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Key Points:

- VLF emissions at frequencies 16–39 kHz with dominant left-handed polarization are identified in ground-based measurements
- These emissions exhibit a clear banded structure, and they occur during dusk-to-night local time sector
- Some of their features resemble those of banded structure in auroral hiss, while others imply links to propagation of lightning sferics

Supporting Information:

- Supporting Information S1

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VLF Emissions With Banded Structure in the 16- to 39-kHz Frequency Range Measured by a High-Latitude Ground-Based Receiver

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Abstract Very low frequency (VLF) emissions of natural origin were identified for the first time by analyzing 1-hr ground-based magnetic field spectrograms in the 0.2- to 39-kHz frequency range. Data were used from the Kannuslehto radio receiver (L-shell ~5.5), recorded during different campaigns between 2006 and 2019. The spectrograms exhibit banded structures, which consist of several strip elements that vary in time and frequency over the event duration. Statistical analysis of 95 events shows that they are observed in the frequency range that extends from 2 to ~37 kHz, and mainly appearing above 16 kHz. The events span from 4 to 110 min and occur in the evening sector (~17–01 magnetic local time), mostly during quiet geomagnetic conditions. Furthermore, they are primarily left-handed polarized and are associated with bursts of lightning-related radio emissions such as sferics and tweeks.

Plain Language Summary Advances in modern technology have created tangible scientific and societal benefits, allowing us to make new discoveries, perform better observations, and monitor important parameters of our Earth's condition. In this study, new digital processing tools are used to uncover a natural, namely, non-man-made, very low frequency (VLF) radio wave emission never observed before. These emissions consist of several strips as appear on our detector screens, with structures having frequency drifts that vary during the event duration. Moreover, the range of frequencies in which these emissions are observed, 16–39 kHz, is higher than the typical one used for VLF observations. The measurements were made in Northern Finland during different campaigns, between 2006 and 2019, using ~10-m size square-loop radio antennas installed on the ground. The duration of the structured emissions ranges from about four to a hundred minutes. These emissions occur during evening and early night hours, and when the Earth's magnetic conditions are calm. Additionally, we learned that the field perpendicular to the wave propagation rotates clockwise when looking at the incoming wave. A remarkable characteristic of these emissions is that they are coincidental in time with the occurrence of bursts of lightning VLF emissions.

1. Introduction

The term very low frequency (VLF) radio wave is defined by the range 3–30 kHz. Yet, systems for monitoring VLF waves can operate in any subset of a wider frequency range covering from about 0.1 kHz up to more than 50 kHz (e.g., Colpitts et al., 2012; NaitAmor et al., 2010). One type of natural VLF emissions can be generated by lightning discharges and then propagate thousands of kilometers inside the Earth-ionosphere waveguide as atmospherics, that is, sferics (Volland, 1995). This emission has a peak spectral density centered at ~10 kHz (Taylor & Jean, 1959). Another type can be generated by plasma instabilities within the magnetosphere (Helliwell, 1965). The latter may propagate in the whistler mode throughout the magnetosphere, and they can be observed, both on the ground and by space probes.

Most of the reports on natural VLF studies involve a large variety of frequency ranges, but usually at values much lower than 16 kHz (Engebretson et al., 2004; Helliwell, 1965; Martinez-Calderon et al., 2015; Titova et al., 2007). Although measurements above 16 kHz do exist, the related observed emissions are mainly due to auroral hiss (Gurnett et al., 1983; LaBelle & Treumann, 2002). Moreover, it seems that not much effort has been placed in trying to analyze phenomena occurring in such frequency interval. This is, however, understandable, since sferics hide possible interesting emissions above 16 kHz. Fortunately, dedicated digital processing tools were recently developed at the Sodankylä Geophysical Observatory (SGO) allowing us to

filter out strongest impulsive sferics. This process helps to uncover atypical high-frequency VLF emissions that have never been observed before (Manninen et al., 2016).

