

3.4 *H*-component of the magnetic field

The role of the horizontal (*H*) component activity in the AS event production was discussed above. The magnetic field components Bx and By were interpolated for solving the ΔH vectors at 1300–50 seconds before the sound events in steps of 50 s. The obtained results are clustered to five classes by using Gaussian mixture method (see Figure 11). The ΔH values of the first and largest cluster with 22 cases are amplified by ten for a better visualization. This cluster has a sharp variation in the Bx-component before the sound events. The analysis shows that about 2/3 of the cases (#48) have a slow and large variation of 20–40 nT and 1/3 (cluster 1) a smaller but fast variation before the AS event.

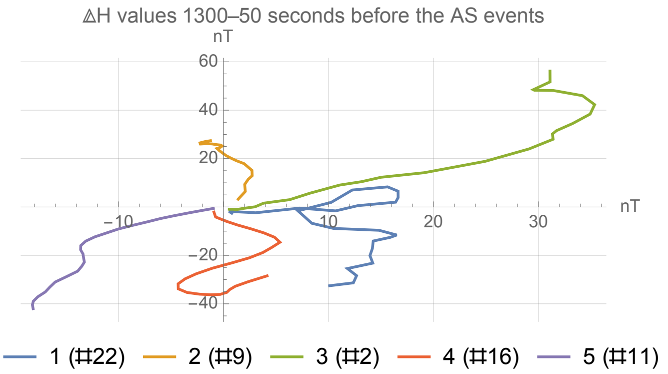

Figure 11. Five cluster means of the ΔH = {ΔBx, ΔBy} before the AS events (at origin).

4 Conclusions

The Auroral Acoustics project started over twenty years ago [18]. That time there was not much hope that this ‘millennial problem’ could ever be solved. Many geophysicists around the globe had fixed their opinions: “Auroral sounds are illusions” and “They are physically impossible”. However, a new, previously unknown sound producing mechanism in the temperature inversion layer was discovered [1]. The present study connects the sound production to the independent magnetic field measurements. The results show that the sound producing mechanism is far more sensitive to the magnetic field variations and the auroral sounds are much more common than has ever been understood. The key issue is the formation of a strong temperature inversion layer. This occurs only during an excellent “*fox weather*” conditions meaning; calm, serene sky, temperature drop around 8°C, and at least a moderate geomagnetic activity.

AS events have a complex relationship to the different types of geomagnetic activities. It was discovered earlier that the patterns of the crackling sounds are connected to the Schumann resonances [16]. The present work shows new connections through period histograms between the magnetism and the sounds. The discovered important periods are on the band 10–40 min belonging to the Ps 6 type magnetic variations that are especially connected to *B*y–component during the recovery phase of magnetic substorms [19]. The discovered 21 min delay between the magnetic fluctuations and the sounds has not yet explanation.

Auroral sounds are produced with a separate process from the auroral light production. However, both have the same geomagnetic background causing synchronism between these phenomena. The creation of auroral sounds may occur and be audible even without any visual aurora, which is one of the revolutionising conclusions of this long project. Still, due to the historical and perceptual (cognitive) reasons, we may still use the term *auroral sounds*, even though the sounds are not ‘auroral’, but *electric discharge sounds* created at 70–100 m above the ground.

Acknowledgements

The author is grateful to the FMI for providing the geomagnetic data of NGO and *Okko Räsänen* as well as an anonymous reviewer for the constructive comments on the manuscript.

References

[1] Unto K. Laine, Auroral Acoustics project – a progress report with a new hypothesis, Baltic-Nordic Acoustic Meeting, BNAM 2016, Stockholm, Sweden, June 2016.

[2] George L. Siscoe, S. M. Silverman, and K. D. Siebert, Ezekiel and the Northern Lights: Biblical Aurora Seems Plausible, Eos, Transaction, American Geophysical Union, Vol. 83, No. 16, 16 April 2002, pp 173–179.

[3] Oleg M. Raspopov, Ezekiel's Vision: Visual Evidence of Sterno–Etrussia Geomagnetic Excursion? Eos, Transaction, American Geophysical Union, Vol. 84, No. 9, 4 March 2003, pp. 77–88.

[4] Sydney Chapman, The Audibility and Lowermost Altitude of the Aurora Borealis, *Nature* Vol. 127 No. 3201, March 7 1931, pp. 341-342.

[5] Carl Størmer, Altitudes of Aurorae, *Nature*, Vol. 97, No. 2418, March 2 1916, p. 5.

[6] W. Dunbar, Notice of the Aurora Borealis of Last Winter. Edinburgh Journal of Natural and Geographical Sciences (New Series), Vol III, ART. V., April 1831, pp. 225-226.

[7] Anonymous, Aurora Borealis, The Knickerbocker 1834 – New-York Monthly Magazine Vol. IV. August, 1834, pp. 98-107.

[8] William C. Baker, a letter to the editor of Journal of the Royal Astronomical Society of Canada, JRASC, Vol XVII, No. 7, September 1923, p. 279.

[9] Fiona Amery, The disputed sound of the aurora borealis: Sensing liminal noise during the first and second international polar years, 1882–3 and 1932–3. https://royalsocietypublishing.org/doi/10.1098/rsnr.2021.0031

[10] S. M. Silverman, T. F. Tuan, Auroral audibility, Adv. Geophysics, Vol 16, pp. 155–266, 1973.

[11] http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/index.html

[12] https://space.fmi.fi/image/realtime/K/quasi_K_NUR.html

[13] Janne Hautsalo, Master's Thesis, Study of Aurora Related Sound and Electric Field Effects, Helsinki University of Technology, 2005. http://lib.tkk.fi/Dipl/2005/urn007898.pdf

[14] https://www.ilmatieteenlaitos.fi/revontulet-ja-avaruussaa

[15] Rudolf A. Treumann, Zbigniew Klos, Michel Parrot, Physics of electric discharges in atmospheric gases: an informal introduction, arXiv:0711.1672v2, 10 Apr 2008.

[16] Unto K. Laine, Auroral crackling sounds and Schumann resonances, 26th International Congress on Sound and Vibration, Montreal, Canada, 7-11 July 2019.

[17] Chao-Song Huang, J.C. Foster, P.J. Erickson, Effects of solar wind variations on the midlatitude ionosphere, Journal of the Geophysical Research Space Physics, 16 August 2002. https://doi.org/10.1029/2001JA009025.

[18] Unto K. Laine, Twenty Years Hunting for Auroral Sounds, Project document, 2021. https://www.researchgate.net/project/Auroral-Acoustics

[19] Robert L. McPherron, Magnetic pulsations: Their sources and relation to solar wind and geomagnetic activity, Surveys in Geophysics (2005) 26:545–592, 2005.