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LOCALIZATION OF SOUND SOURCES IN TEMPERATURE INVERSION LAYER DURING A GEOMAGNETIC STORM

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The sounds that occasionally accompany the bright and active northern lights – the aurora borealis, have been studied in a small project called *Auroral Acoustics* at the former Helsinki University of Technology (2000-2009) and the Aalto University (since 2010). In September 2011, the project succeeded in localizing sound sources in the open sky some 70 meters above the ground. On March 17–18, 2013 during an intense auroral display over southern Finland, hundreds of short duration sound events were recorded with a three-microphone array accompanied by a loop antenna for magnetic field measurements. In sixty cases the sound source was estimated to be directly above the microphone array. A pulse in the magnetic field preceded each of the strongest sounds, indicating an impulsive current in the vicinity of the sound source. Rank correlation between the RMS values of the magnetic pulses and the sounds showed a 99.9% probability that the sounds had a causal relation to discharging currents (possibly corona) about 75 meters above the ground. Concurrent atmospheric measurement data also show that a temperature inversion layer was located at the same altitude.

This paper presents detailed analysis of one sound type in the March 2013 data. The inversion layer hypothesis (published in 2016) is described and tested by fitting a model to the data. The obtained results support the hypothesis and estimates that the altitude of the active inversion layer on that evening was at 78–80 meters. Moreover, the analysis revealed a new noise producing process that is associated with those low frequency sound events in both audio and magnetic field (VLF) components. This noise producing process likely takes place in the inversion layer, too.

Keywords: sound source localization, auroral sounds, geomagnetic storms

1. Introduction

This work is a continuum of the free running project *Auroral Acoustics* that started in the former Helsinki University of Technology (TKK) in the spring 2000 and continues in the Aalto University. The main goal was to study the problem of so-called *auroral sounds* [1, 2]. Based on human observations made under bright and lively aurorae plenty of evidence of these sounds have been collected around the world for hundreds or even thousands of years. However, the earliest testimonies were interpreted in terms of different magical, spiritualistic, or religious beliefs. Before *Galileo Galilei* the sky was some times filled with scaring and noisy “heavenly armies” instead of aurora borealis. Yet in the modern era these testimonies were still quite much looked as a part of a rich folk tale. There was no known physical theory in the sciences able to explain the production and propagation of those eerie sounds. How then could an open, clear sky produce sounds like these?

Some papers dealing with the topic emphasized the possibility that the observers have mistakenly associated some common environmental sounds to the aurora borealis. Even tinnitus was added to the category of *subjective* explanations. On the other hand *objective* explanations included studies by physicists who tried to show that these sounds are physically impossible, and that the sounds are more than likely just illusions. This is understandable, because a mechanism that could explain these audible sounds under the aurora borealis was missing. And further, even if the possible sound source were at the altitude of the lowest visible aurora (about 80–100 km from the ground), no audible sound would reach the ground. The sound attenuation in the atmosphere in the audio range is so large that only infrasounds from the aurorae have been detected on the ground level. However, they travel more than five minutes from those altitudes to the ground whereas auroral sounds were observed almost simultaneously with rapid and wide movements of the aurora. How then they could come from the aurora itself?

Today it may be possible to explain why these sounds were so strongly associated with the visible aurora. There are two obvious reasons. First, the sounds appear *almost simultaneously* with the auroral movements. If the movements are rhythmical then so are the sounds. Secondly, the sounds are almost always observed to come *from the direction of the aurora*, from the open sky.

Researchers like the Norwegian *Stœrmer* adapted a view that the sound source must be close to the observer. He was right. The sound attenuation and the delay caused by its travel through the atmosphere rule out the possibility that the sound source could be at the altitude of the visible aurora. His hypothesis was: "*A strong northern light generates a local discharge on the ground and it is this discharge that can be heard as the crackling auroral sound*" [3]. The general idea of coronal discharges as the cause of these sounds has lived long. However, the proposal that the sound source could be on the ground contradicts the observations. The first known attempt to study this problem with physical measurements was performed in Alaska during 1963-1964 without any clear outcome that could support the existence of the sounds or explain the sounds in another way [4].