Another reason for the scarce number of reports on VLF emissions above 16 kHz is that these frequencies are used by navy transmitters. Their intense signals make it difficult to detect natural emissions, especially when the emission is weak. Indeed, a significant part of the 16- to 39-kHz frequency range is filled up with these man-made signals (e.g., NaitAmor et al., 2010; Zhang et al., 2018). In spite of all these, it is possible to identify frequency windows where new natural VLF emissions are worth exploring. Here, we report for the first time ground-based observations of VLF emissions with banded structure (BS) occurring in the 16- to 39-kHz frequency range. We discuss their possible formation mechanisms, suggesting two different hypotheses: (i) they might be due to plasma instabilities in the magnetosphere, as is the case of structured auroral hiss (Titova et al., 2007), or (ii) they could be formed in the Earth-ionosphere waveguide as a result of a long-distance propagation of lightning generated VLF emissions (Záhlava et al., 2015, 2018).

2. Observations

The initial data set employed in this study consists of 290 days of magnetic field measurements made using the Kannuslehto radio receiver (67.74°N, 26.27°E, L-shell ~5.5). The measurements were held in November 2006, October 2007, February 2008, December 2013 to January 2014, September 2017 to January 2018, and January–March 2019. These are some of the campaigns operated at Kannuslehto, data from which are currently available for analysis. During campaigns, the receiver system performs 24-hr wideband VLF recordings in the 0.2- to 39-kHz frequency range. The receiver system, that is, two orthogonal air-core loop antennas, electronics, and acquisition software, was developed and implemented at SGO. The two horizontal components of the magnetic field were sampled at 78.125 kHz, with 24-bit resolution. The spectral response of the receiver is almost flat in the 1- to 39-kHz frequency range, and the threshold of sensitivity is about 0.1 fT in each 1-Hz bandwidth within that range; that is, the noise level of the receiver is $\sim 10^{-14}$ nT²/Hz. The measurement site is located 9 km from the nearest power line and human settlements, thus minimizing the artificial noise. All these characteristics make the data highly reliable and optimally suited for analyzing weak events (Manninen et al., 2016).

In addition to sferics filtering, which removed 15% of the strongest sferics, we also removed electromagnetic signals radiated by the electric power network (power line harmonic radiations), and narrow band transmitter signals. The sferics filtering is useful to identify weak events as the ones presented in this article. The data analysis is performed in a complex plane defined by the measured signals. It means that the signal sensed by the north-south antenna is considered as the real component, while the one sensed by the east-west antenna is considered as the imaginary component. Performing the Fourier transform allows to decompose a signal at a given frequency into a sum of right-handed and left-handed powers. The resulting high-resolution frequency-time spectrograms were visually inspected for the presence of natural emissions using 1-hr-long spectrograms. An example of this is displayed in Figure 1a for magnetic field fluctuations measured on 15 December 2017 between 18:52 and 19:52 UT. This spectrogram covers the 0.2- to 39-kHz frequency range, where empty horizontal lines correspond to the removed navy transmitter signals. In this figure, weak band elements, having a time-dependent frequency drift, are observed between about 19:17 and 19:43 UT, primarily in the 27- to 35-kHz frequency range. The black rectangle emphasizes the frequency and time ranges where the event is better observed. The value of the frequency separation between individual bands seems to change as a function of time and frequency over the event duration. Based on their visual appearance in the spectrograms, we call them “banded structures.”

Figure 1b corresponds to the same time interval as Figure 1a, but it contains the spectrogram of signal polarization ratio that is defined as the ratio of right- and left-handed powers. In this representation, the right-handed polarization is indicated by reddish colors, whereas the left-handed polarization by greenish colors. The banded emission is clearly more visible in this representation than in the power spectral density. In other words, Figure 1b gives better insights on the event duration (18:58–19:44 UT) and the observational frequency range (5–37 kHz). Consequently, the polarization ratio spectrograms were used to identify the banded emissions instead of traditional power spectrograms.

Figure 1b also shows that the background VLF emission has frequencies characterized by left- or right-handed polarization. For instance, at about 10, 15, and 30 kHz, the polarization is right-handed.

Figure 1. Banded emission observed at Kannuslehto on 15 December 2017. The empty horizontal lines indicate the removed navy transmitter signals. The black rectangles emphasize the frequency and time ranges where the event is better observed. (a) One-hour frequency-time spectrogram of power spectral density, starting at 18:52 UT. (b) Its corresponding spectrogram of right-handed (reddish colors) and left-handed (greenish colors) polarization ratio. (c) Two-minute zoom time interval of panel (b), starting at 19:22 UT. (d) One-second zoom interval of panel (c), starting at 19:23:12 UT. (e) The corresponding power spectral density of panel (d). (f) Twenty-millisecond long magnetic field waveform of the east-west loop antenna.

Analyzing more in detail each band element in Figure 1b, we observe that the ones with a more circular left-handed polarization correspond to those in Figure 1a with a significant enhancement in total power.

Figure 1c shows a 120-s zoomed interval of Figure 1b, starting at 19:22 UT. There, individual band elements remain clearly observable, particularly for the frequency ranges of 10–18 and 25–37 kHz. Furthermore, the figure shows that the band elements are not continuous, but they appear intermittently. In Figure 1d, a detailed polarization spectrogram is shown spanning over 1-s time interval starting at 19:23:12 UT. There, the band elements are still observed, particularly in the time interval 0.3–0.5 s. During this interval, bursts of lightning emissions, such as tweeks and sferics, are observed in Figure 1e, which show the power spectral density corresponding to Figure 1d.

Figure 1f shows 20-ms waveform measured using the east-west loop antenna, where the starting time ($t = 0$) is 19:23:12 UT. To obtain the waveform, narrow band spectral lines caused by VLF transmitters have been removed. In this figure, several intense pulses are noticeable with an approximate time separation between 0.5 and 4 ms. In frequency domain, this time separation would correspond to band elements separated by about 0.25 to 2 kHz. This is roughly comparable to the frequency separation of the band elements (~ 0.27 – 1.30 kHz) observed on 15 December 2017 (Figure 1b).

From the original data set of 290 days, emissions were identified in 79 days with a noticeable BS in the 16- to 39-kHz frequency range, that is, similar to the one showed in Figures 1 and S1 in the supporting information. Out of the 79 days, 15 contain more than one banded emission per day. Altogether, 95 banded events were analyzed and they are listed in Table S1 in the supporting information. The amplitudes of the events in the frequency range of 34–35 kHz vary between 0.5 and 2 fT. It is evident that the high sensitivity of the receiver together with the removal of sferics allows us to measure these rather weak, previously unreported, signals.

Figure 2a shows the frequency range of each of the 95 detected events. The events are sorted according to the minimum frequency of observation to determine whether there is any pattern of occurrence in frequency. The identification of BSs is truncated at 37 kHz, as indicated by the red horizontal line. Evidently, the upper limit of observation can be higher than this frequency limit. The reason for this is that frequencies about 37 and 38 kHz are used by navy transmitters, and those are removed from the spectrograms. The red horizontal line at 25 kHz indicates a truncation for the lower limit of our observations. The events may be present at frequencies between 16 and 25 kHz. However, this frequency range is used by navy transmitters, making it difficult to identify the actual lower limit of the banded emission. Figure 2a shows that 80 events have a common frequency range of 25–30 kHz. It is worth noticing that the lower frequency of about one half of the events is below 16 kHz. Thus, the banded events are observed over a wide frequency range at frequencies above about 2 kHz.

Analyzing the 95 events we found that the banded emissions can last from 4 to 110 min, with median time duration of 23 min and lower and upper quartile of 11 and 44 min, respectively. The diurnal distribution of the events shows that they occur in the evening, from about 17:00 to 01:00 magnetic local time (MLT). Regarding the global geomagnetic conditions, we found that the events are generally observed during quiet periods, that is, $\sim 80\%$ of the events occur when AE-index < 400 nT ($\sim 62\%$ of the events occur when AE-index < 200 nT). Measurements from Sodankylä and Kevo magnetometers, both belonging to the IMAGE network (Tanskanen, 2009), were examined searching for possible correlations. They are located roughly at the same longitude as Kannuslehto, but 44 km to the south and 226 km to the north, respectively. The measurements confirm that the events occur during quiet conditions. Additionally, about 65% of the events stop been observed at about the beginning of the growth phase of substorms.