In 1973 *Silverman* and *Tuan* published an excellent study of the topic where almost 200 observations were analysed [5]. In a detailed examination based on the laws of physics they showed that almost none of the proposed sound producing mechanisms could function as the source of these sounds. E.g., the electro-magnetic (EM) fields produced by geomagnetic storms are too weak at the ground level to produce sparking or other audible effects in the objects located close to the observer. They are even less likely to cause any neurological malfunctions in our cognitive system. However, one single hypothesis did survive and it was left in the category of possible explanations awaiting further examinations. It was the *coronal discharging mechanism*. The authors write:" *One hypothesis remains to be discussed, that of brush discharges ... in our opinion, this hypothesis allows for the most satisfactory explanation of the observations …*" [5, p. 208]. Based on the fact that the observed sounds were often described to be similar to those of coronal discharges this mechanism was also proposed by other scientists during the history of research in this field. Størmer was not the first one with this idea. *Chant* (1923) and *Beals* (1933) made similar proposals [6, 7]. Professor *Eve*, too, wrote in the Nature Suplement in 1936: *"... men cannot possibly hear the Northern Lights, which can make little or no noise, but they may hear something else not far from them, such as a local brush discharge* [8]." Coming back to the fundamental study of Silverman and Tuan, they suggested that the sound measurements during the coming solar max should be performed "*in a station at geomagnetic latitude of 55°*". This is surprisingly close to the latitude where the recent successful measurements were done (57.5° N).

Nevertheless, the problem stayed. Where could these coronal discharges take place? The electric field measurements made on the ground level were conflicting. In some cases an active aurora seems to increase the static electric field and in some other cases to decrease or even reverse its direction. Not even a long term monitoring could show any systematic variation that could be associated with the aurora. Could these changes in the electric field be so systematic and large that they could cause coronal discharges in the vicinity of the observer? And if this is the case, where and under which conditions this occurs? Many of the human observations were made on open fields were the supporting structures needed for the discharging to take place are rare.

The outcomes of Silverman and Tuan also contradict the hypothesis called *electrophonics* where the strong EM-fields are assumed to cause vibrations in different materials and sounds close to the observer [6]. This hypothesis has the same weakness as the idea proposed by Størmer. People working in the field of psychoacoustics can notice this quite easily. Human directional hearing is highly accurate for most of the time. Our attention is focused immediately to the direction of any strange new sound in our environment. The *precedence effect* or the law of the first wave front [7] will even fix our attention to the direction of the very first sound waves in hundreds of milliseconds thus helping us to define what caused the sound and whether it indicates any danger. Surprisingly, the importance of the *human directional hearing* has never been discussed in the past literature dealing with the problem of auroral sounds even though this aspect is *fundamental* considering our auditory system and all the binaural sound observations we make. This may indicate that quite a few researchers with good background in acoustics and psychoacoustics have worked with this problem. It is a fact that a clear majority of the auroral sound observers around the world have reported that the sounds they heard were coming from the open sky, from the direction of the visible aurora. The expressions like: "…then I heard strange sounds *in the air…"* are used in the testimonies since the 17^{th} century. They were not heard "in front of my left ear", "inside of my head", or "on the ground". If the direction was not clear then the expressions like "the noise was everywhere, it surrounded us" were used (the author also observed a similar event in April 2000). This may still speak for a wide active layer above our heads that produces thousands of small sound events randomly. Some times the loudest, isolated sound events are even accompanied with echo or reverberations. Generally, sounds we imagine or hear "in the head" cannot have a clear *direction* or include *echo*. Also, there are no material objects (except the air itself with space charges) "flying" on the open sky and ready to produce sparks or vibrations during geomagnetic (GM) storms. Sounds from the open sky must have another explanation. The only way to find a solid explanation for these sounds is to perform measurements under active aurora and then based on a detailed analysis of the collected data, test different hypotheses made for their possible mechanisms.