Riometer measurements at Sodankylä and Ivalo (99 km to the north of Kannuslehto) as well as ionosonde measurements at Sodankylä were also investigated. Using these data, we noted that the banded emissions occur independently of the presence of ionospheric disturbances. Similar behavior can be noted with respect to auroral hiss, which can happen just before, during or after the banded emissions, or not occur at all. Fluxes of auroral electrons and protons were also analyzed for the region 60 – 78° in latitude and 5 – 50° in longitude. The fluxes are obtained from the total energy detector on National Oceanic and Atmospheric Administration's (NOAA's) Polar Orbiting Environmental Satellite (POES). Out of the 95 banded emissions, 36 were cotemporal with POES. About half of latter are associated with significant charged particle precipitation.

The sense of polarization (right-handed, left-handed) of an incoming wave can help us to determine whether the emissions consist of whistler mode waves coming from the magnetosphere, or if they are dispersed sferics propagating inside the Earth-ionosphere waveguide. The computation starts by obtaining the product of the total power (a) times the polarization ratio sign (b). The result is a frequency-time matrix (c) containing the intensity-weighted polarization ratio. Using the times and frequencies of the event occurrence, a subset of such matrix was selected. Finally, the sum of the subset elements was normalized using the sum of the total power matrix. The outcome is a single scalar value representing the event's sense of polarization. This process was performed for each banded event. From these representative values we found that $\sim 95\%$ of the events are dominantly left-handed polarized.

Figure 2. (a) Frequency range distribution of the observed banded structures. The red horizontal lines indicate truncation due to interference of navy transmitters. (b–g) Example analysis of spectral shapes of two distinctive events (left and right columns). (b and c) Frequency separation as a function of time for consecutive band elements. (d and e) Frequency separation as a function of frequency for consecutive band elements. (f and g) Frequency drift rate as a function of time for selected elements.

3. Spectral Analysis

The left and right column panels of Figures 2b–2g show spectral features of banded emissions observed on 15 December 2017 and 21 February 2019, respectively. The data gaps are due to navy transmitters interferences. Figures 2b and 2c show the time evolution of the frequency separation. These frequency separations correspond to at least three pairs of contiguous band elements calculated for at least five different times along the elements duration. In total, data sets of at least 15 frequency separation points were obtained. A linear fitting was made, and the resulting line was used to compute the absolute and relative frequency separations. The absolute frequency separation is the initial and final separation difference, while the relative frequency separation is the ratio of the absolute to the initial frequency separation. The same analysis was applied to

Figure 3. Histograms of (a) slopes and (b) median values of the frequency drift rate of band elements. (c) Frequency separation of consecutive spectral band elements.

all the events. From a statistical distribution of the absolute values, a median increase of 119 Hz was found, with lower and upper quartiles of 33 and 478 Hz, respectively. Employing the same analysis but using the relative values, we found a 21% median increase in frequency separation, with lower and upper quartiles of 3% and 48%, respectively.

Figures 2d and 2e display the frequency separations of consecutive band elements as a function of their observed frequency. These separations were obtained in two steps: first, at least five different times during the event duration were selected; and second, for each time, the difference in frequency between consecutive band elements was calculated. These steps were applied to all events in order to analyze the frequency separation as a function of frequency and to compute their slope and median values. Analysis of the median values is presented in the last paragraph of this section. For the data set displayed in Figure 2d, a slight positive slope of 0.01 (dimensionless) is observed; while for the data in Figure 2e, the frequency separation is independent of frequency. From a statistical distribution of the total number of events, 70% of the slopes lie in the range -0.01 to 0.02 . Furthermore, the frequency separation increases with frequency in 65% of the events.

Figures 2f and 2g show the frequency drift rate as a function of time for the same band elements used to compute the frequency separation as a function of time (Figures 2b and 2c). Figure 2f shows that initially the drift rate was high and then it decreased, finally remaining stable with a median value of 5 Hz/s and fairly high variance. For the event shown in Figure 2g, analogous decrease is also seen but less evident. The event median value is ~ 1.5 Hz/s, and the spread is much smaller. The same analysis was applied to all events, and their slope and median values were calculated. The slope values range between -0.17 and 0.46 Hz/s². However, most slope values lie in a narrower range (Figure 3a), with median value of $\sim 10^{-3}$ Hz/s², and lower and upper quartiles of $\sim -7 \times 10^{-3}$ Hz/s² and $\sim 6 \times 10^{-3}$ Hz/s², respectively. The median values of the frequency drift rate range between -7.6 and 43.7 Hz/s. From a histogram analysis of these values (Figure 3b), a median of 4.5 Hz/s is obtained, with lower and upper quartiles of 1.6 and 8.3 Hz/s. Additionally, in as many as 81% of events, the sign of the frequency separation change and the sign of the frequency drift are the same; that is, they tend to increase or decrease simultaneously.