The most important milestone on our journey was the microphone array measurements made in the fall of 2011 in southern Finland [8]. For the first time in the history of research in this topic the sound sources were shown to be on the open sky. This was a real surprise and hard to believe. Because of the number of collected sound events was limited and most of the sounds were of low level causing problems in their analysis the measurements had to be continued and the methodology improved. The March 2013 aurora event provided a new excellent opportunity to study these sounds further. The obtained material supports the coronal discharging mechanism that takes place in the open sky. The aurorally induced electric fields may not be large enough to directly produce coronal discharges at ground level. However, they may be large enough *to trigger discharging in the temperature inversion layer*, where the space charges from the ground and also from the upper atmosphere have accumulated during a calm and clear evening. This new hypothesis called the *inversion layer hypothesis* (ILH) was published in Stockholm in the summer 2016 [2].

In the current paper the material obtained during the March 2013 event is studied further to explore and test the ILH. A small set of easily detectable sound events that have their main energy just at the boarder of the infrasound region (below 20 Hz) is studied in detail. They are synchronized and the directions of their sources in the sky are estimated. Finally, the simultaneous, local magnetic field measurements (VLF signals) related to these sounds are synchronized and summed in order to reveal the general structure of the electro-magnetic (EM) pulses preceding the sounds. These pulses probably indicate the coronal discharging processes in the inversion layer that then operate as the sound sources. The distances of the sound sources to the microphone array can be estimated based on the time delay between the EM pulses and sounds. The coherency of the pulses was obtained based on a simple model that is constructed on the ILH. The obtained results support the hypothesis of an electrically active inversion layer at about 78-80 meters altitude as the source of these aurora related sounds and even more as the source of the noises associated with these sound events.

2. Methods, materials, and the hypothesis

The auroral event on March 17–18, 2013 and the sound measurements have been described in an earlier report [2]. In short, the set-up consisted of a four tract recorder (Roland R44), three microphones (AKG stereo pair CK62 called **L**- and **R**-mic and Brüel & Kjær 4165 called **X**-mic) and a self constructed VLF loop antenna with *bifiliar winding* and a symmetric output that fits directly to the microphone XLR connector of the R44-recorder. The **L**- and **R**-microphones were mounted 1.7

m above the ground and the **X**-microphone in the focal point of a parabolic reflector on the ground. The distances of the microphones were: **X**-**L** 7.0m, **X**-**R** 5.25m, and **L**-**R** 9.7m (projections on the ground level). All four signals were recorded at 48 kHz rate with 24 bit/sample. The measurements were taken from around 6 PM LT till 6 AM LT. The temperature during the night was around -20 °C. The weather was totally calm and clear. The geomagnetic (GM) storm started as G1-class event but reached gradually the G4-class (Kp=8). It was the strongest geomagnetic storm of the solar cycle #24 up to that day.

The amount of the collected raw data is about 26 GB. Because the work had to be done at the boarder of a village (Fiskars) the material consists also sounds of traffic on the ground and even on the air, sounds of birds, dogs, etc. The environmental sounds together with the plurality of the aurora related sounds make it very hard to develop any fully automatic system to do the analysis. In the earlier phase a semi-automatic system was able to detect hundreds of different sound events from which the 69 most promising cases were selected for closer studies. They occurred on the sky above the microphone array. Together with the associated VLF pulses it was estimated that the sound sources are located about 75 meter above the ground. High correlation (r = 0.999) between the RMS values of the EM-pulses and the sounds was obtained with the sixty best cases with sufficient energy in audio and VLF. Thus the EM-pulses must have a causal relation to the sounds.

According to the present hypothesis the space charges that are accumulated in the inversion layer during the evening construct the source for the coronal discharges. The discharging mechanism is triggered by the GM storm. Thus the energy for the sounds is not coming from the GM-storm alone but mainly from the inversion layer. Naturally, the space charge accumulation rate may be higher during a GM-storm based on higher conductance of the upper atmosphere, larger ground currents, and activated X-ray ionization. All these could boost the accumulation rate. How the coronal discharging is triggered is still an open question. This may be related to the increased electric fields induced by the rapidly changing magnetic field. Also, the strong infrasounds coming down from the altitude of the ionosphere may have an effect.

In order to test the ILH seven very similar and energetic sound events were selected from the material. They all occurred during the first two hours of the recording (6-8 PM LT). The directions of the sound sources were estimated and the sounds (obtained by the **X**-microphone, B&K) were synchronized. The strongest event (#2) was selected to form the "basis" in the search for the corresponding magnetic field pulses associated with the sounds. Then knowing the directions of the sources and assuming different altitudes of the layer between 70–90 meters it is possible to solve for the distances from the sources to the **X**-microphone. It locates at the origin of the coordinate system of the set-up (see Fig. 2). When synchronizing the sounds the corresponding (connected) VLF signals go out of the synchrony due to the different distances the sounds have from their sources. Keeping the case VLF#2 as a fixed reference and knowing the differences in the distances it is possible to synchronize all the other VLF signals in relation to this reference. We have to repeat this procedure for all considerable altitudes of the inversion layer to find out the most probable value. The coherency of the VLF pulses should occur at the time instance where it occurs in the reference when the selected altitude of the inversion layer is correct. The success of this method is based on the premise that the ILH is valid. Thus its validity is tested simultaneously with the estimation of the altitude of the inversion layer.

Now we need a method to evaluate the results and to select the most probable altitude. The criterion could be based on the shape, the maximal amplitude or the "sharpness" (max derivative) of the obtained average VLF pulse. However, all these proposals are more like subjective *opinions* how such an EM pulse should look like. Better criteria are needed. Based on the previous result where the magnetic pulses showed a high correlation with the sounds (between their RMS representations) the RMS values of the VLF signals are computed in a window around the place of the assumed maximal coherency and then these values are correlated with the corresponding sound RMS values for each selected altitude. This method led finally to new interesting results.

3. Analysis of seven sound events, their EM-pulses, and noise

The selected seven sound events with partially inaudible and audible components have probably been described in earlier literature as a low frequency "flap" sound (like a flag in the wind). The easiness to find them in the audio signals and also the accuracy they provide for the cross-correlation computations between the **X**-**R**- and **X**-**L**-signals (when solving the sound source directions) motivated this choice. They were of special interest also because their main energy is just at the boarder of the infrasound region (<20 Hz). These signals also serve as a test set in the development of new computational methods where the ultimate goal is a fully automated analysis of the aurora night data.

The set of the seven signals (normalized) and a typical spectrum are shown in the Fig. 1 where a high-energy peak in the infrasound region (14 Hz) is visible. However, on a level about 20 dB lower and close to 30 Hz the spectrum shows also audible components. Moreover, these sounds are associated with a high frequency noise that rises about 0.1 s after the start of the oscillation around 14 Hz. This noise is visible in the waveforms and will be analyzed and discussed later.