The median of frequency separation as a function of frequency (e.g., Figures 2d and 2e), ranging between 300 and 2,000 Hz was used to compute the histogram shown in Figure 3c. From the histogram a median value of 576 Hz is obtained, with lower and upper quartiles of 452 and 818 Hz.

4. Discussion

We have identified and analyzed 95 VLF emissions, in the range 16–39 kHz, with BS measured during several campaigns carried out between 2006 and 2019 at Kannuslehto (Northern Finland). To the best of our knowledge, this is the first time such emissions are reported in a not well-explored VLF frequency range. To explain our observations, two different hypotheses can be put forward. First, they might be due to plasma instabilities in the magnetosphere, as in the case of structured auroral hiss (Titova et al., 2007). Second, they could be formed in the Earth-ionosphere waveguide, as in the case of long-distance propagation of lightning generated VLF emissions (Záhlava et al., 2015, 2018).

As far as we know, there are only two reports of possibly similar banded emissions observed on the ground, but they were observed at much lower frequencies than 16 kHz, more specifically, below 9 kHz. Andrianova et al. (1977) reported emissions observed at midlatitudes, during high geomagnetic activity and occurring independently on the local time. Titova et al. (2007) reported emissions observed at high latitudes, during quiet geomagnetic conditions and between 19:00 and 23:00 MLT. The authors named them banded structures (BSs) in auroral hiss and proposed that they can be related to a resonant interaction (either in the generation process or via absorption) of VLF waves with protons in the upper ionosphere and magnetosphere. BS emissions were also observed using rockets and satellite sensors (Kintner et al., 1991; LaBelle & Treumann, 2002). Although the monitored frequency range spanned up to 16 kHz (Kintner et al., 1991), the emissions were identified only at frequencies up to 7 kHz. Interestingly, the frequency separation between the bands, which the authors found to be related to proton gyrofrequency harmonics, are of the same order as the typical values found in our study.

Based on previous observations and the unusual characteristics of our observed events, we can consider that the emissions presented in this study may be the same as those presented by Titova et al. (2007). In fact, making an analogy, we can extrapolate their event characteristics and contrast with our events. We note that both are observed on the ground at high latitudes, equatorward from the auroral oval, and during magnetically quiet periods. Their local times of observation are also comparable. However, the duration of BS hiss has a longer range (30–300 min) than ours (4–110 min). The difference in the range of durations may not be relevant, having in mind that only 12 events were analyzed by Titova et al. (2007). Regarding fluxes of auroral particles, half of our events are associated with significant charge particle precipitation.

According to Titova et al. (2007), the frequency separation between adjacent bands of BS hiss lies in the range 200–300 Hz, corresponding to proton gyrofrequencies at altitudes between 4,000 and 3,000 km (Titova et al., 2007). In our case, detailed analysis of event internal structure reveals that their typical frequency separation is within the range 452–818 Hz. This would correspond to proton gyrofrequency at altitudes below 1,400 km for the Kannuslehto location. The intensity modulation related to the proton cyclotron frequency could naturally explain why the observed frequency separations of consecutive spectral band elements are approximately constant. Furthermore, the same signs of the frequency separation change and the frequency drift observed in most of the events (81%) can confirm a resonant interaction of VLF waves with protons at harmonics of the proton cyclotron frequency. Certainly, more analysis is needed and it would be thus very helpful to analyze VLF measurements from low Earth orbit satellites in order to verify whether the emissions are indeed coming from above the ionosphere or not.

Surprisingly, the observed emissions with BS presented in this study are typically left-handed polarized. Should the observation be due to auroral hiss, right-handed polarization might be expected. However, the wave polarization can change to left-handed during the subionospheric propagation, as left-handed polarized waves are comparatively less attenuated and better confined to the Earth-ionosphere waveguide. Thus, if the ionospheric entrance point (to the waveguide) of the auroral hiss is situated at a distance long enough, then the original elliptically right-handed polarized signal would eventually become left-handed polarized (Ostapenko et al., 2010; Yearby & Smith, 1994). Another possible explanation might be that the waves are generated by lightning emissions. When these emissions propagate considerable distances inside the Earth-ionosphere waveguide, they become primarily left-handed polarized, as the right-handed polarized part of the signal continuously escapes to the outer space in the form of whistlers (Ostapenko et al., 2010; Santolík & Kolmasová, 2017; Yedemsky et al., 1992).

Considering the hypothesis of lightning generated VLF emissions propagating inside the Earth-ionosphere waveguide, it appears that the occurrence of banded emissions may be associated with the presence of bursts of lightning emission, such as sferics and tweeks, or intense preliminary breakdown pulses (Kaspar et al., 2017; Kolmasová et al., 2016, 2018). An example of this is shown in Figures 1e and 1f. We point out that although the time duration of a single sferic or a preliminary breakdown pulse is much lower than the typical length of observed events, for long time series a sequence of many consecutive sferics or preliminary breakdown pulses may form nearly continuous emission bands (Záhlava et al., 2015, 2018). Thus, the event formation may be related to the propagation of VLF lightning emissions in the Earth-ionosphere waveguide and to changes in the emission's frequency spectrum. Eventually, the long distances travelled by the sferics

before being observed (in the form of banded events) seem to be consistent with the power loss leading to the rather weak total power displayed in the spectrograms.

VLF waves in the 12–18 kHz frequency range are least attenuated when propagating inside the Earth-ionosphere waveguide. (Wait & Spies, 1964). Then, one may expect that the lower and higher frequency parts of the signals effectively disappear at larger propagation distances. We assume a train of at least two wave packets (pulses resembling the shape of preliminary breakdown pulses or long-distance sferics), of 0.5-ms duration, 30-kHz frequency, and with a time separation between pulses of 1 ms. The spectra of such a signal consist of a number of bands separated by 1 kHz. This picture suggests us that the frequency separation between wave packets could be related to the time separation between pulses. If the frequency of such signal is shifted, a shift in its spectrum emerges giving the appearance of band elements. To complement this suggestion, a synthetic signal with pulses and its frequency-time spectrogram of power spectral density are shown in Figures S2 and S3 in the supporting information.

A rough estimation of the lightning generation region using the sferics observed during the banded events (e.g., Figure 1f) suggests that they are located in a range of 5,000–7,000 km from the receiver. We have verified, using the World Wide Lightning Location Network (WWLLN) data, that significant lightning activity accompanied every event within distances of 7000 km from Kannuslehto.

The lack of observation of banded emissions after midnight MLT can be explained by the intensification of tens to keV electron precipitation occurring after that time. Precipitating electrons, coming from the magnetotail and travelling to the morning side sector, increase the ionization of the ionosphere's lower boundary. The increase in ionization results in low reflection heights and strong attenuation (Hunsucker & Hargreaves, 2003). As a result of this, the VLF lightning-related emissions, generated by any of the various processes that comprise a lightning, cannot propagate efficiently, or may even vanish. A similar argument can be given to justify why banded events tend to stop being observed before the growth phase of substorm, which is a period in which particle precipitation affects the ionosphere. Furthermore, lightning-induced particle precipitation (e.g., Barr et al., 2000; Inan et al., 2010) can also occur.

Certainly, more data are required to be able to confirm whether the BS events presented in this article are of the same nature as BS in auroral hiss or result from lightning related emissions propagating in the Earth-ionosphere waveguide. Coincidentally, we found out that there exists at least one recent work, Lebed et al. (2019), which Figure 3 suggests us the presence of emissions with BS. Yet this observation happened below 8 kHz and was made at a different place and with different equipment than ours. This could imply that the phenomena we observe may not be so uncommon after all. Finally, we consider that the observations presented in this paper and their particular characteristics open interesting research possibilities in a new VLF frequency window. Thus, it will be very good to investigate and report more observational data, especially if they also include electric field measurements and if they are obtained at different geographical locations.

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