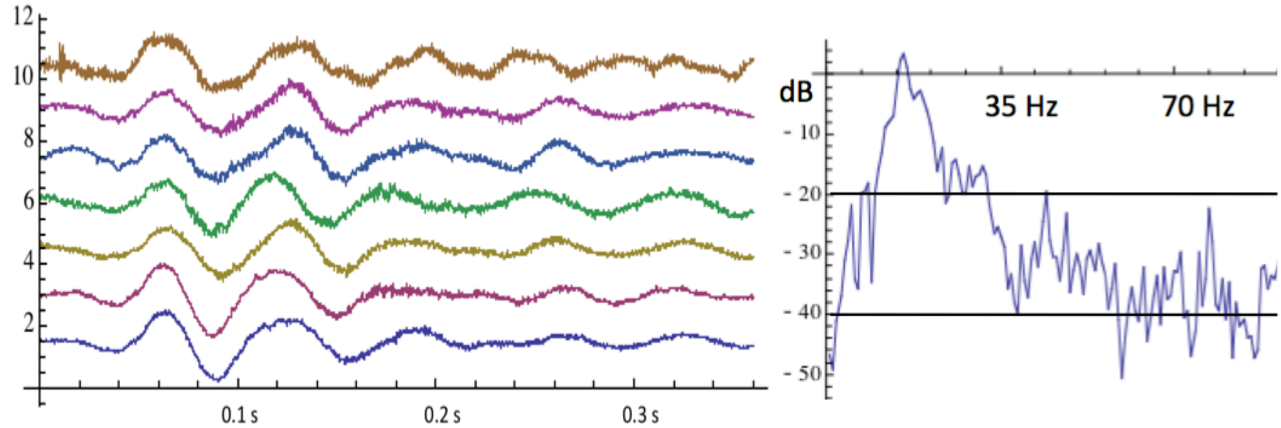

Figure 1. Acoustic waveforms of seven sound events used in the study (left, y-scale arbitrary) with a typical spectrum (right).

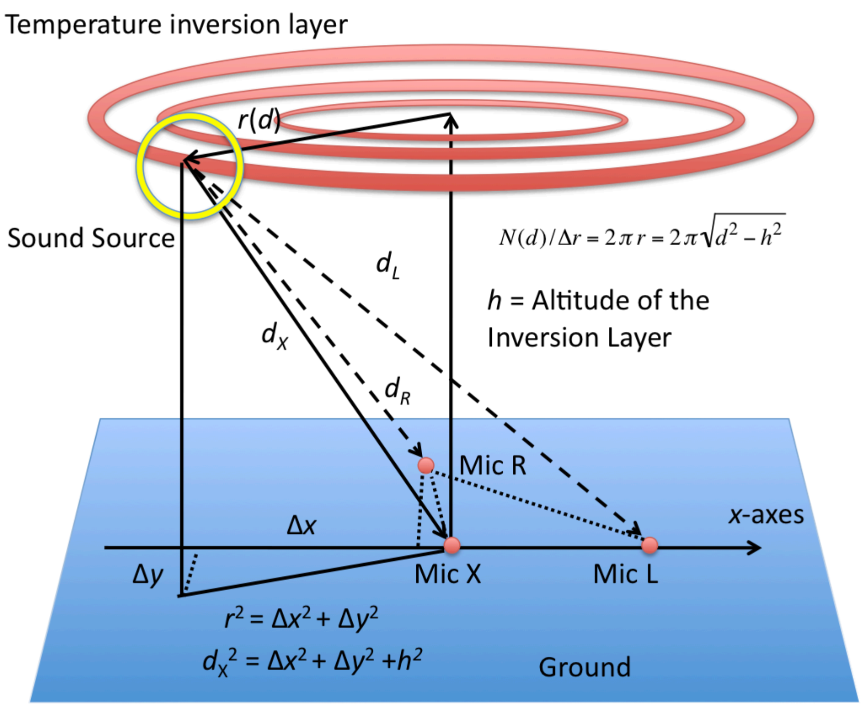

Figure 2. The geometry related to the ILH. Three microphones (**X**, **L** and **R**) on the ground receive sounds from the inversion layer at the altitude h. Based on different arrival times of the sounds the direction of the source in terms of Δx and Δy can be solved as well as the distance r from the zenith line (z-axes).

The ILH is explained geometrically in the Fig. 2. The directions of the sound sources in terms of Δx and Δy are estimated based on the cross-correlations between the microphone signals **X**-**L** and **X**-**R** (time delay estimation). The values for Δx and Δy in meters as well as the distances from the source to the microphones (d_X , d_L, and d_R) can be solved only when the altitude h is known. The equation given in the figure for $N(d)$ per unit distance Δr is a model for the number of sources at a distance d from the **X**-microphone in the case when the sources are distributed uniformly (randomly) in a thin inversion layer at the altitude h. When $d \approx h$ N is small (few sources at zenith) but it starts to grow fast. When $d >> h$ then N grows approximately linearly. The model has been preliminary tested and the number of sources in the data follows this rule quite well. The problem here is that when d grows the sources are increasingly far from the focus of the reflector of the **X**-microphone and the signal SNR is getting at the end too low.

At the altitude of 79 meters the distances of the sources (of the seven sounds) from the z-axes (r in Fig. 2) were estimated to be between 27.5 and 43.1 meters with the mean of 34 meters. Their average angle from the zenith line was 23.3°.

3.1 Processing of the VLF signals (magnetic field measurements)

The RMS value of the electromotive force (voltage) at the output of a loop antenna with N turns and A cross-sectional area is: $V_{\text{rms}}=2\pi f N A B_{\text{rms}} \cos\theta$, where B is magnetic field (T), f the frequency (Hz) and theta the angle between the B and the A normal. In order to measure B we have to integrate the measured signal. This can be done easily with DSP in frames where the DC component is first removed. The next step is to remove 50Hz interference and all the harmonics. This is also a trivial task when the exact value of the frequency is known (may vary between 48–52 Hz). After these operations the relatively wide pulses that are assumed to be caused by the coronal discharging can be recognized in the most waveforms. They all should not be measurable because the source location may form an angle ($\approx \pi/2$) with the antenna and the cosine term vanishes.

The method described in section 2 is now applied. Fig. 3 shows the obtained correlation values between the VLF and audio RMS values as a function of the layer altitude d. This curve is the mean of the results obtained by using three different window lengths in the VLF signal RMS-value computation centered in the time instance of the assumed, synchronized EM-pulses. The window length is not critical. Varying it 1:3 will cause only small changes in the outcome. All the tested windows showed the maximum at the same point: 79 meters. The maximum correlation value is r = 0.69 (Pearson's correlation). The curve is quite flat around its maximum at h = 78–80 meters.

This is logical because the data is noisy and also it is very plausible that the sources must have some variation in their altitudes. Our simple model forces the locations of the sources on the same altitude when solving for the most probable layer position. For this reason the result should be interpreted as a statistical mean of the actual altitudes that have certain deviations around the mean.

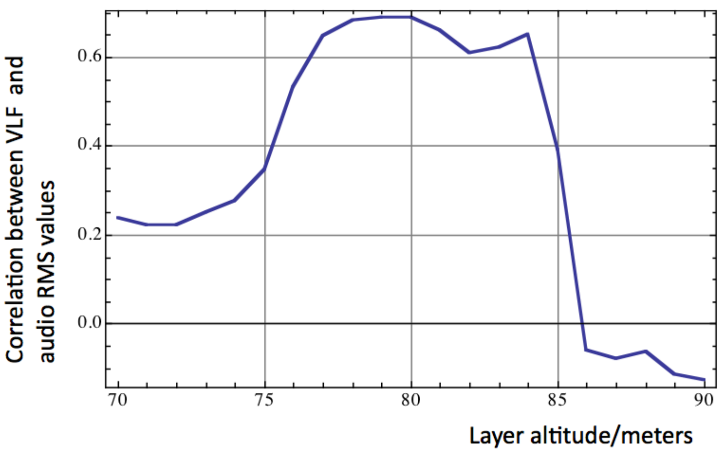

Figure 3. Testing the ILH by varying the hypothetical layer altitude and looking for the maximal correlation between the RMS values of the VLF and audio signals.

The flatness of the curve may also explain why this correlation is clearly lower than that obtained earlier when the pulse locations were selected individually and independently on the altitude of the source in question. The second peak in the correlation curve needs closer analysis. It may speak for a multiple layer structure that occurs in some cases, or it is an indication of a secondary event (excitation) in the discharging process.

3.2 Associated auroral noise

It was observed in the Fig. 1 that a noise was associated with the acoustic pulses. A simple method to analyse the amount of high frequency noise is to low-pass filter the absolute values of the differentiated signal. This was used for all seven sound signals and the mean of the obtained results was computed. The same procedure was also applied for the corresponding VLF signals. The results are shown in Fig. 4.

To discover this event synchronized noise in the data was a surprise and unexpectedly the noise in audio and VLF signals are correlated with r = 0.82 (Pearson, p=0.02). The delay of the noise component is clearly larger than that of the audio pulse in comparison to the VLF pulses (excitations). On the average it corresponds to a distance of 134 meters. Interestingly, the noise component starts to increase gradually, not simultaneously with the oscillating component. How this could be explained? The measured acoustic events on the altitude of 80 meters are quite loud. The present estimation is that they may be around 80 or even 90 dB (at one meter distance). The produced low frequency pressure wave may trigger some secondary discharging processes when travelling *along* the inversion layer. The ring shaped pressure wave component expands with the speed of sound lowering the threshold of coronal discharging locally and momentarily. This type of process could explain both the gradual increasing shape of the noise and its larger average delay. However, this is just a preliminary guess and the topic still needs more work.

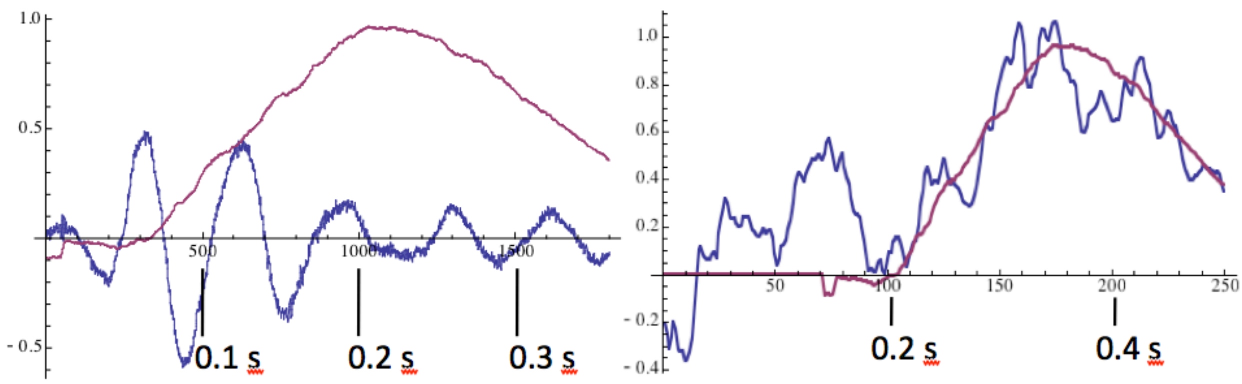

Figure 4. Left frame: Mean of the synchronized sounds (in Fig. 1, blue) with the mean of the associated noise component (red). Right frame: Noise component associated with the corresponding VLF signals (blue). The time shifted mean of the acoustic noise fitted to the VLF noise (red). In both frames: x-scale time in seconds, y-scale arbitrary. The point of synchronization and the primary excitation is slightly before 0.2 s.

4. Summary and discussion

In this paper a subset of acoustic events collected during the March 17–18 2013 geomagnetic storm was analyzed in details and fitted to the ILH model in order to test its validity and to produce new estimates for the layer altitude. New methodology was developed for this purpose that is based on cross-correlations of the audio and VLF data in RMS form. The estimated altitude is slightly higher than that which was published in 2016. However, the altitudes of 78–80 meters are still in line with the balloon measurements made by the Finnish Meteorological Institute during the same night. The analysis revealed a noise process that is associated with these auroral sounds. The noise process seems to follow a different dynamic behaviour than the oscillating, low-frequency component.

Interestingly, the measured sounds may be related to those studied in 1971 in Alaska by using microbarographs [12]. Unfortunately the frequency band in their case was limited to 16 Hz and we do not know if some high-frequency components were present. They reported that especially "*during the temperature inversion* and low humidity characteristic … excellent conditions for long-range detection of sounds existed." Possibly indicating that the conditions were favourable for detection of these sound events. Further, these events occurred in a calm weather and with relatively intense aurora overhead. They could not find any co-occurrences with similar sounds observed simultaneously in two other stations even though this was expected based on the assumption that the sources locate at 80–100 km altitude. They reported: "This *localized nature* of acoustic aurora remains to be fully explained…" Based on the high similarity of the signals they measured with those presented in this work one may ask whether their origin could be in the inversion layer, too. Many details in that paper back up this view.

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